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Energy Internet:
Cyber-physical Deployment of Future Distribution Grids

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Definitions

Energy Internet is a concept broadly used by researchers and other practitioners indicating the increased use of information and communication technologies (ICTs) in the management of decentralized electric power grids with distributed energy resources. The Energy Internet is conceptually similar to the (Data) Internet (The Economist, 2004).

More precisely, the Energy Internet refers to a large-scale cyber-physical system built upon packetized energy management of flexible loads in single or networked microgrids, enabled by the advances in ICTs, especially machine-type communications (Nardelli et al., 2019).

1 Introduction

Energy decarbonisation is critical to mitigate the adverse impacts of climate change. Today, nearly 66% of the global greenhouse gas emissions is a result of using energy from fossil fuels (International Renewable Energy Agency (IRENA), 2019a). Renewable energy is a globally recognized pathway to substantially reduce these emissions without compromising on energy access for all. As a result, the electric power sector has increasingly adopted renewable energy sources (RES) as a way to reduce the industry's carbon footprint.

RES-based distributed energy resources (DERs) are being installed across the world at a rapid pace. By the end of 2017, the installed capacity of renewables comprised 34% of the total power-generating capacity (International Energy Agency (IEA), 2018). Variable renewable energy (VRE), especially wind and photovoltaics (PV) technologies, has demonstrated tremendous growth—the global installed capacity of PV increased more than seven-fold between 2005 and 2016, while onshore wind capacity increased nearly three-fold (International Renewable Energy Agency (IRENA), 2019b). At the same time, global electricity demand is also increasing. Electricity demand grew by 4% in 2018, at nearly twice the average rate of growth since 2010, and it is estimated to increase by 90% from 2018 to 2040 (International Energy Agency (IEA), 2018, 2019). And, as a result of the higher electricity consumption, CO_2 emissions rose by 1.7% in 2018 and created a new record. Hence, it is critical to further accelerate the energy transition and significantly increase the participation of RES-based electricity production systems in the electric power system.

RES-based DERs in power distribution grids, especially PV and battery energy storage systems (BESS), are typically installed in a distributed manner. This represents a paradigm shift for the electrical power supply industry that has so far employed a top-down electric power system architecture to deliver electricity. In the traditional power system design, centralized electric power production plants supply electricity via long transmission lines to distant customers. In the new distributed architecture, electricity flows bidirectionally, leading to a range of challenges and opportunities. Bidirectional power flows cause problems in the quality, reliability, and safety of power supply, and the traditional power system is not equipped to handle them. Therefore, new technologies, equipment, methodologies, and innovations are needed to ensure that the electric power system can efficiently and intelligently handle the bidirectional power flows. The electric power grid must be upgraded and modernized to a "smart grid" to meet these modern challenges (Nardelli et al., 2014).

The smart grid enables systematic communication between intelligent devices in the grid with the objective to manage the power flows caused by DERs, such as PV, BESS, and electric vehicles (EVs), as well as flexible loads (i.e., loads that can be time-shifted). Since intelligent electric devices (IEDs) continuously exchange information, data flow and information management are central to the smart grid. As a result, the smart grid concept emphasizes the *application* of digital processing and communications to the power grid. In other words, communication infrastructure systems are the backbone of future power grids. Therefore, it is important to develop a robust and resilient communications network system that enables effective management of the smart grid.

The Energy Internet is a cyber-physical system enabled by such a communications infrastructure, firstly conceived to support the implementation of modern smart grids. This new concept specifically refers to the packetized management of future energy systems composed of networked microgrids, mirroring the way in which exchanges are managed in the (Data) Internet. In this sense, while the smart grid *applies* information and communications technologies (ICTs) to improve the operational efficiency of the power grid, the Energy Internet *is constituted* by communication technologies from scratch. Roughly speaking, power grids can work without the ICT features that make them smart grids; the Energy Internet, on the other hand, cannot work nor exist without ICTs.

In the next section, we will describe the historical background of the Energy Internet and introduce some important published literature in the field. In Section 3, we define the Energy Internet and discuss its underlying concepts in greater detail. Section 4 introduces the challenges to the practical deployment of the Energy Internet and the consequent research opportunities.

2 The Energy Internet: Background

The Energy Internet vision takes inspiration from the Data Internet, i.e., the connected architecture adopted by the computer industry in the 1980s and 1990s based on packet switching. In just two decades, the computer industry moved from traditional centralized mainframes to a client-based distributed computing infrastructure that was networked to a worldwide *Internet* (e.g., refer to (Leiner et al., 2009)). Internet users were not only connected to other users across the entire world but could also actively participate in the network by exchanging data. Data Internet users could act either as producers or consumers of data. This led—and is still leading—to massive technological innovations and productivity enhancements in multiple sectors and industries (Huang et al., 2011). Moreover, the current omnipresence of Internet-based mobile connectivity changed society and their constitutive social relations in disruptive, many times unpredictable, ways.

Over the last two decades, researchers in electric power systems endeavored to achieve a similar shift by trying to develop new distributed and connected architectures with the following broad objectives:

1. To support high proliferation of RES-based DER;
2. To ensure that the supplied electricity meets the required quality standards;
3. To support consumers to play developmental roles.

In 2004, *The Economist* published an article "Building the energy internet" that depicted its vision of the future energy systems (The Economist, 2004). Any network has to not only manage data (or power) but also be resilient enough to quickly and effectively handle disruptions. Therefore, *The Economist* visualized future grids to mirror the Data Internet's ability to react to a crisis (e.g., the failure of a network link) by re-routing data packets swiftly and efficiently. The future electricity grid would then be "smarter" (i.e., able to adapt to changes in operational conditions in smaller time-scales) and "more intelligent" (i.e., capable of learning, planning, coordinating, and organizing its smart elements). The grid would be "self-healing" with real-time sensors and "plug and play" software creating an Energy Internet that enables RES-based DERs to attach, communicate, and manage (i.e., organize and coordinate) their operations.

One of the ways that the Energy Internet, as understood by *The Economist*, can support the interconnection of the distributed components of a power system is by *discretizing electrical energy into packets*. The *The Economist* article itself explicitly stated that "packet-switching energy" would be impossible. However, such approaches to energy networks using discretized energy packets in a similar manner to the management of data networks is not impossible and was not even a new concept at that time. As early as 1996, two Japanese researchers Saitoh and Toyoda had introduced the concepts of "open electric energy networks" and "packet electric power transportation" (Saitoh and Toyoda, 1996). They had proposed a conceptual system where excess energy is packetized and used based on the demand patterns from the consumers.

Their work inspired Abe et al. to propose the concept of a "Digital Grid" more than a decade later (Abe et al., 2011). The large connected grid is divided into smaller sub-grids (so-called *cells*), which work asynchronously but are connected via digital grid routers. These routers need to communicate to send power between the segmented grids into cells while connecting them via power lines that exchange physical energy packets. Using Internet protocol (IP)-inspired addresses and power line communication (PLC), the authors claim that their proposed architecture would lead to a more efficient use of power lines and accommodate distributed sources, enabling the development and operation of new digitalized services.

This research was further extended by the development of a router-to-router transfer, creating a networked power packet distribution system (Takahashi et al., 2015). An intelligent power router was proposed to fully control the power flow by using voltage source converters. The operation of the router was validated in both test-bench experiments and with simulations (Rodriguez-Bernuz et al., 2015). Another approach toward building an Energy Internet was envisaged in Tsoukalas and Gao (2008), where alternate current (AC) power was treated as discretized packets by using cyber-physical packets.

Recent contributions are conceptually closer to a more holistic idea of the Energy Internet and attempt to solve its many sub-problems. In Ma et al. (2018a) and Ma et al. (2018b), the authors proposed a distribution grid with local area packetized power networks. This essentially creates an Energy Internet based on physical energy packets. In 2019, Zhang et al. (2019) considered a multi-router local area packetized power network (LAPPN) and proposed a power packet dispatching protocol to achieve peer-to-peer (P2P) power transmission in the LAPPN. Optimal routes were determined for power packets with the objective to maximize the utilization efficiency of the power packets.

Since electricity production from RES-based DERs is variable due to its dependence on the weather conditions, mismatches between production and demand become harder to predict and consequently to manage. In this context, load flexibility becomes important to support the grid operation to allow some particular electrical loads to be shifted following the energy availability. Due to the decentralized nature of the Data Internet, a few concepts from communication network theory were revisited for load shifting via packetized energy management. For example, a technique based on tokens and queueing system models was proposed for the load management of air conditioners in large apartment complexes (Lee et al., 2011). Zhang and Baillieul formalized the concept of packetized direct load control and then extended it to enable the desired appliance to request the consumption or withdrawal of energy packets according to its requirements; they designed and implemented a queuing system to achieve this objective (Zhang and Baillieul, 2012, 2013). In Rezaei et al. (2014), Rezaei and Frolik described a decentralized packetized approach to manage electric vehicles' charging. Almassalkhi et al. (2017) presented a packetized energy management scheme to asynchronously and anonymously manage thermostatically controlled loads such that grid requirements are fulfilled and without any specific knowledge about the loads' state. A packetized energy management methodology was investigated systematically in Espinosa et al. (2018) where the authors considered a system in which different loads request energy packets to an energy server, that may grant, schedule, or not grant these requests. In a more theoretical vein, Gelenbe and his team conducted an analysis and demonstrated that energy packet networks rely on the G-Network theory, which is a a generalization of queuing theory that incorporates traffic re-routing and destruction (Gelenbe, 1994, 2012; Gelenbe and Ceran, 2016).

All in all, these contributions illustrate how Energy Internet concepts can be employed to effectively manage the potential flexibility in loads. In fact,

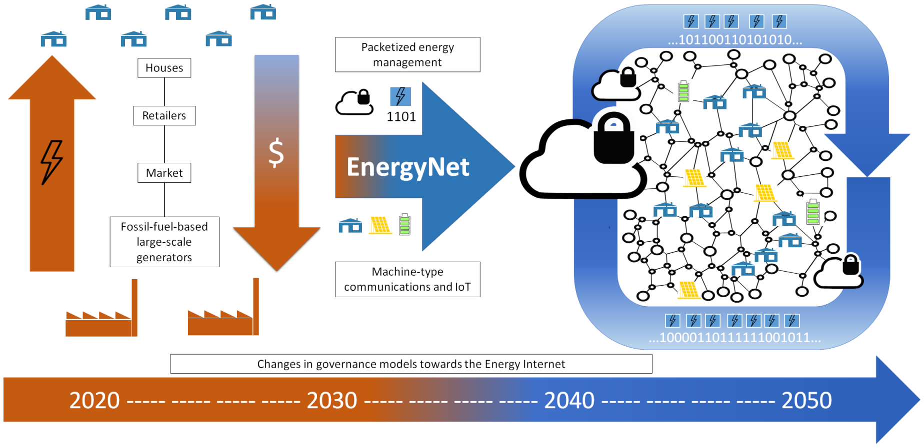

Figure 1: Global aim of enabling transition from today's non-renewable-energy-sources (NRES)-based power system to a RES-based power system built upon packetized energy management, which is enabled by machine-type communications. The end point of this transition is the Energy Internet.

some of these research results have been commercialized by the researchers in the form of a startup company called Packetized Energy (Frolik et al., 2018; Packetized Energy, 2019). In Almassalkhi et al. (2018), they describe their current results achieved by focusing primarily on the control-theoretic aspects of the solution.

3 Energy Internet and its Characteristics

3.1 Definition

As shown in Fig. 1, the Energy Internet is expected to play an important role in the ongoing transition from the current fossil-fuel-dominated power systems to RES-based ones. Smart grids rely on ICTs to intelligently manage the large amount of data generated during electricity delivery and efficiently manage electricity grids. As mentioned before, the Energy Internet is more than this: it is an upgraded modern power system with a constitutive underlying ICT framework to support the grid operation. Nevertheless, a clear definition of the Energy Internet is yet to be formulated in the literature.

Up to this day, the most appealing definition of the Energy Internet follows Nardelli's and Ma's conceptual view that the packetized energy management is the key constitutive operation that makes "the Energy Internet becoming the Energy Internet." In this sense, the Energy Internet is defined as the *large-scale cyber-physical system that virtualizes and discretizes electric energy in packets to manage supply and demand in distribution grids, considering the existence* *of BESS and flexible consumption*.

Roughly speaking, the basic idea of the Energy Internet is to virtually split energy into packets to be consumed during a certain time period, e.g., x Wh in y minutes. This basic idea is exemplified in Fig. 2. Here, three residential households with appliances that employ "intelligent" switches send energy packet requests to fulfill their service needs, and an energy server manages their requests. The main energy production is from RES so that the energy server has the function of allocating the available energy resources such that supply and demand match each other. In the example, House 1 send a request at 20:00 to use a washing machine whose program has a predefined energy packet need for one hour and fifteen minutes continuously, and the service must be completed by 6:00 in the next day; this request is not flexible and can only be accepted or rejected. House 2 requests an EV to begin charging when the car arrives (in this case, 17:30) and to finish by 8:00 in the next day; since this load is flexible, the packets can be distributed during this period if the final goal is reached. House 3 requests at 7:00 that the house needs to be maintained at 23 $^\circ$C at 16:00 considering that the internal temperature is between 15 and 30 $^\circ$C; this allows for greater flexibility in packet delivery (many packets in a short period, or slow heating through a longer period).

The energy server takes decisions on the basis of many factors such as network congestion, storage level, load priorities, and predicted generation (that can be supplemented by external sources). The ultimate optimization objective underlying the decision making may be minimizing household costs or system costs or maximizing self-sufficiency based on the microgrid energy inventory.

3.2 Characteristics of the Energy Internet

The Energy Internet focuses on the required technological developments in ICT necessary to realize a future free of fossil fuels. The proposed vision considers that electricity customers in current retail markets will become part of new governance models that will regulate the electricity exchanges between (small-scale) producers, prosumers, and consumers within microgrids whose management will be based on packetized energy. To manage new distributed architectures, energy routers and servers (secure clouds) should work autonomously and hierarchically to regulate energy exchanges based on intelligent switches.

Ideally, the Energy Internet requires (and presupposes) certain technical characteristics for it to function as intended to support the (physical) electrical grid. The main characteristics are as follows:

1. **Speed**—Communications should be fast and be able to support short-term (milliseconds in grid protection mechanisms) to long-term (hourly, if

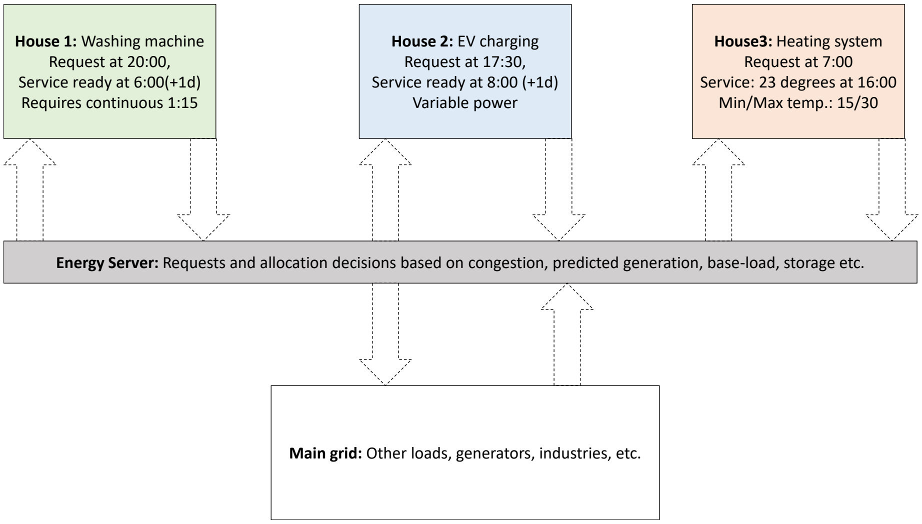

Figure 2: Example of an Energy Internet concept in which three households request energy packets to be supplied. The energy server considers many factors such as network congestion, predicted generation, storage level, and load priorities before managing their requests. Adapted from Nardelli et al. (2019).

following some electricity markets) to super-long-term time scales (days to years, for market players' strategic decisions).

2. **Scalability**—The Energy Internet should be able to accommodate thousands of IEDs.
3. **Low latency**—The communication network should allow for arbitrarily small latency for specific applications (e.g., protection).
4. **High availability**—The communication system shall be available to be used when needed.
5. **Security**—Intruders should not be able to disturb or harm the communications network in any way.
6. **Privacy**—All communications and data should be kept private (unless there are other requirements).
7. **Reliability**—Communications should not stop under emergency conditions, and if they do, there should be adequate backups.

Note that different applications may require a different subset of these characteristics, but the Energy Internet as a whole will need all of them to be present.

4 Challenges and Future Researches

The Energy Internet concept envisages a highly integrated and connected network of power electronic and smart grid devices that are optimally coordinated to efficiently manage and deliver electrical power based on energy packets. This Energy Internet vision is ambitious and challenging, but also critical to achieve climate change goals. To build a robust Energy Internet, it is important to take advantage of the massive connectivity, ultra-reliability, and low-latency guarantees promised by the modern communication systems, especially in the machine-type communications (MTC) regime. MTC is a key enabler to build the Energy Internet because it provides ubiquitous wireless connectivity that can be leveraged to fulfill the strict quality requirements of the physical grid.

MTC, which is an essential component of the 5th generation of wireless networks (5G) and beyond, can be used for a wide range of heterogeneous smart grid applications with different requirements (Nokia, 2016). For example, the smart grid requires simple daily electricity metering to advanced real-time frequency control, and they can be solved using two parts of MTC—massive MTC (mMTC) and ultra-reliable low-latency communications (URLLC) (Nouri et al., 2018). mMTC incorporates applications with a very large number of connected devices (connectivity goal) while URLLC focuses on mission critical (high reliability and low latency goal) communication (Nouri et al., 2018). Thus, an mMTC technology can be used to integrate numerous and diverse sets of IEDs, and a URLLC technology can achieve the strict latency and reliability imposed by the electricity grid (Kuzlu et al., 2014). In the future, it is an important area to efficiently use MTC in smart grids for autonomous exchange of information to solve its data connectivity problems.

New governance models are also required to enable socio-economical solutions based on local markets or energy communities. In energy communities, the consumers transact and trade with each other to share their energy resources. However, such a P2P exchange of energy is challenging from the Energy Internet point of view because there may be additional transactions. For example, P2P energy trading is often enabled by local markets in which energy is purchased or sold at prices determined by bidding and auctions. As a result, the Energy Internet has to be extra robust to also account for monetary exchanges, sometimes at short time scales depending on the system setup. In this case, some type of governance models—either centralized or decentralized—could be developed to ensure smooth and privacy-enabled transfers of energy and its costs. Researchers have attempted to incorporate blockchain-enabled methods to enable these transactions but both proof-of-concepts and practical implementations are still nascent (Sousa et al., 2019).

Additionally, the social acceptability of an Energy-Internet-based solution is not clear yet and must be studied. The Energy Internet assumes active management strategies for monitoring and controlling the distribution network over a reliable communication infrastructure. As a result, customers may have serious concerns about privacy and security of their data. Further, the social impacts of such close monitoring of electricity usage are an important area of investigation. According to some researchers, the modern energy control-based solutions will have greater acceptance if the customers themselves are engaged in active participation in decision-making. For example, customers should be engaged to actively participate in demand-response programs hat require changes in energy consumption instead of just imposing top-down, price-based demand-response policies (Perlaviciute et al., 2018).

Current regulations in most electricity markets across the world are not completely aligned with recent advances in smart grid technologies and Energy Internet researches. Moreover, business models are also not synchronized, creating obstacles to a systemic modernization of the grid (Nardelli et al., 2014). For example, distribution system operators (DSOs) are not always keen to introduce new innovations quickly to the grid because they may adversely impact the quality of electric supply. In addition to theoretical advances, numerous on-field testing and practical implementations need to be completed to convince both regulatory bodies as well as businesses to implement the new ideas.

Overall, there are several indications that the Energy Internet can emerge via packetized energy management. However, the actual transition from the current (smart) power grid to the future Energy Internet is not guaranteed at all. Both technological and regulatory conditions should be aligned with socio-economic aspects based on specific governance models so that such a transition will actually occur smoothly. A smooth and uncomplicated transition to RES-based energy systems will have significant global impacts on the reduction of carbon emissions. And in this way, we can meet our common goal of building a cleaner and sustainable environment for mankind.

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