Convergence and Interoperability for the Energy Internet

From Ubiquitous Connection to Distributed Automation

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Abstract: To increase the share of distributed renewable energy resources and enable a flexible energy transaction network with customer-engaged production, innovative energy-aware service as well as real-time balancing of supply and demand, Energy Internet is proposed to integrate advanced IoT-based architectures, ICT-based end-to-end digital energy chains, customer-centric energy efficiency programs, energy-aware real-time platforms and intelligent distributed control algorithms. But how can we achieve convergence and interoperability of all these heterogeneous resources from different levels and domains? This article comprehensively discussed how IoT-enabled Micrgrids as controllable units to help achieve energy digitalization from two perspectives: one is vertical convergence from things-based communication to energy-based automation and the other is horizontal interoperability from Home Area Network (HAN) to Wide Area Network (WAN). Finally, the IoT-MGLab at Aalborg University is discussed as a specific instance to show how to establish an IoT-enabled Microgrid based platform for achieving Energy Internet.

1. Introduction

According to Jeremy Rifkin who is the principal social architect of the Third Industrial Revolution long-term economic sustainability plan, industrial revolutions are driven by the invention of new kinds of energy and their impacts on how people connect and share information. The First Industrial Revolution occurred in 1700s was driven by water and steam energy to achieve mechanized production, the Second occurred in 1800s was driven by electric energy to create mass production and the Third occurred in 1970s used electronics and information technology to automate production [1]. The expansion of the Third Industrial Revolution witnessed the development of the electronic-based automation, the computer-based Information and Communications Technology (ICT) as well as the universal access to renewable energy. It leads to the new energy stage "Energy Internet" which is the key trigger of the Industry 4.0. Energy Internet envisions a digitalized virtual world in which a customer-centric and ICT-based end-to-end digital energy chain is established with personalized production, individualized service, as well as maximized producer/customer interaction. Totally different from the electricity grid-centralized traditional energy system, to achieve the end-to-end customer-centric Energy Internet, it is necessary to consider the following features:

- Multi-directional flows of renewable energy resources will have great impact on grid reliability, stability and controllability.
- Random distributed energy generation will make utilities hard to do real-time prediction on generation and distribution at a given time.
- The role of customer changed into prosumer enables two-way energy trading. Sudden dips and jumps in energy generation and consumption make it hard to balance energy supply and demand in the grid level and even lead to blackouts.
- IoT-based smart loads enhance the customers' capability to manage and control their own energy generation, consumption and transaction with other ends. Comfort-oriented innovative services need to be developed to help customers make smart energy-aware decisions and cut the edge of energy supply chain.
- Various kinds of energy processing data are collected from customers and transmitted among different business platforms. It is a big challenge to integrate these IoT-based energy solutions into the existing energy platform.
- Ubiquitous connection highlights the need to protect customer-critical consumption data and private-aware management information. Leading-edge safeguards are necessary to be built to guarantee the cyber security layer by layer at all points.

Microgrid, which is playing a huge role of integrating variable energy units such as DERs, storages and controllable loads, has been regarded as one of the most essential parts to achieve smart grid and lead the future energy era of Smart Energy Internet. Especially with the emergency of IoT, Big data, AI, blockchain and 5G, Microgrids will have its wings to serve as the backbone of Energy Internet: coordinating things-based perception layer, network-based connection layer and analysis-based management layer at its best to maximize the value of power transaction. It is the key element to establish the interactive relationship among customers, the main grid and the distributed renewable energy resources. Fig. 1 shows the new roles of IoT-enabled Microgrid in Energy Internet from three aspects: 1) Renewable energy resource integration; 2) Grid stability and sustainability; 3) Demand-Response (DR) based energy optimization and individualization.

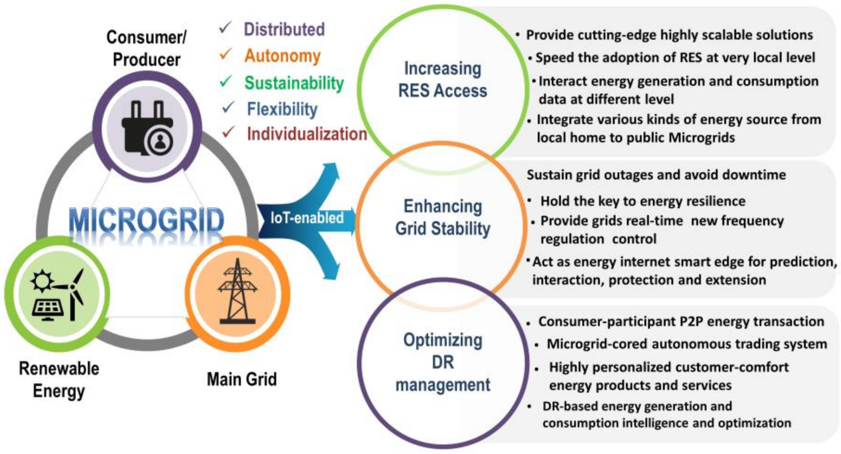

Fig. 1 New roles of IoT-enabled Micro grid

2. Vertical convergence: from things-based communication to energy-based automation

A. Vertical architecture from IoT based residential side to hierarchical control based Microgrid side

From IoT's perspective, to achieve ubiquitous communication, a general structure should consider:

- Ubiquitous sensing needs to be granted to the physical things to make them smart, including seeing, hearing, smelling, communicating and thinking.
- Ubiquitous network needs to be provided to make them connect and communicate with each other.
- Ubiquitous cross-sectorial services need to be cooperated to enable a customer-comfort ecosystem.

On the other hand, from energy's perspective, to achieve efficient automation, a Microgrid-based hierarchical control structure should be established based on the IEC/ISO 62264 international standard, which includes:

- Power quality control.
- Power quantity control.
- Business management control.

Fig.2 shows the closed-loop framework from things-based communication to energy-based automation.

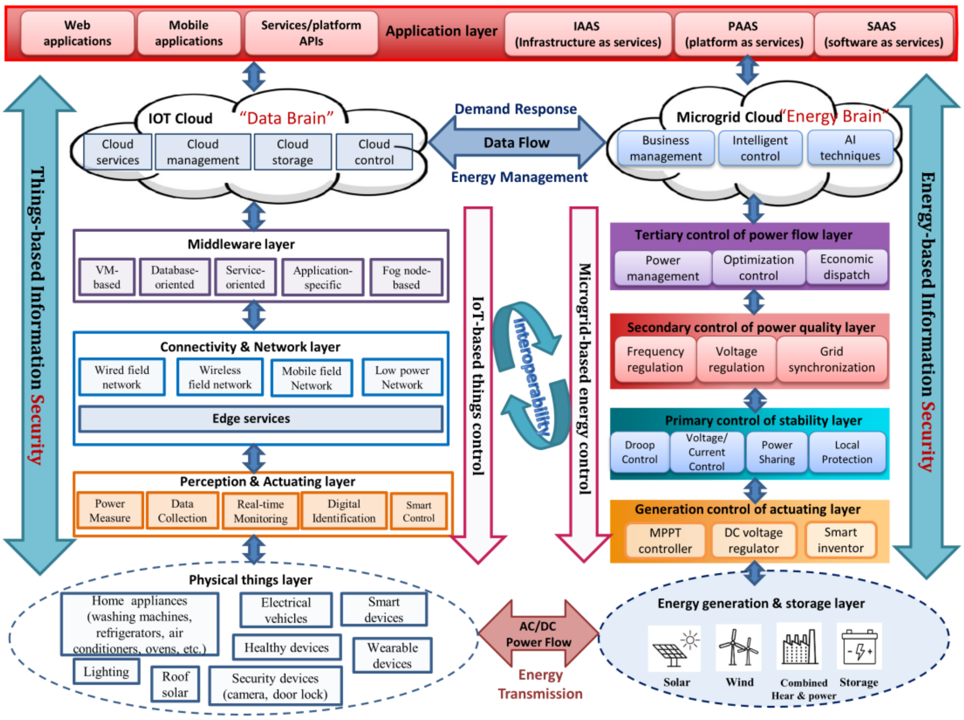

Fig. 2 Residential-based closed-loop distributed energy automation framework

(1) The residential-side five-layer IoT architecture

The IoT architecture acts as the backbone to support cross-device integration, cross-network integration, cross-data integration, cross-service integration and even cross-domain integration. Therefore, no single architecture could be agreed and be adapted universally to all specific IoT-based applications [2]. From the initial three-layer architecture to the Fog/Edge based architecture, the trend of IoT architecture tends to be more edge-smart, data-cognitive, scalable, interoperable, customized and extensible [3-4]. Cisco follows the Fog/Edge based architecture and proposes a seven-layer architecture, which introduces IoT "Edgeware" [5]. IBM proposes Watson IoT architecture and focuses on cognitive data processing, which introduces IoT "Dataware" [6]. Intel focuses on end-to-end values, which introduces IoT "Endpointware" [7]. Microsoft proposes Azure IoT reference architecture with high scalability by providing independent deployed key subsystems. It focuses on individual requirement, which introduces IoT "Serviceware" [8]. Considering the participation of Microgrid and the maximization of its roles in Energy Internet, the residential-side IoT architecture with bottom-up data flow and up-bottom control flow is defined:

1) **Physical things layer**： focus on physical convergence of devices involved in this IoT based system, including:

- Residential energy consumption devices for integration with smart energy, such as heating, ventilation, air conditioning (HVAC) system, home appliances (washing machines, refrigerators, air conditioners, ovens, etc.), lighting systems, smart devices, electrical vehicles, etc.
- Residential energy generation and storage devices for integration with smart energy, such as roof solar, roof wind turbine, home batteries, and mobile storage devices like electric vehicles.
- Security devices for integration with smart home, such as camera, door lock, smoke transducer, etc.
- Healthy devices for integration with smart health system, such as patient monitoring devices, fitness tracking devices, wearable tracking devices.

2) **Perception & actuating layer:** focus on how to make physical things smart. It enables things comprehensive senses, acts as a translator to identify various physical world languages and convert information into digital signals, which will be sent to the connectivity & network layer. To make the perception & actuating layer more intelligent and more autonomous, microchips with embedded intelligence can be integrated into sensors and actuators. Adapters can also be added to enhance the convergence of incompatible devices and systems. The main functional building blocks in this layer are: data collection, real-time monitoring, digital identification, power measure and smart control, which are achieved by:

- Sensors, such as smart meters, door sensors, humidity sensors, smoke sensors, motion sensors, solar radiation sensors, UV-Index sensors, temperature sensors, wind speed sensors, wind direction sensors, pressure sensors, etc.
- Control devices, such as smart switches, smart cables, smart relays, smart plugs, smart thermostats, etc.
- Adapters, such as software-based adapters, IC-based adapters, embedded adapters, etc.

3) **Connectivity & network layer**: focus on the convergence of telecommunication network carriers to connect Internet. Communication is the key backbone to IoT. This layer generally provides two kinds of network services: one is access network service to support IoT devices communicating with each other or with gateways, the other is routing network service to support standardized TCP/IP Internet communication. Moreover, to reduce clouds load and enhance real-time intelligent distributed automation, edge services are becoming more critical to be integrated in this layer before accessing Internet. Therefore, from the bottom up, this layer includes:

- Edge services, such as data storage, data filtering, data security, intelligent control, etc.
- Internet access devices, such as wired field network gateways, wireless field network gateways, mobile field network gateways, low power network gateways, etc.
- Core IPv6 Internet routers to support backbone network communication.

4) **Middleware layer**: this layer is focusing on how to provide seamless interaction between IoT devices and various applications from different domains. It acts as an intermediary bridge to pad the communication gap between the heterogeneity of physical things and the diversity of existing applications by abstracting the complexities of the lower layer. It is generally presented as a dynamically adapted software system and served as an interface between physical world and virtual world. Therefore, the middleware layer is the most challenging designable layer, which should consider architectural requirements (programming abstraction, interoperable, context-aware, autonomous, adaptive, service-oriented, lightweight, distributed, etc.), functional requirements(resource discovery, resource management, data management, event management, code management) and non-functional requirements(scalability, security, availability, reliability, real-time, privacy, etc.) [9]. The design solutions include:

- VM-based solution, such as Maté, MagnetOS, SwissQM, TinyVM, TinyReef
- Database oriented solution, such as SINA, COUGAR, IrisNet, Sensation, TinyDB, GSN, KSpot+.
- Service oriented solution, such as LinkSmart, SenseWrap, TinySOA, CHOReOS, KASOM, Servilla, Xively, CarrIoTs
- Application specific solution, such as AutoSec, Adaptive Middleware, MiLAN, TinyCubus, MidFusion, FIWARE KIARA.
- Fog node based solution: EMCP [10], sensiNact [11], eclipse kura [12].

5) **Application layer**: This layer is focusing on the convergence of a variety of cross-domain applications and cross-sectorial

services. It makes data useful and visible by providing added value services for consumers, suppliers and other third party stakeholders, such as increasing energy efficiency, enhancing demand-response (DR) based energy optimization and individualization, helping customers make smart energy-aware decisions, making real-time prediction on generation and distribution at a given time, balancing energy supply and demand in the grid level and so on. From Fig. 3 we can see that between application layer and middleware layer it is Cloud. Cloud in IoT is just like a living space for all the data (processed, communicated, generated, stored) in the middleware layer and all the services (software, platform, infrastructure) in the application layer [13-14]. The existing form of the Cloud contains: Public Cloud (owned by company), Private Cloud (private user can have his own entity over the public cloud) and Hybrid Cloud (integration of public cloud services and native cloud service to support multi-cloud management [15]. Applications are usually presented in form of services/platform APIs, web applications and mobile applications in various domains, including:

- Smart home applications: HAVC management, Remote monitoring & management, AMI, Security and privacy management, Environment control, Emergency alarm management, Energy consumption management, etc.
- Smart health applications: Healthcare monitoring and alert (pulse, respiratory rate, blood pressure, body temperature, etc.), Remote medical assistant, Sudden Infant Death Syndrome (SIDS), Electronic Health Record (EHR), etc.
- Smart energy applications: Automatic Meter Reading, Information Management Systems for EVs, Power Demand Management, Distributed Energy Resources Management, Energy efficiency monitoring and management, SCDAD, EMS, DR, etc.

(2) The Microgrid-side five-layer control architecture

The increasing injection of distributed energy resources from power factories and private homes will definitely have significant impacts on both the stability problem of grid like frequency/voltage regulation and the coordination problem of control objectives in different levels like DR-based energy efficiency management, maximization of renewable energy integration and reliability enhancement of energy system. IoT-enabled Microgrids can be taken as the controllable energy middleware with two operation modes (islanded mode and grid-connected mode) to bring benefits for both the main grid and the individual energy participants (consumers and providers). Based on the IEC/ISO 62264 international standard for a hierarchical Microgrid with three-level control objectives (primary, secondary and ternary) [16], this IoT-enabled Microgrid also contains five layers to coordinate with residential IoT-side architecture, converging information from energy consuming, generating and storage layer, providing hierarchical services (IAAS, PAAS, SAAS) to achieve hierarchical control objectives. Each layer is defined as follows:

- **Generation control of actuating layer**: The main source of renewable energy is generated from wind and solar. The characteristics of high fluctuation, nonlinearities, random dynamics and output uncertainties make the power supply not dispatchable. For the wind turbine, the objective of the generator side control is focusing on the maximization of energy power generation and the balance of the inertia mismatch between the mechanical and electrical power [17]. For the solar panel, generally, the power capacity is smaller than wind turbine and the inertia of PV system is compatible with the main grid. The most important objective is to provide as much power as possible to the system [18]. Therefore, the main function of this layer contains: 1) MPPT control . 2) DC voltage regulation control. 3) Smart inverter interface control**.**
- **Primary control of stability layer**: this layer is focusing on the autonomous reliability control of system without communication. Due to the lack of synchronous machines, Microgrids usually have fast dynamics because of the low stiffness and inertia, primary controllers should be fast enough to respond the change and maintain system stability in milliseconds. In islanded operation mode the controllers need to regulate voltage and frequency as well as achieve power sharing among various distributed generators, while in grid-connected operation mode the controllers need to synchronize safely with the main grid as well as ensure the system supply required for P and Q by external reference [19]. Hence, the main function of this layer contains: 1) Voltage stability control. 2) Frequency stability control. 3) Plug and play capacity control. 4) Circulating current suppression control.
- **Secondary control of power quality layer**: this layer is focusing on the accuracy regulation of both PCC voltage and frequency on the nominal value. Generally, the primary control layer only considers system stability problem and the droop control will cause the PCC voltage or frequency derivation due to the load variation. The secondary control layer will compensate the voltage and frequency derivation to remove the steady-state error as well as guarantee the seamless transfer between two operation modes. Both centralized structure and decentralized structure can be implemented in this layer's controller [20]. Communications are needed in this layer. The main function of this layer contains: 1) Frequency regulation control. 2) Voltage regulation control. 3) Grid synchronization control

- **Tertiary control of power flow layer**: this layer is focusing on the power flow control from high-level requirements, including power flow among different distributed generators, import or export of power from Microgrid to the main grid, power flow among residential energy resources, import or export of power from home to Microgrid. It is usually the highest control level of Microgrid system, so it takes the role to coordinate the demand from specific applications and the behaviors of energy resources to achieve various control objectives, such as doing real-time prediction on generation and distribution at a given time, balancing energy supply and demand at the global level, enabling energy-aware decision making for prosumers, optimizing energy flow from business perspectives, economic perspectives or environment perspective. Information including generator capacities, power demands, power prices and battery levels can be collected and communicated in real-time to achieve prediction control, optimal control and business control [21]. The main function of this layer contains:1)Power management control (business plan). 2) Optimization control (energy efficiency, environment protection, demand response). 3)Economic dispatch control (power price, balance of supply and demand).
- **Application layer:** this layer is covering both residential IoT side and Microgrid side. It achieves the convergence of cross-domain applications. There is still a Cloud on the Microgrid side as the "energy brain" to provide cloud services for Microgrid, such as business management services/platforms, intelligent control services/platforms and AI techniques support services/platforms [22].

B. Convergence of energy-efficiency platforms based on data-aware services

Generally, an IoT-based system involves a huge amount of sensors from different vendors. Firstly data-collection services will be needed and data-aware services will be provided based on different objectives, such as data storage, data processing, data analysis, data management and so on. Then the high-level applications will be developed to converge and integrate heterogeneous data sources from various kinds of platforms to enable cross-domain services for different purposes. Finally the corresponding control signals will be generated from hierarchical control services to achieve distributed automation. There are multiple kinds of platforms acted as data agent for connecting different types of data sources with different applications, such as platform and APIs [23], databases [24], storage files [25-26] or cloud-based systems [27]. Fig.3 shows the data flow and control flow between sensors/actuators of different domains and applications of different systems. Table 1 shows the summary of diverse kinds of platforms, in which typical applicable instances are listed out and the choice criteria are given.

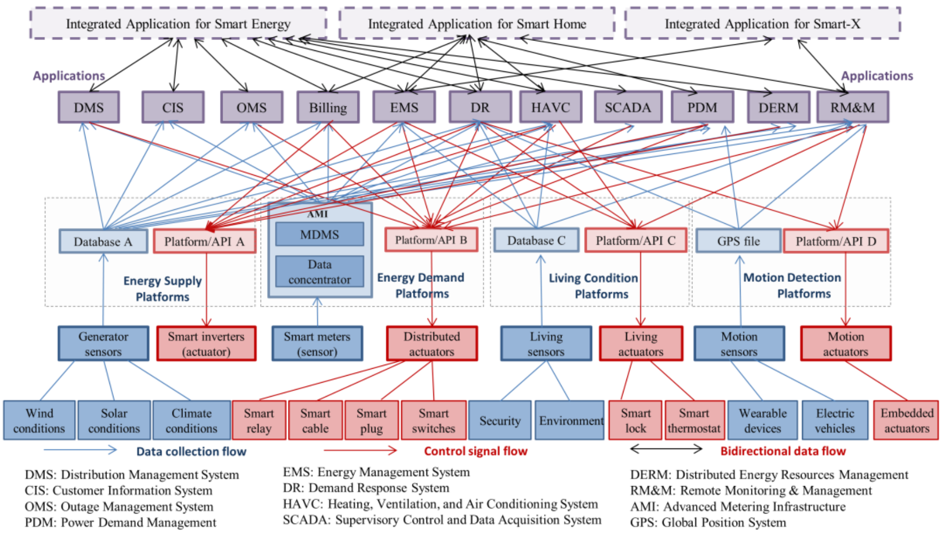

Fig. 3 Data flow and control flow between perception layer and application layer

Table 1 Summary of different platforms of IoT-enabled Energy Internet

Platform Types	Characteristics	Examples	Choice Criteria
Platform and APIs	▪ Provide services to collect data from IoT devices or IoT gateways. ▪ Provide services to manage data (processing, filtering, analyzing, visualizing, etc.) ▪ Provide kinds of components (security, storage, intelligent agent, context broker, ▪ Provide services to create customized components. ▪ Provide interface to connect with third party systems ▪ Provide scalability services for specific applications	▪ FIWARE ▪ Big IOT ▪ VICINITY ▪ Inter-IOT ▪ 52 North Timeseries API ▪ OGC SensorThings ▪ ThinkSpeak ▪ Amazon AWS IoT ▪ OpenRemote ▪ Xively ▪ WoTkot ▪ LinkSmart/Hydra	▪ Expect function coverage for specific domains ▪ Security scheme for hierarchical levels, such as end-to-end data encryption, access and authorization control (ruler-based, policy-based), activity auditing. ▪ Open APIs for interconnection and integration with other platforms and applications ▪ Scalability and flexibility for specific customized requirements ▪ Cost and extensibility ▪ Strength of vendor and partnership involved in

Databases	▪ Provide services to collect data from IoT devices or IoT gateways. ▪ Provide services for data storage and classification ▪ Provide services to interoperate with other platforms and applications	▪ CrateDB ▪ MongoDB ▪ TimeScaleDB ▪ InfluxDB ▪ RethinkDB ▪ SQLite	▪ Size and scalability for massive and fast increasing number of data sources ▪ Effectiveness and real-time ability to handle and process data ▪ Flexibility and capability to deal with heterogeneous data from various data sources ▪ Reliability and security ▪ Transportability and compatibility with other systems. ▪ Cost and maintainability
Storage files	▪ Provide services for data storage in structural ways in different format for easy to write and read. ▪ Provide services for raw data processing. ▪ Provide agent services for data exchange between different databases, platforms and applications.	▪ CVS file ▪ GPS file ▪ JSON file	▪ Lightweight data-interchange format. ▪ Language-independent format. ▪ Performance and Scalability. ▪ Interoperability and compatibility with multiple databases and platforms.
Cloud-based systems	▪ Provide more scalable and flexible services for data management. ▪ Provide worldwide services from a wide range of applications. ▪ Provide real-time and innovative services for fast response to market	▪ Google cloud platform ▪ Microsoft OneDrive ▪ IBM Waston IoT ▪ Cisco IoT Connect	▪ Scalability for handling increasing growth of IoT device numbers ▪ Connectivity and communication speed with various kinds of applications and data sources ▪ Security and interoperability ▪ Edge intelligence

3. Horizontal interoperability: from Home Area Network (HAN) to Wide Area Network (WAN)

To comprehensively describe how IoT-enabled Microgrids empower the interoperability of Energy Internet, a horizontal angle of view on the interaction of energy and information at different levels is given and shown in Fig.4.

A. Home Area Network (HAN)

HAN is a kind of local network deployed in the residential side and HAN is the first level of Energy Internet [28]. The role of consumer changes into prosumer and devices in HAN can be classified into two categories:

- **Consumer-side sensors and actuators:** smart sensors collect power consumption information of the residential side in real-time and send them to IoT gateways to achieve ubiquitous connection for the neighborhood area network communication [29]. Control units schedule the energy consumption priority of residential loads to minimize the electricity power bill of consumers. Smart actuators execute control signals from energy-aware services to achieve intelligent energy automation. Customers can make their own decisions on how to consume their energy.
- **Supply-side sensors and actuators:** smart sensors collect power generation information of the residential side in real-time and sent them to IoT gateways to support customers participating in the energy trading program. They can store or sell redundant energy to others after meeting their own demands. Therefore, energy can be traded among neighbors to reduce the operational cost and energy losses, which is formed into neighborhood area network. It can also relieve the demand pressure at the peak times of power consumption.

B. Neighborhood Area Network (NAN)

NAN is the second level of energy internet, which collects the information from multiple HANs and provides a platform for NAN to communicate with each other for P2P energy trading [30]. Gateways are the core elements to collect information from HAN and send control signals back to HAN. Gateways are also acting as the communication agents to automatically perceive the power fluctuations and demands of neighbors and then fast response to reach a consensus agreement regarding a certain rule of interest, such as nearest transaction principle, energy bidding mode, demand response management, etc. Electricity power will be transmitted through energy bus.

C. Field Area Network (FAN)

The central unit of FAN is the IoT-enabled Microgrid. As analyzed above, power management becomes more complicated than ever before due to the following reasons: firstly, various types of distributed energy resources with different volume and voltage levels from local home to Microgrid will participant in the power distribution program, which will cause the cross-edge integration problem and energy transaction problem. Secondly, large penetration of renewable energy resources will bring a huge source of uncertainties and randomness for the main grid, which will cause stability and reliability problems of the whole energy internet. Thirdly, to achieve DR based energy optimization and intelligent distributed automation, consumer-participant P2P energy program should be performed smoothly in FAN. With the support of Microgrid, there are five energy transmission modes in FAN: Home to Home (H2H), Home to Grid (H2G), Home to Microgrid (H2M), Microgrid to Grid (M2G) and Microgrid to Microgrid (M2M). It enables the Energy Internet more flexible, more observable, more interoperable, more controllable, more efficient, more intelligent and more economical. Customers can make their own decisions based on the power price provided by Microgrid or the main grid. If the price is low during the off-peak hours, customers can buy energy from the rid and save them in their own home storage device for future use. If the price is high during peak hours, customers can sell energy back to the grid to earn money. Energy can also be traded freely among neighborhood based on some energy efficiency rules.

D. Wide Area Network (WAN)

WAN is the highest level of energy internet, which serves as the backbone network to connect IoT-enabled Microgrid FANs, cloud of things (analysis services, platform services, data storage services, visualization services, management services, or extension services), big data related applications (deep learning, data science, machine learning, artificial intelligence, or big data analysis), web applications for and mobile applications for end users, and so forth [31-33]. From the horizontal view of Fig.4, it is clear that there are two kinds of bidirectional flows. One is data flow, which collects information from HAN to WAN and sends control signals back from WAN to HAN. The other is power flow, which is transmitted back and forth in HAN, NAN, FAN and WAN. The power flow is controlled by data flow. Thus, data services are running through the whole system from things-based perception to energy-based automation. There are three basic data services: the first one is data perception, the second one is data analysis and the last one is data automation. Among them, ***data analysis can be taken as the "system brain" to guide the advancement and intelligence of the system***, *which includes* **big data analysis, deep data analysis and real-time data analysis** **[34-36].**

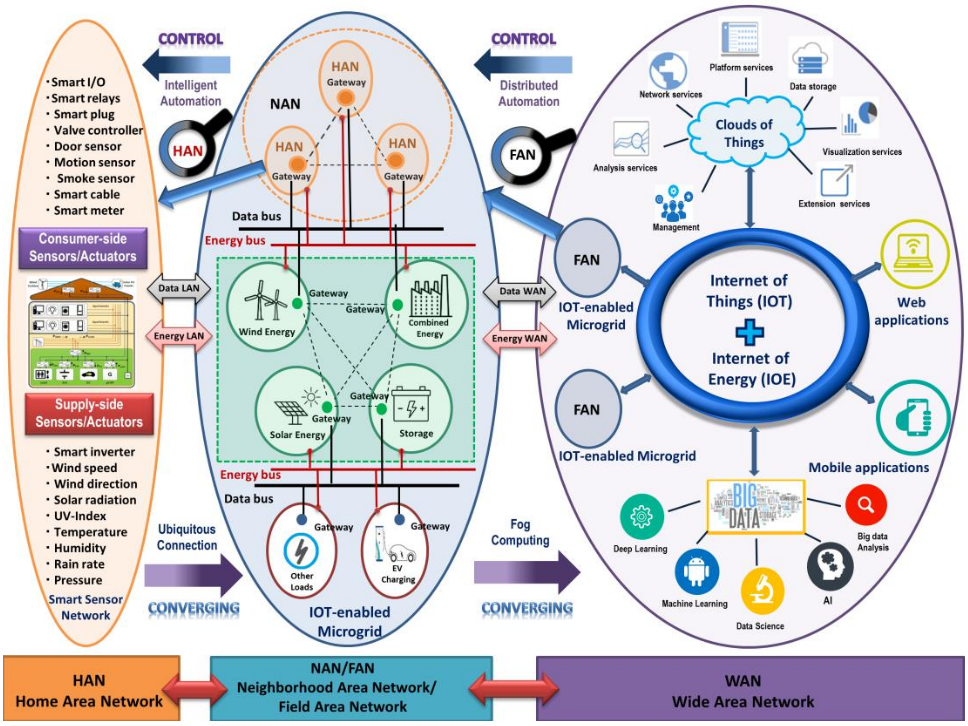

Fig. 4 Multi-level communication architecture of data and power from HAN to WAN

4. Case Study: IoT-MGLab in Aalborg University

The IoT-MGLab in Aalborg University is an example to achieve things-based convergence and energy-based interoperability by establishing an IoT-enabled Microgrid based platform, in which future smart home, smart energy, smart health and smart living will be largely expanded [37]. It intends to be developed as a pilot to help significant breakthrough in fundamental research on models, methods, techniques and supporting tools from different research areas, which includes: 1) cross-discipline integration of massive hot fields: energy, communication network, computer science, control, data science and AI; 2) cross-technology integration of communication network: wireless network, cellular network, low power WAN and power line communication; 3) cross-network integration of different modes: device to device, device to cloud, device to gateway and back-end data sharing model;4) cross-conversation integration of different context brokers: publish/subscribe patterns (MQTT, AMQP, JMS,...) and request/response patterns (HTTP, CoAP, SoAP,...); 5) cross-hardware integration of different devices: sensors, generators, storages; 6) cross-domain integration of different services: AMI, MDMS-based programs, EMS, HAVC, DR, SCDAD, Remote monitoring and management from smart home, smart energy, smart health and so on; 7) cross-sector energy transmission: Vehicle to Home (V2H), Vehicle to Microgrid (V2M), Vehicle to Grid (V2G), Vehicle to Vehicle (V2V) [38].

The IoT-MGLab uses FIWARE, an open source platform generated in Europe from the Future Internet Public Private Partnership (FI-PPP), to integrate massive services of different domains and applications of different systems. FIWARE has the following characteristics: 1) a market-ready open source framework defining a universal set of components to access and manage heterogeneous context information through open APIs; 2) a standard to facilitate the exchange of context information from various domains through FIWARE NGSI(next generation service interface); 3) a smart solution to provide a series of smart services for supporting data processing, analysis and visualization as well as for collaborating with external data access, publication and security mechanism; 4) a solid foundation to support easy plug & play integration with other shared resources across the entire value chain as well as to promote the development of new smart applications of various domains [39-40]. Fig.5 shows the implementation of FIWARE based on IoT-A standard reference architecture.

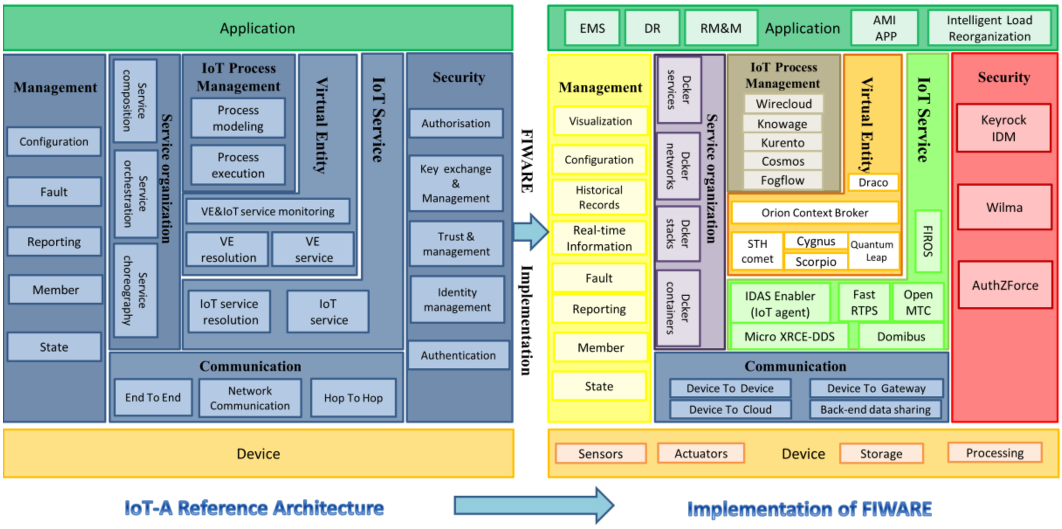

Fig. 5 IoT-A Reference Architecture and Implementation Instance based on FIWARE

Functions of every component in each layer of Fig.5 are listed in Table 2 and the implementation instance of IoT MGLab-based Energy Internet developed from FIWARE is shown in Fig.6. There are fore modules, which are Devices Layer, FIWARE Framework, Application Layer and System Portal. It can be seen that FIWARE framework is the organizer of all the resources across the entire value chain and it is responsible for the logic of data management and service regulation.

Table 2 Functional group in IoT-A and functional component in FIWARE

Functional Group (FG) in IoT-A	FG Function	Functional Component (FC) in FIWARE	FC Function in IoT MGLab
Security	√ Ensures the security and privacy of IoT systems; √ Ensures legitimate interaction between trusted peers	**KeyRock**	▪ PDP (Policy Decision Point) ▪ Identity management to implement secured access to component ▪ Enables OAuth2-based authentication and authorization security to users and devices ▪ Support user profile management, privacy-preserving disposition of personal data, Single Sign-On (SSO) and Identity Federation across multiple administration domains.
		Wilma	▪ PEP (Policy Enforcement Point) ▪ Enforce access control to backend applications ▪ Support OAuth2-based authentication schemas ▪ Support XACML-based access control schema
		AuthZForce	▪ PAP(Policy Administration Point) ▪ XACML Server ▪ support PDP/PAP functions within an access control schema based on the XACML standard
IoT Services	√ Enable interaction with real world √ Provide well-defined and standardized interfaces to access heterogeneous Resources	**IDAS Generic Enabler (IoT Agent)**	▪ IoT Agent for JSON:a bridge between HTTP/MQTT and NGSI ▪ IoT Agent for LWM2M: a bridge between the Lightweight M2M protocol and NGSI ▪ IoT Agent for Ultralight: a bridge between HTTP/MQTT and NGSI ▪ IoT Agent for LoRaWAN: a bridge between the LoRaWAN and NGSI ▪ IoT Agent for OPC-UA: a bridge between OPC and NGSI ▪ IoT Agent for Sigfox: a bridge between Sigfox protocol and NGSI ▪ IoT Agent library – library for developing your own IoT Agent.
		Fast RTPS	▪ Interface with robotics systems
		OpenMTC	▪ Open source implementation of the OneM2M standard
		Domibus	▪ Exchange electronic data and documents
		FIROS	▪ Interface between the robotics domain and the cloud
Virtual Entity	√ Provide functions to interacting with the IoT System on the basis of VEs √ Establish, Manage, update, retrieve and delete associations between VE's and IoT Services.	**Orion Context Broker**	▪ The core and mandatory component ▪ Enable highly decentralized context information management ▪ Manage the entire lifecycle of context information including updates, queries, registrations and subscriptions by NGSIv2 API
		STH Comet	▪ Store short-term historical data on MongoDB (typically months)
		Cygnus	▪ Manage historical data to be injected into multiple data sinks, such as PostgreSQL, MySQL, MongoDB or AWS DynamoDB as well as BigData platforms like Hadoop, Storm, Spark or Flink.
		Scorpio	▪ Support the new NGSI-LD linked data standard
		Quantum Leap	▪ Support the storage of NGSI data into a time series database like CrateDB and Timescale.
IoT Process Management	√ Implement smart behavior to process, analyze data from any applications and integrate with other IoT sub systems	**Wirecloud**	▪ Enable highly customized operational dashboard development
		Knowage	▪ Enable intelligent integration of business traditional sources and big data systems
		Kurento	▪ Enable real-time processing of media streams.
		FogFlow	▪ Support dynamic processing flows over cloud and edges.
		Perseo	▪ Enable Complex Event Processing (CEP) mechanism to trigger inter-action with other external systems, such as Web (HTTP), Email (SMTP) or SMS (SMPP) servers.
Service Organization	√ Acts as a communication hub to compose and orchestrate services of different levels of abstraction.	**Docker**	▪ Services: define configuration information of registered service with specific functions in containers ▪ Networks: manage networks to connect services in their own networks, provide foundation to build tiered applications and provide added values between each service. ▪ Volumes: the preferred mechanism for persisting data in Docker containers, specially design a directory in the container ▪ Images: the combination of a file system, libraries, tools and parameters with multiple layers, which

			is used to execute code in a Docker container ▪ Containers: the open source software platforms to abstract applications for further integration

This project has facilitates lots of multi-disciplinary research activities in IoT-based Energy Internet, such as implementation of open IoT infrastructures for smart home energy management [41], real-time energy management for the hybrid AC/DC residential Microgrid [42], techniques and challenges of achieving intelligent DC home [43], roles of smart meter and advanced metering infrastructure in smart home and smart Microgrid [44-45], hierarchical control strategy for the Internet of Things-based home scale Microgrid [46-47], energy management and control over IoT-based residential Microgrid [48-49], integration and interoperability techniques of future smart home and smart energy [50-51] and so on.

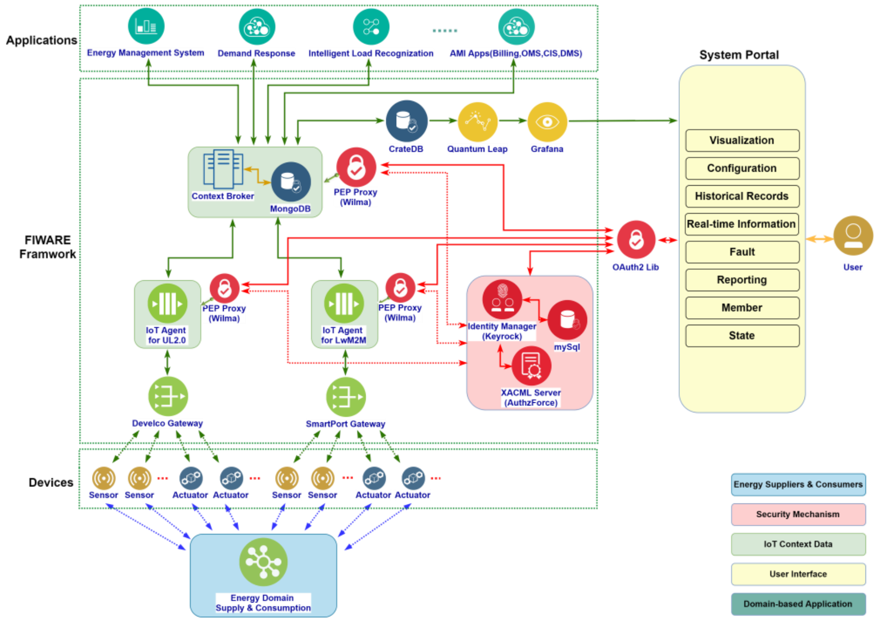

Fig.6 IoT MGLab – An Implementation Instance of Energy Internet based on FIWARE

5. Conclusions and Future Trends

With the fast development of wide-range technologies around Internet of Things and ubiquitous access of multi-direction renewable energy resources anytime and anywhere, the way we generate, distribute and consume energy is changing. Advanced IoT-based architectures, ICT-based end-to-end digital energy chains, customer-centric energy efficiency programs, energy-aware real-time platforms and intelligent distributed control algorithms are developed to support the modernization of Energy Internet. This article comprehensively discusses how IoT-enabled Microgrids help achieve convergence and interoperability of these heterogeneous resources to enhance digitalization and automation of Energy Internet. Related architectures, infrastructures, standards, models, technologies, services, applications and tools are analyzed respectively in detail to explain the digitalization progress from ubiquitous things-based communication to distributed energy-based automation [52]. The dynamic interaction relationship of data flow, control flow and power flow is also discussed in different network scales from HAN to WAN. The trend of Energy Internet is to create an online energy cloud that realizes universal energy trading modes, including H2H, H2G, H2M, M2G and M2M. Customer-centric platforms provide plug and play opportunities to expand cross-domain ecosystem over service composition, service orchestration and service choreography. With the modernization of Energy Internet, the energy paradigm will be developing towards four dimensions: clean energy, intelligent energy, mobile energy, and distributed energy. Energy cloud based technologies and services will be generated to unlock the value of energy chain over these four dimensions. This article also provides a comprehensive view on the roles of infrastructures (hardware, software) and opportunities of advanced technologies in the fundamental research of Energy Internet.

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