Energynet

National
Technology Initiative

CENTER FOR STRATEGIC RESEARCH NORTH WEST

Infrastructure Center EnergyNet

Internet of Distributed Energy Architecture

WHITE PAPER (PRELIMINARY VERSION)

DECEMBER 2018

IDEA
БИБЛИОТЕКА

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTERNET OF DISTRIBUTED ENERGY DEFINITION

1.1 AIMS OF IDEA

Conventional centralized architecture of power grids and power industry in the whole has exhausted to a considerable degree its potential of effectiveness. In the context of challenges that emerge for power industry on a global scale, its outdated architecture can no longer be considered capable of addressing these challenges effectively.

The most distinctive challenges that power industry faces in its development are:

- changes in the nature of consumer demand, namely increasing its diversity and moving to so-called "digital demand";
- the decrease in efficiency due to low utilization of existing grid and generating capacities and increasing operating costs of power systems;
- "Energy transition" (decarbonization, decentralization, digitalization): rapid spread of renewables, DER (distributed energy resources), new business models and services based on digital technologies;
- development of uninhabited and underdeveloped territories: remote and isolated areas require effective power supply.

Taking into account the above-mentioned trends and challenges, the key barrier to power industry development seems to be that the power systems are unable to address them without significant increase in costs and decrease in system's efficiency. The growing trend towards the use of renewables only exacerbates the inefficiency of the existing power systems, lowering the installed capacity utilization factor (ICUF) of power sources and requiring more peak and stand-by capacities.

Distributed energy, including small-scale power generation, energy storage systems, adjustable load on the side of end users will play the crucial role in upcoming development of power industry. These solutions, being interconnected and integrated into the centralized grid represent an untapped resource for raising the electrical efficiency of power systems and thus have a potential to address the current challenges.

Introduction of DER increases the efficiency of power grid due to lower dependency on connected capacity, emerging of local self-balanced low-scale generators and consumers, involvement of power assets of end users into power grid control. Thus, the power system that is capable to integrate new users with plug&play interaction and manage large numbers of DER in decentralized way can successfully address the above-mentioned challenges.

With present power grid architecture, the large-scale development of distributed energy is facing the growth of various costs:

- transaction costs that increase as the number of participants of each transaction grows;
- high capital expenses on digital integration of equipment into control loops;
- high capital and engineering expenses on integration of equipment into the grids and system stability maintenance costs.

Therefore, we must introduce a vision of decentralized power industry architecture where such costs are eliminated or reduced to their minimum while the distributed energy itself could increase operational efficiency of the grid.

The power grid based on new architecture will become:

Transactional: Economic interactions between users should be based on peer-to-peer-transactions that allow implementation of wide range of services that provide users with customized values. Within this paradigm the users can play various roles.

Smart: Simplicity of integration (plug&play) of power equipment into the loops of automated control of various services.

Sustainable and flexible: physical connection of equipment units with the grid should be established in a convenient and user-friendly way using plug&play technologies to ensure static and dynamic stability of the system where large number of devices and equipment units influence each other.

Users integrate into the system through specific interfaces and become participants of new services and business models. They can carry out transactions that will lead to optimal and coordinated work of power equipment while the sustainability of power system is ensured.

1.2 IDEA AND ENERGY TRANSITION

The Internet of distributed energy represents a decentralized power grid where smart distributed control is performed through energy transactions among users of the system.

The Internet of distributed energy as a new architecture of power industry has emerged as a systemic and technical response to the Energy transition — a global process that transforms the structure and composition of energy systems. The Energy transition is characterized by the following features:

- user requirements for operational parameters of energy systems become more diverse and sophisticated;
- types and components of power generating units as well as shares of power sources in energy mix experience transformation;
- new types of power equipment emerge, providing technological possibilities for energy systems users who can now exercise new functions within the power grid;
- new technological possibilities emerge in the fields of smart control and transaction cost reduction for power grid users that engage in economic relationships.

Energy Transition is often described with “3-D” concept: decarbonization, decentralization and digitalization.

Decarbonization — the transition to environmentally-friendly carbon-free economy and energy with the aim to globally reduce greenhouse effect. This process includes:

- increase of renewable energy share in global energy mix;
- phase-out of any technologies that lead to greenhouse gas emissions, including coal-fired power plants, gas heating systems, ICEs;
- increased share of electric transportation, especially private electric vehicles.

In advanced economies where hydroelectric potential is almost fully utilized, a growing share of renewables in energy mix is ensured by adding solar and wind energy and, to a lesser extent, biofuel usage and municipal solid waste (MSW) incineration.

Decentralization — the process of transition to geographically distributed energy resources with a high number of diverse power producers and consumers. This trend includes:

- increase in the share of decentralized, diversified and relatively low-power sources of various types (e.g. domestic PV or mini-CHP);
- the emergence of prosumers – a new kind of power industry stakeholders engaged in both electricity production and consumption. They can participate in demand response, energy storage, power generation for their own use or for feeding it into the grid;
- the emergence of active consumers who can flexibly change their electricity consumption profile using remote control;
- end users and other actors of power grid gain access to the means of control of the operational modes within the grid system.

Digitalization — the widespread application of digitally-controlled and Internet-connected devices, including generators, power grids as well as domestic devices and white goods. It speeds up the implementation of smart control through IoT and M2M (machine to machine) interaction.

The conventional architecture of centralized energy systems with its one-way power flow, hierarchical single market for electric power and capacity, centralized control, standardized quality levels and fixed roles can no longer satisfy ever-changing demands of new type of consumers, who are craving mobile, flexible and sustainable solutions.

It is no longer possible to build a power system which is capable to function effectively and sustainably within current centralized energy architecture once the energy transition trends are present.

We suggest that only DER-based power industry with decentralized control and distributed markets as well as high level of user involvement into grid control can lead to reliable, optimal, flexible and high-quality power supply, helping to address the challenges that energy transition brings.

1.3 IDEA CONCEPTUAL MODEL

The Internet of distributed energy is a kind of decentralized power grid, where smart distributed control is implemented based on energy transactions between system users (prosumers, active consumers, etc).

In this context, smart control represents a type of control performed using machine-to-machine interaction between system components through which each component can independently form a decision on its operational regime and possible impact on the system. It is made possible because the components analyze the information (digital) models of themselves, their surroundings and the system, and are able to coordinate their actions with the surrounding environment. The following are distinctive features of the Internet of distributed energy:

- decentralized nature of power grid that allocates vast numbers of decentralized consumers and producers of electric energy on the level of distribution networks;
- presence of two-way power flows and more flexible roles assigned to power grid users;
- digital communication and collaboration between electric power equipment units that exists along with electric interaction;
- entirely decentralized smart control which is performed based on machine-to-machine communication;
- peer-to-peer contracting for purchase and sale of electric energy as well as providing services within decentralized market;
- direct transactions between system users both trigger and manage all processes within the grid.

Therefore, Internet of distributed energy is a peer-to-peer energy ecosystem in which direct transactions between users enable interactions between producers and consumers of electricity, manage electricity trading, services and power system operating modes.

The conceptual model of Internet of distributed energy is based on Navigant's "Energy Cloud" concept (Figure 1).

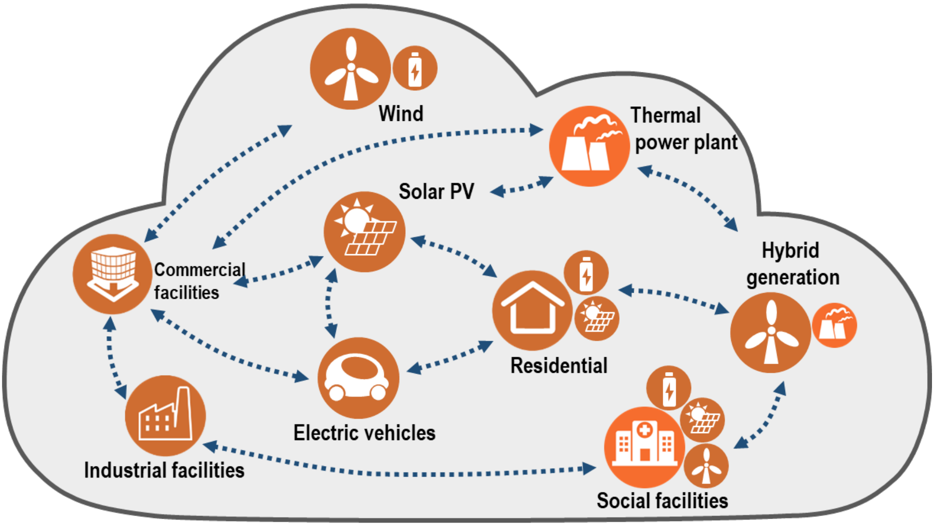


Figure 1: Conceptual model of Internet of distributed energy (Energy Cloud). Source: Navigant Research.

According to this concept, Internet of distributed energy is an ecosystem of users interconnected both by technical means and economically. Users of Internet of distributed energy include owners of any energy equipment, which can generate, store and consume electricity, as well as providers of different services for equipment owners. This means that the users of Internet of distributed energy can participate in decentralized power generation, private power generation (including residential electricity generation), energy storage (home battery storage and EV). Industrial, commercial and residential consumers of electricity with their own power supply systems can also be a part of this ecosystem.

Power cell — is a structural unit of Internet of distributed energy which is formed by pools of electric power facilities and equipment of its users. These pools have a single point of connection to power grids and data channels that integrate them into the Internet of distributed energy ecosystem. A Power cell interacts with other power cells as a single whole regardless of complexity of its inner structure and composition.

By means of power cells users of Internet of distributed energy can play different dynamic and flexible roles while providing various services to each other. These services may include electricity supply, voltage and frequency control, equipment rental, providing of reserve margin in relation to expected peak load and discharge, and other services that can emerge within the power grid ecosystem.

All the services are provided through **Energy Transactions**. The same Energy Transactions are used by power cells to communicate with each other. An Energy transaction (Figure 2) is an act of technical and economical interaction between users of Internet of distributed energy and power cells, through which a coherent control of power cells operating parameters is carried out. As a result of this cooperation one party of the energy transaction acquires a certain value or an asset, while the other party receives a payment for this value.

Institutional Economics defines transaction as the alienation and acquisition, between individuals, of the rights of property with respect to the assets (*John R. Commons "Institutional Economics"*). There are transactions through which the alienation and acquisition of such rights are carried out on an interim basis. In this context Energy transaction is the alienation and acquisition of ownership of power cell between two parties of the energy transaction. As a result, the second party receives a certain value in form of electricity supply from the first party and pays for it.

Energy transaction represents a unity of financial, legal, physical, electrical, informational and control interaction between users and power cells of Internet of distributed energy. Financial and legal interaction is carried out in form of smart contracts – contracts with automatic administration, signing, completion, verification, billing and payment. Within each energy transaction an informational interaction (digital interaction) between power cells leads to exchange of data and commands, which results in coherent control of operational modes of power cells with the aim to complete the energy transaction. Lastly, the electrical interaction occurs between two power cells during which the power cells operate coherently. Direction and parameters of active power and/or VAR flow that are generated or consumed by power cells are being coordinated on this level. Energy transactions become a foundation to various services that users

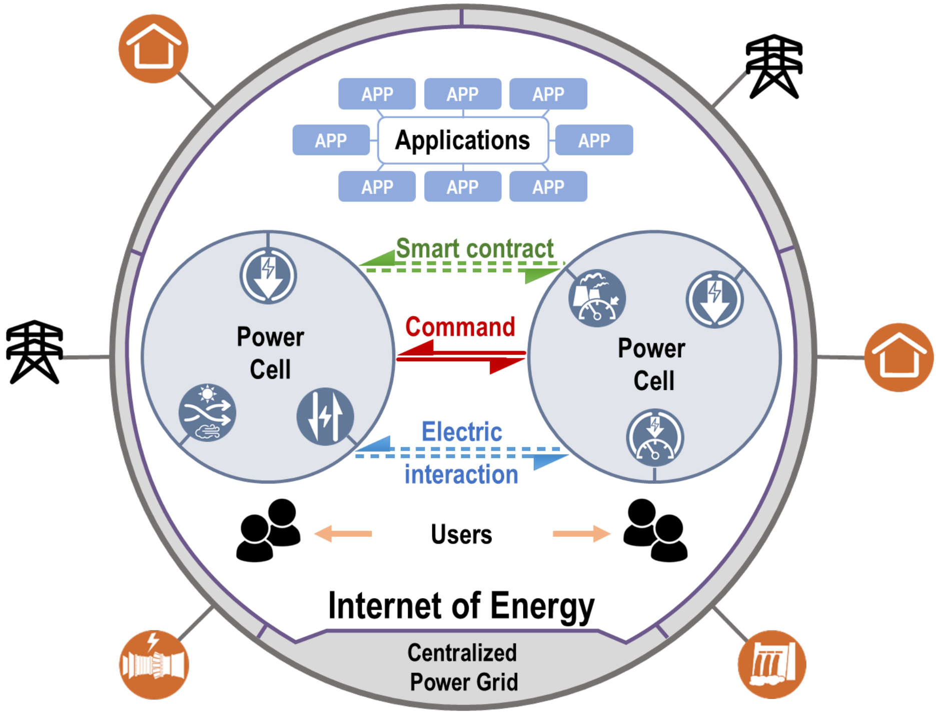


Figure 2: Energy Transaction in Internet of decentralized energy. Source: Center for Strategic Research North-West.

of IDEA provide to each other with the robotic help of **Applications** of Internet of distributed energy. Applications acting as service tools, independently establish communication between power cells through development of set of energy transactions in order to provide various services. Applications ensure that users of Internet of distributed energy cooperate and exchange services in a transaction costs-free manner, which couldn't be possible if they provided the same services directly to each other.

In fact, applications themselves provide various services to the users of Internet of distributed energy while developing the energy transaction set for them. Thus, another layer of user services market is created within peer-to-peer market. Applications also help users of Internet of distributed energy (and corresponding power cells) to interact with centralized power grid and its subjects that lay outside of Internet of distributed energy. In order to do this, applications form one-sided energy transaction between the user and an **app operator**. The App operator plays a role of an intermediary as he interacts with Internet of distributed energy users through energy transactions on one side, and works with centralized energy system entities (such as system operators and utilities, various actors of market for electric power and capacity) on the other. Large number of energy transactions that occur between power cells form multi-agent decentralized economic and technological control of Internet of decentralized energy system. The coordinated work of power cells is what makes Internet of decentralized energy an ecosystem.

2 INTERNET OF DISTRIBUTED ENERGY USE CASES

The main principle of the Internet of distributed energy lies in the concept of energy transactions that enable service applications with all possible types of services they can offer. Such services can be provided exclusively between users of power cells or between users of power cells and centralized power grid entities.

The New Institutional economics suggests an interpretation of "economic transaction" as a form of transfer of property rights. In this case, the transaction is marked by consistency of standard stages:

- a market study is undertaken to identify the existing offers (sellers, prices, quality);
- bidding between participants is carried out to determine the contract parameters;
- contracting;
- monitoring of contract compliance;
- contract enforcement and dispute management.

The order mentioned above can also be applied to energy transactions, except that when energy transaction occurs, the physical feasibility of such transaction should be ensured as well as modification of power cell condition.

Energy transactions within the Internet of distributed energy ecosystem serve as basic acts of interaction and building blocks for user applications. This means that two types of use cases should be taken into account to build the Internet of distributed energy architecture: use cases for energy transactions and use cases for auxiliary (infrastructural) services required to enable these energy transactions. Because of the presence of two types of actors—users and operators of user applications, two types of energy transactions are available:

peer-to-peer transaction — conducted between two users of the Internet of distributed energy;

peer-to-operator transaction — conducted between a user of the Internet of energy and an operator of the user application.

Auxiliary (infrastructural) use cases include operations necessary to integrate the essentials for energy transaction elements into the system, and support the data updates on their status:

- registration of the user;
- registration of the power cell;
- registration of the service application.

2.1 MAIN USE CASES

2.1.1 PEER-TO-PEER ENERGY TRANSACTION

Objective:

Pursuant to the agreements adopted between the users, energy transaction changes the physical state of the power cell, affecting the volume of power received from and supplied to the grid according to a power curve to which the parties have agreed.

Execution algorithm:

Step 1. Two participants of a transaction are determined and a draft contract is compiled.

Based on registered requests, the application determines two users that will

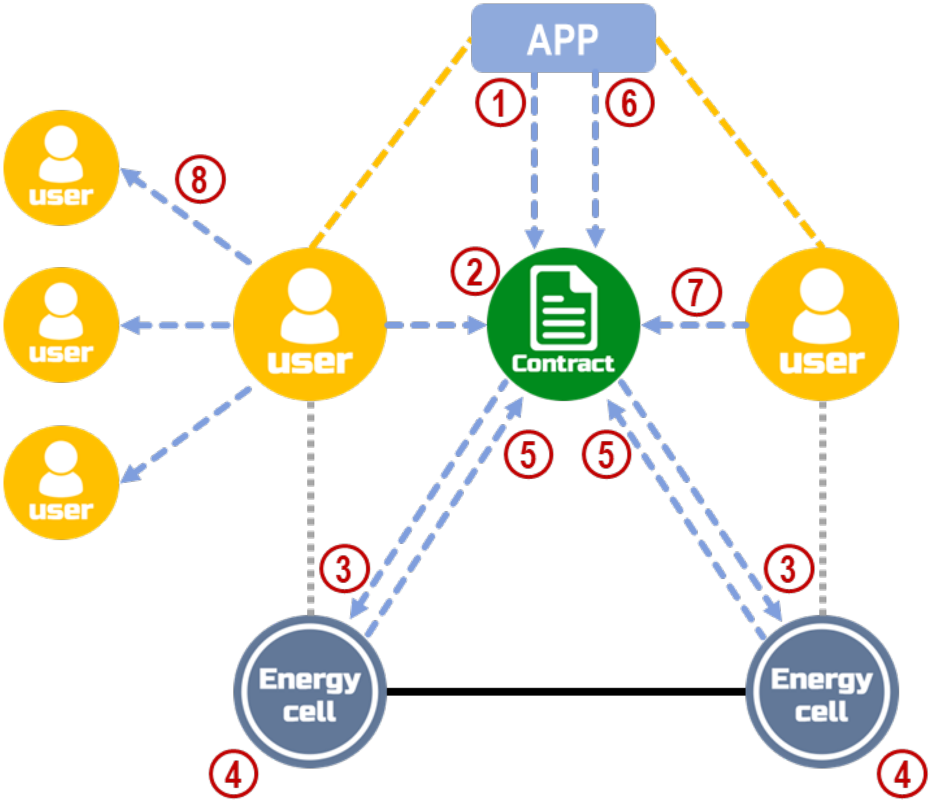


Figure 3: Peer-to-peer energy transaction. Source: Center for Strategic Research North-West.

participate in the transaction. Based on p2p terms formulated by the users, a draft contract is formed and sent to the users.

Step 2. The contract is signed by the users.
The users sign the contract, which contains the terms and conditions of p2p-transaction (terms regarding the change in the physical state of the power cell and conditions of completion).

Step 3. The data regarding the terms of the p2p transaction are obtained by the power cell.

The power cell obtains the data in terms of p2p-transaction to change its physical state. The configurational parameters of the IDEA define the way in which the data are converted and transferred to the power cell.

Step 4. The physical parameters of the power cell are changed.
The power cells change their physical parameters according to the terms of the p2p-transaction: the amount of power received from and supplied to the grid is adjusted during the term of the smart contract.

Step 5. The information on the results of contract completion is obtained.
An application displays the actual data regarding the change in the physical state of the power cells.

Step 6. The actual obligations of the users are measured.
The application determines financial obligations of the users based on the contract terms and the actual data regarding the contract completion.

Step 7. The financial obligations of the users are fulfilled.
The users exchange their digital financial assets to fulfill their financial obligations based on the results of contract completion.

Step 8. Digital financial assets are distributed among the users (owners of energy cell).
In the case if there are several co-owners of an energy cell (users whose financial obligations and operations must be divided), the digital financial assets are redistributed between the co-owners according to the ownership terms and conditions.

2.1.2 PEER-TO-OPERATOR ENERGY TRANSACTION

Objective:

Pursuant to the agreements adopted between the user and the service app operator, the changes in the physical state of power cells occur (i.e., changing the amount of power received from or supplied to the grid according to the power curve to which the parties have agreed).

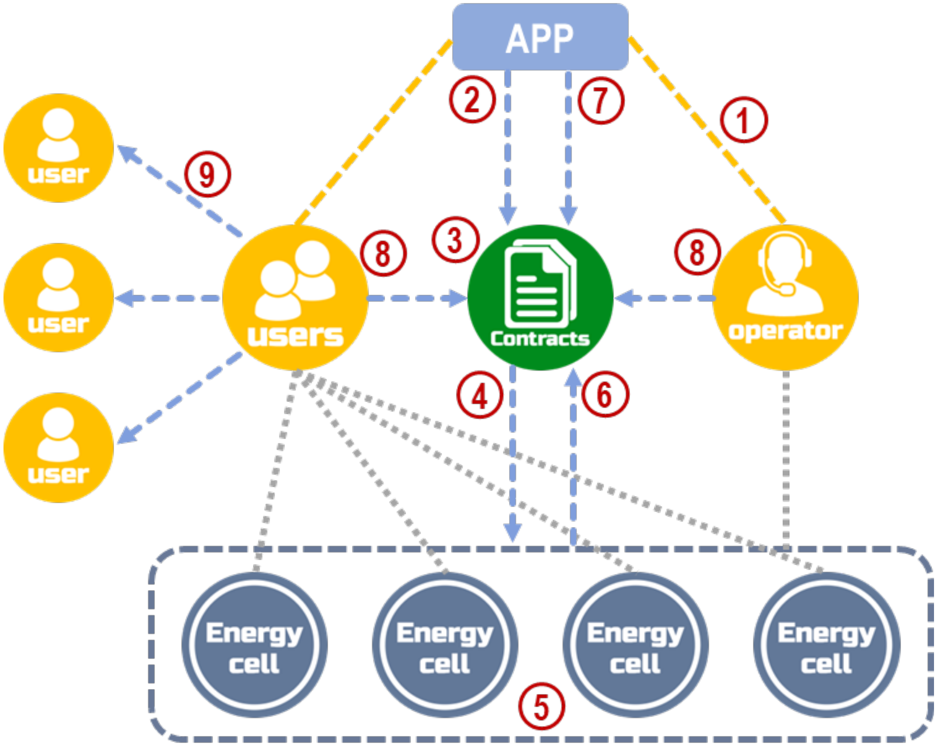


Figure 4: Peer-to-operator energy transaction. Source: Center for Strategic Research North-West.

Execution algorithm:

Step 1. The operator initializes a command to change the physical state of the power cells.
The operator sets requirements on changes of the state of the power system (including the power cells of the Internet of distributed energy).

Step 2. A draft contract is formed and sent to the users.
The users whose power cells can potentially perform the operator's request are selected. They receive draft contracts.

Step 3. The contracts are signed.
The service app operator and the owners of power cells sign the contracts

that contain the terms and conditions of p2o-transactions (terms regarding the change of the physical state of power cell and main conditions of completion).

Step 4. The power cells receive information on the terms and conditions of the p2o-transaction.
The power cells receive data regarding the conditions of the p2o-transaction to change their physical state. The configurational parameters of the IDEA define the way in which the data are converted and transferred to the power cell.

Step 5. The physical parameters of the power cell are changed.
Power cells change their physical parameters according to the terms of the p2o-transaction: the amount of power received from and supplied to the grid is adjusted during the term of the smart contract.

Step 6. The information on the results of contract completion is obtained.
The set of actual data regarding the change in the physical state of the power cells is formed.

Step 7. The actual obligations of users and user app operator are measured.
The application determines the financial obligations of the users and user app operator based on the contract terms and the actual data regarding the contract completion.

Step 8. Financial obligations of the users and user app operator are fulfilled.
The users and the user app operator exchange their digital financial assets to fulfill their financial obligations based on the results of contract completion.

Step 9. Digital financial assets are distributed among the users (owners of the energy cell).
In the case if there are several co-owners of an energy cell (users whose financial obligations and operations must be divided) the digital financial assets are redistributed between the co-owners according to the ownership terms and conditions.

3 ARCHITECTURAL FRAMEWORK OF INTERNET OF DISTRIBUTED ENERGY

3.1 IDEA IN REGIONAL CONTEXT

The energy transition as a global process is highly heterogeneous and usually determined by local features of certain countries and their economies. Energy sectors of developed countries and unions such as the EU, Great Britain, the USA, Canada, Japan, Australia etc. are involved in the energy transition trends more than others. The most drastic changes affect the sector of distributed energy and the "final frontier", which includes distribution networks, distributed generation and end users. These changes will not only have an impact on technological configuration but also on economic relations between industry's stakeholders, as well as the architecture of the energy sector.

The following list of parameters helps to classify regional energy sectors and requirements for power systems which can be met with the Internet of distributed energy architecture:

- level of economic development of a county (UN and International Monetary Fund classification);
- type and level of urbanization of a county;
- type and level of industrialization of a county.

Developing countries (with both rural and industrial economies) where national grid is not present are expected to have a particularly higher demand for the Internet of distributed energy due to the absence of competition with well-established conventional energy infrastructure.

Table 1 leads to three target scenarios for IDEA application:

Power supply for rural territories: accessible and affordable electricity supply;
Power supply for urbanized and industrialized economies: reliable power supply with a reasonable quality level;
Power for "digital society": green energy with a high level of differentiated quality.

Urban society	Rural society
Post-industrial economy	
Wide variety of rapidly changing requirements for environmental friendliness, quality and reliability of power supply, price and accessibility. Network connectivity within the energy system.	Wide variety of rapidly changing requirements for environmental friendliness, quality and reliability of power supply, price and accessibility. High level of autonomy and self-sufficiency of power supply.
Industrial developing economy (medium development level)	
High level of accessibility and reliability of power supply, growing power consumption, centralized consumers.	High level of accessibility and reliability of power supply, growing power consumption in autonomous energy systems.
Industrial developing economy (low development level)	
Accessibility and low prices (consumer affordability), growing power consumption, centralized consumers.	Accessibility and low prices (consumer affordability) of autonomous power supply for growing power consumption.
Rural developing economy (low development level)	
Accessibility and low prices (consumer affordability) of the power supply, centralized consumers.	Accessibility and low prices (consumer affordability), power supply in islanding mode.

Table 1: Types of energy sectors based on energy system requirements.

Each of these scenarios should provide the most economically suitable and optimal solution for challenges that the power industry can face.

3.2 IDEA AND ITS COMPONENTS

The Internet of distributed energy is a decentralized electric power system in which smart decentralized control is implemented by energy transactions between its users. The architecture of the Internet of decentralized energy must ensure both the execution of energy transactions and power cell control based on machine-to-machine interaction. It must also support real-time distributed control of power system operating modes, which helps to maintain power balance within the energy system and its static and dynamic stability.

The Internet of distributed energy represents a System of Systems which is composed of three integrated platforms:

Transactive Energy (TE): a system where smart contracts are composed, implemented and paid;

Internet of Things (IoT): a system of machine-to-machine interaction and exchange of control actions between power cells and power equipment;

Neural Grid (NG): a system that provides mode control, power balance maintenance, and ensures the static and dynamic stability of the power grid.

Each of these systems can be deployed independently and perform its function separately from other systems, but only a set of interconnected (and interacting via specific protocols) TE, IoT and NG systems can form the Internet of distributed energy.

Interconnection and interaction between systems are achieved through energy transactions that occur between users and respective power cells. The smart contract as an artifact of energy transaction is formed in the TE system, then the information related to the smart contract's financial obligations is passed on to the IoT system. Within the IoT system, the data from the smart contact are processed and implemented in the form of synchronized work of power cells (power flow parameters setting) with the help of machine-to-machine interaction.

At the same time, the NG system receives the mode parameters, formed by numerous energy transactions (in other words, by the work of energy cells). The NG system ensures the mode stability, maintaining the power balance, both at the level of power cells and at the level of power flows between them. The control of completion and payment of the smart contract are carried out within the TE system.

If the NG system cannot ensure the power balance maintenance at all boundaries by its own means (only by using the components of NG), it requests a

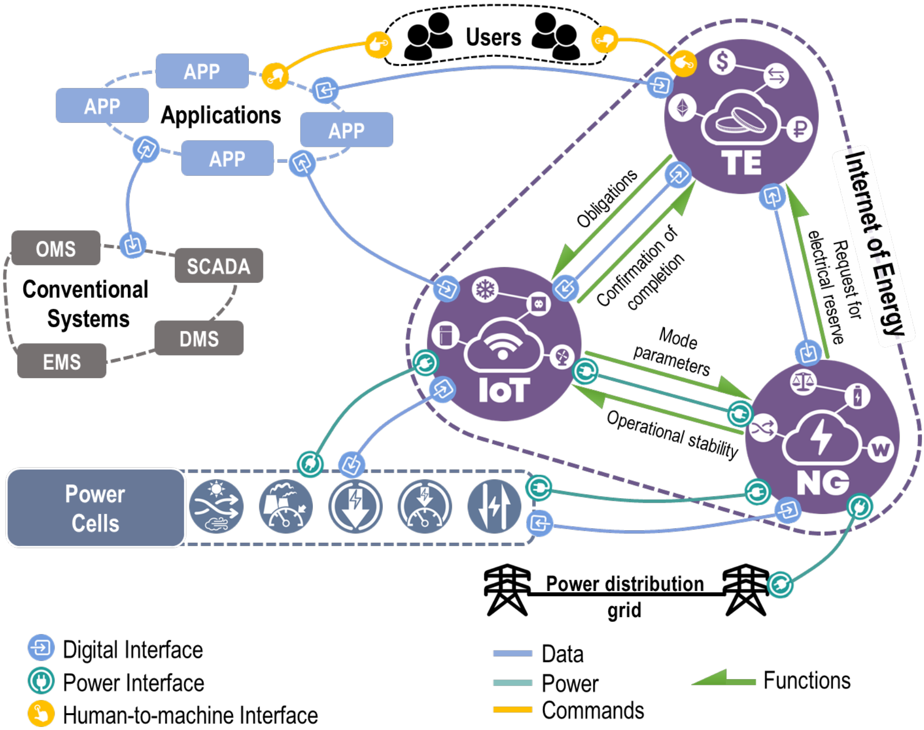


Figure 5: The IDEA is represented as a system of systems: boundaries of systems and interactions between them. Source: Center for Strategic Research North-West.

reserve power via the TE system. In other words, NG initiates an energy transaction for providing the capacity reserve.

The power equipment of the Internet of distributed energy users, being placed at the respective power cells and connected to distribution systems, is integrated both into NG and IoT systems on informational (digital) and electrical levels via specific interfaces.

The users of the Internet of distributed energy interact with the TE system via the man-machine interfaces and participate in transactions that involve their financial assets. They may also determine parameters of smart contracts if necessary. Applications (apps) represent an environment where energy transactions are formed and settled in the form of synchronized work between TE and IoT systems. Applications interact exclusively with the TE and IoT systems via data channels.

Apps are also utilized by users of the Internet of distributed energy and the power cells to interact with data and control systems of the centralized energy system or local control systems like SCADA, DMS, EMS, OMS, that operate outside the Internet of distributed energy.

3.2.1 TRANSACTIVE ENERGY SYSTEM

The Transactive Energy system (Figure 6) is designed for administration, signing, execution, verification, billing and payment of smart contracts. It consists of the following components:

avatars: "digital twins" of users;

digital wallets: accounts that contain digital financial assets (tokens);

human-to-machine interfaces that allow users to interact with their avatars and digital wallets;

data interfaces that ensure the connection between the TE system and measurement tools located at the connection points between power cells and power grid;

system application that converts the measurements of operational parameters of power cells and power equipment into tokens;

other system applications that ensure functional operability and stability (safety) of the system;

transaction platform: a digital environment where avatars interact with each other and with applications;

interfaces of user applications that allow apps to interact with avatars and system applications of TE within the TE platform.

The architecture of the TE system maintains the strict compliance between the users, their avatars and digital wallets.

Therefore, the TE system helps to ensure data interconnection between:

- avatars of the users that sign peer-to-peer smart contracts;

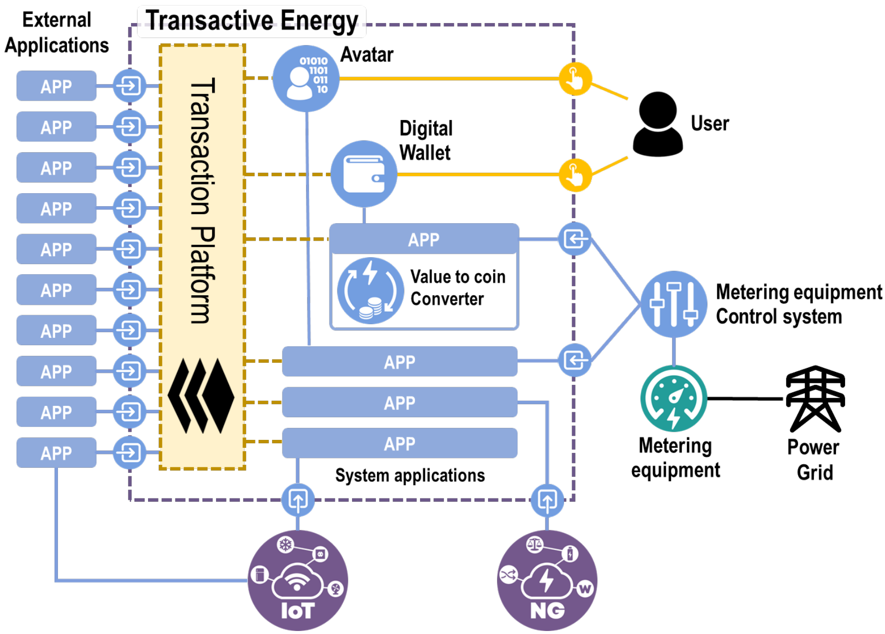


Figure 6: A functional diagram of the Transactive Energy system. Source: Center for Strategic Research North-West.

- user applications that provide a variety of services by smart contracts;
- measurement tools that control the contract execution;
- digital wallets that exchange payments under smart contracts.

At the current level of development of digital financial technologies, the distributed ledger solutions are the most up-to-date, efficient and reliable means to put the TE system into practice. In this scenario, the TE platform utilizes its own cryptocurrency (own tokens) that serves as a digital financial asset being placed in digital wallets of the users, while all the smart contracts, namely all interactions of avatars with each other and with the applications are recorded in the distributed ledger.

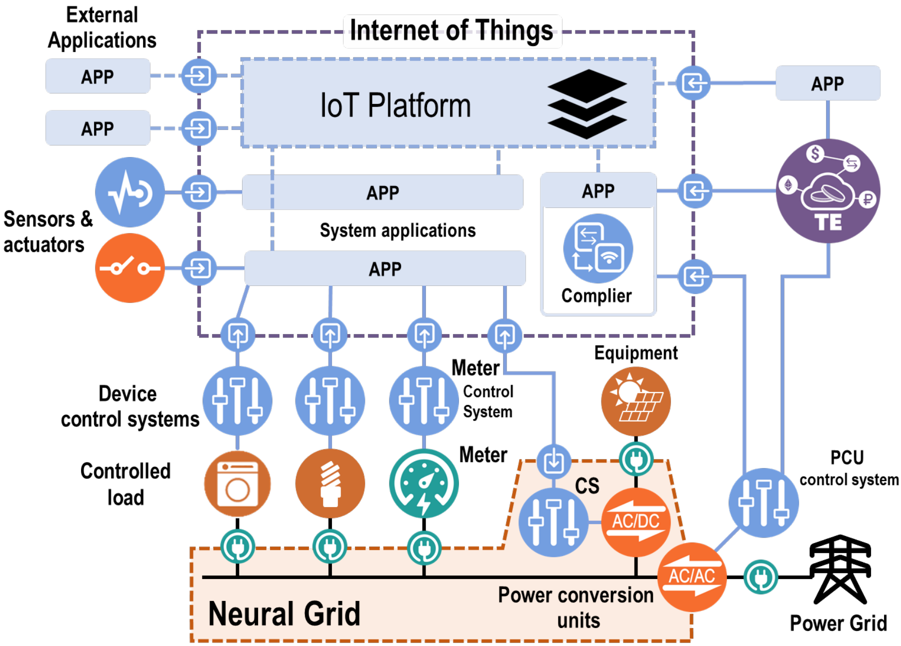


Figure 7: A functional diagram of the Internet of Things (IoT) system. Source: Center for Strategic Research North-West.

3.2.2 INTERNET OF THINGS SYSTEM

The IoT system (Figure 7) ensures machine-to-machine interaction between load control systems and power equipment control systems, including various power converters that integrate the power equipment of users into the power grids.

Machine-to-machine interaction between power equipment control systems creates a multi-agent environment that manages pools of distributed power equipment within the IoT platform. Interactions within the IoT system coordinate the functioning of this equipment and form the electricity transmission modes by managing its generation, storage and consumption. They also implement various functions of mode control related to secondary and tertiary power balance control and power supply quality on the side of end users.

The IoT system consists of the following components:

digital interfaces with control systems of various power equipment — power converters and controlled load;

digital interfaces with measurement tools that are necessary to obtain the up-to-date data on mode parameters;

various sensors that are necessary to obtain certain data required by the system to implement economical management and technical control of pools of power equipment. These data do not include power transmission mode parameters;

various actuators that are necessary for stable control of pools of power equipment. These actuators do not belong to the control systems of this power equipment;

system applications that ensure functional operability and reliability of the system, including energy management systems that are integrated into the IoT;

data interfaces with user apps;

IoT platform — a digital environment where applications, equipment control systems, sensors and actuators can interact with each other.

The IoT system allows user apps to build a multi-agent grid control based on machine-to-machine interaction and coordinated work. This control aims to create and manage the power transmission mode and its parameters, as well as economical optimization of the power grid and pools of power equipment within the grid. The IoT system allows maintaining economical self-organization and optimization, mutual adjustment of such pools.

3.2.3 NEURAL GRID SYSTEM

The Neural Grid system (Figure 8) provides static and dynamic stability for the energy system at all necessary levels: within each power cell as well as at the level of the network of power cells. The static and dynamic stability of the energy system and the maintenance of electricity transmission modes are ensured by smart control of primary power balance in the power grid. This feature is even more relevant for local power grids that are isolated from the centralized grid completely or have only a weak connection to it.

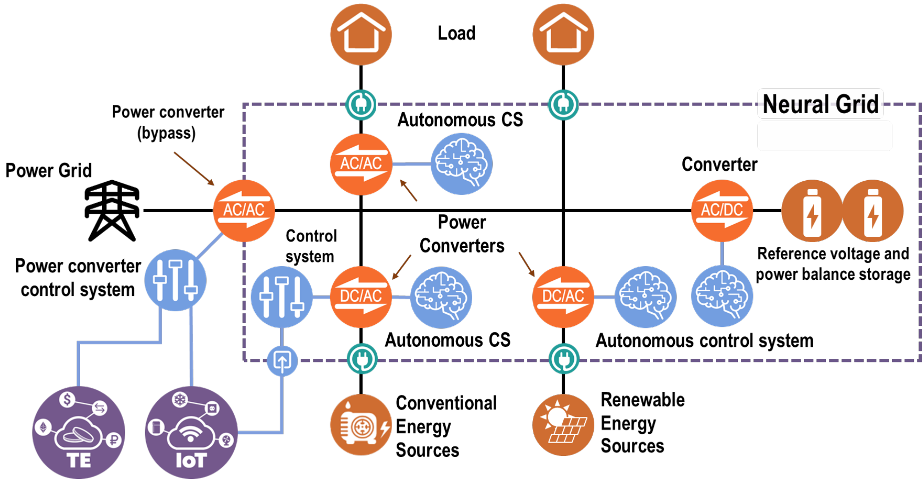


Figure 8: A functional diagram of the Neural Grid (NG) system. Source: Center for Strategic Research North-West.

The NG system maintains power balance among all its equipment units by means of autonomous systems of power converter control. This way there is no need for data exchange between the equipment units.

The NG system consists of the following components:

- power interfaces (converters) with autonomous control systems that integrate both conventional and DER generators;
- power interfaces with the electric load;
- reference voltage and power balance unit (RVPB unit) with power converters and smart autonomous control system. The RVPB unit consists of two types of storage units (each enables either power input or output) and provides primary power balance in the grid.

Using its own autonomous control systems and power interfaces (converters), the RVPB unit ensures mode maintenance by setting the reference frequency and reference voltage, as well as by providing the load balance in case if the system experiences power imbalance. Power interfaces (converters) react to this imbalance and adapt to the reference frequency and voltage so that the system can operate as a system of synchronized units. In this case, the most efficient mode of power takeoff is sustained for each power generation unit in an autonomous and self-contained way.

3.2.4 STRUCTURAL DESCRIPTION OF IDEA

The Internet of distributed energy is a network of interconnected systems of TE, IoT and NG that interact through specific protocols. A **Power cell** represents pools of electric power equipment that belong to users of the Internet of distributed energy and has a common connection point to power grids and to data channels. Thus, the Internet of distributed energy represents a network of power cells.

A power cell is established when a user of the Internet of distributed energy connects (via applications and power equipment) to all three platforms — TE, IoT and NG using applications and power equipment.

Therefore, a power cell is a digital electrical system that:

- can play one of the five functional roles within the Internet of distributed energy that are determined by the power cell's capabilities in relation to electric power flow;
- has a power interface on the boundary where the power cell connects to other power cells, power grid, IoT and NG systems. Power interfaces also enable energy transactions between the power cells. The type of power interface corresponds to the type of the power cell;
- is connected to the IoT and TE systems via its own data interface with a control system.

The Interface that ensures the connection between a power cell and the Internet of distributed energy (meaning the connection of a power cell to other power cells via distribution networks and data channels) combines the functions of interfaces of all three systems — TE, IoT and NG. Power cells of the Internet of distributed energy create a fractal network so that each power cell can contain smaller sub-cells and/or be a part of a bigger power cell. Power cells are typologically and structurally identical regardless of their size.

This means that a power cell can consist of power equipment (e.g., generators, power storage, controlled load) as well as be a part of a larger power cell where it can play a flexible role — be either a generator, a storage unit or a consumer, depending on the type of energy transaction.

The mandatory feature of a power cell is a self-sustained support of static and dynamic stability during the power flow exchange with other power cells or with the centralized power grid. Meanwhile, a self-sufficient maintenance of power balance and stability of the system isolated from the grid is an auxiliary feature.

3.2.5 TYPES OF THE INTERNET OF DISTRIBUTED ENERGY ENTITIES

An entity of the Internet of distributed energy represents a power cell that is connected to the Internet of distributed energy. The power cell is established when its user connects to all three platforms — TE, IoT and NG via applications and power equipment.

There are five types of power cells that are based on the power cell's functional capabilities in relation to electric power flow. Each type is determined by the combination of the two following parameters:

Power flow direction: determines whether the power cell produces or consumes the electricity;

Flexibility (maneuverability): the ability to maintain flexible control of power flow direction and power flow value.

Based on the combination of the two above-mentioned parameters, the following types of power cells have been specified:

- prosumer;
- flexible generator;
- stochastic generator;
- active consumer;
- passive consumer.

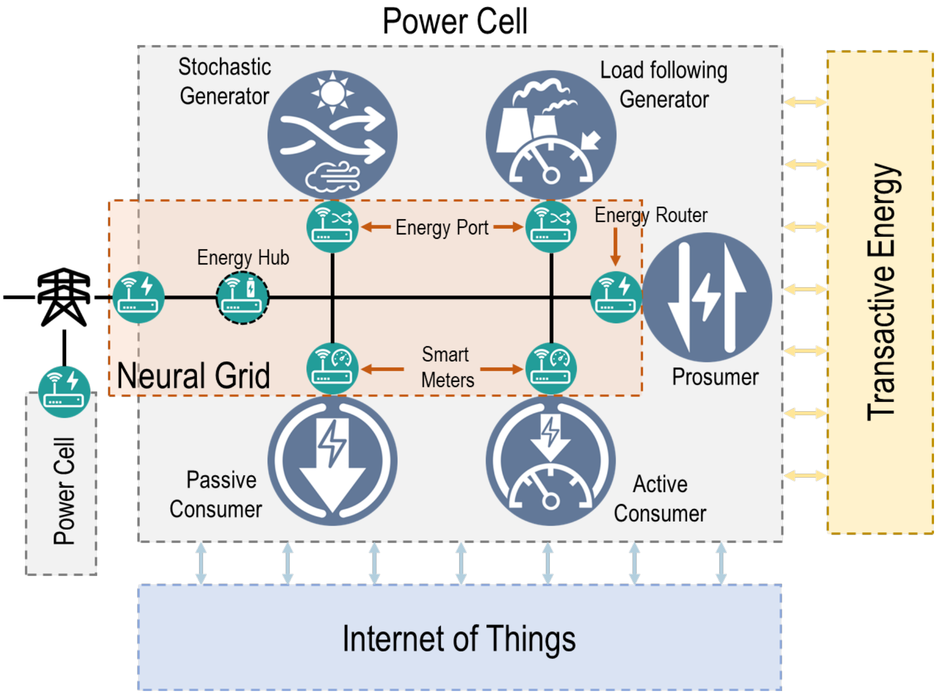
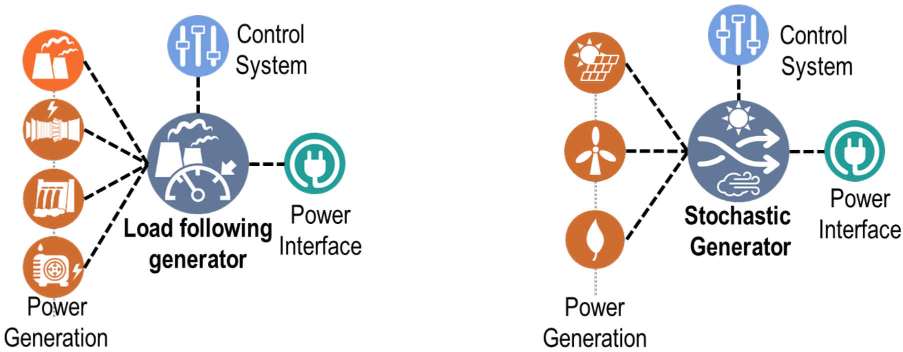


Figure 9: Power Cell and types of its elements. Source: Center for Strategic Research North-West.

3.2.6 ENERGY TRANSACTION AND SERVICES WITHIN INTERNET OF DISTRIBUTED ENERGY

The main operational principle of the Internet of distributed energy is the ability to provide all the possible services through energy transactions, both among the users and corresponding energy cells and by the users toward the centralized power grid. This way, energy transactions play a role of basic acts of interaction within the Internet of distributed energy and can form a basis for user apps functional operability.

Each power transaction begins with a smart contract being composed by a user app within the TE system. Within the IoT system, the smart contract transfers operational settings (active power or VAR values) to a certain power cell via the



Flexible generator

Stochastic generator

Figure 10: Electricity generators (only outgoing power flow).

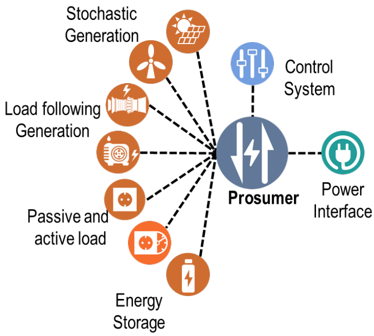
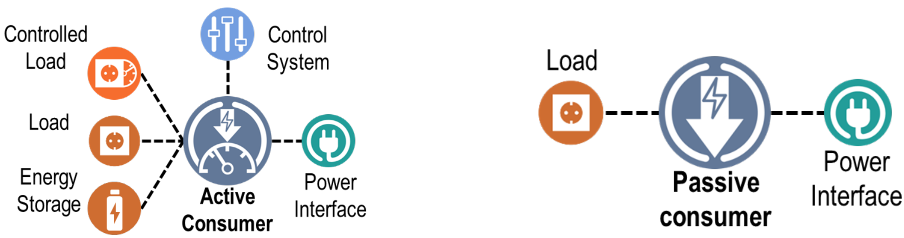


Figure 11: Power generator and consumer (incoming and outgoing power flow).



Active consumer

Passive consumer

Figure 12: Electricity consumers (only incoming power flow).

interface. Then, the operational parameters are measured, and the results are transferred to the TE system via a specific protocol. The energy transaction is completed when the fact of the electricity transmission is confirmed by the IoT system and the smart contract is paid.

3.2.7 NECESSARY AND MANDATORY COMPONENTS OF IDEA

The necessary and mandatory components of the Internet of distributed energy include:

Digital power interfaces with power cells — controlled by cyber-physical tools installed on the boundaries of power cells that connect them to each other or to power grids. They ensure physical implementation and metering control of energy transactions by combining the functions of TE, IoT and NG interfaces.

Transaction platform — a digital environment where avatars interact with each other and with applications.

IoT platform — a digital environment where apps, control systems of power interfaces, sensors and actuators can interact with each other.

The typology of digital controlled power interfaces is determined by the typology of power cells to which these interfaces are attached.

Smart meter

A smart meter represents a universal module that is used to register electrical parameters of the grid and electricity consumption. It also helps to utilize the transaction platform.

The main functions of the smart meter are:

- measurement of the power grid parameters and electrical energy consumption
- two-way communication between the meter and the transaction platform
- control of the parameters of the power consumption mode.

The smart meter has several circuits that maintain its operability:

Power circuit — contains a relay that breaks a circuit in case of emergency or for load management;

Power cell type	Interface type
Prosumer	Energy router: • measuring the operating conditions at the connection points; • controlling the power flow; • maintaining the maximum power takeoff mode.
Stochastic or flexible generator	Energy port: • measuring the operating conditions on the boundary of the power cell; • limiting the power flow; • adaptive maintenance.
Passive or active consumer	Smart meter: • measuring mode parameters on the boundary of the power cell.

Table 2: Types and functions of power cell interfaces.

Metering circuit — contains voltage and current measurement systems that ensure electrical mode control;

Digital circuit — contains computing resources that implement control system; real-time clock to synchronize metering and actuating signals; data storage to record metrology and control actions.

The control system by default includes software that implements the following operational modes:

- real-time relay control;
- database management.

Smart meters are the basic components of the Neural Grid and can be used to build a functional interoperability with other components of the Internet of distributed energy.

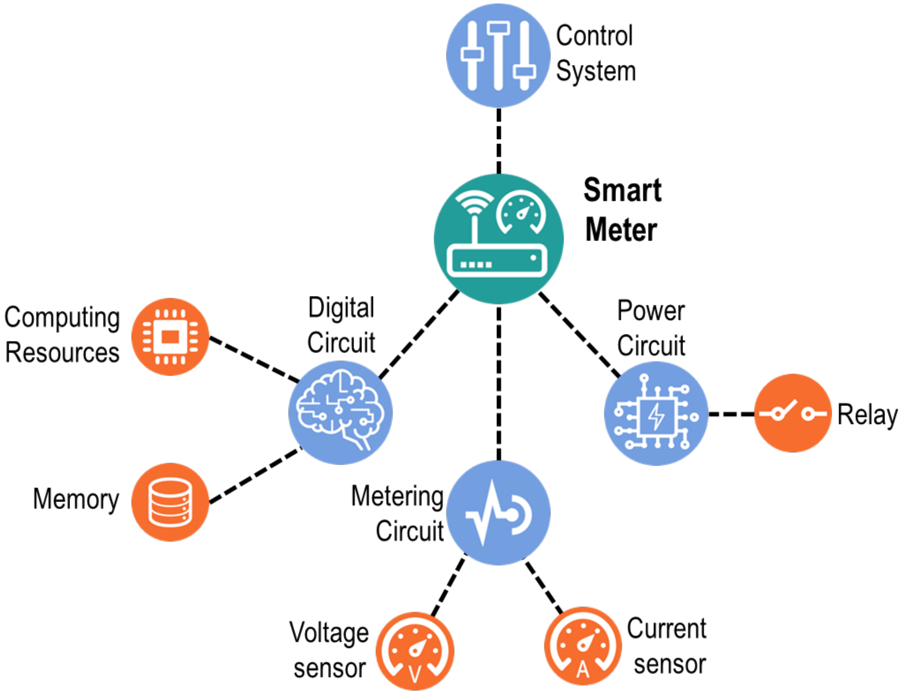


Figure 13: Typical architecture of a smart meter. Source: Center for Strategic Research North-West.

Energy port

An energy port is a universal power tool that enables connection of power cells with generators or storage devices. The main functions of the energy port are:

- ensuring a two-way power flow between generating equipment and the grid as well as power flow into power storage if one is available;
- functioning as a virtual synchronous machine (inverter connected to the grid operates identically to a synchronous generator);
- ensuring maximum power takeoff from generating equipment that is connected to the energy port (tracking the maximum capacity point).

The energy port contains several circuits that ensure its functional operability:

Power circuit — contains a two-way static voltage inverter with wide voltage

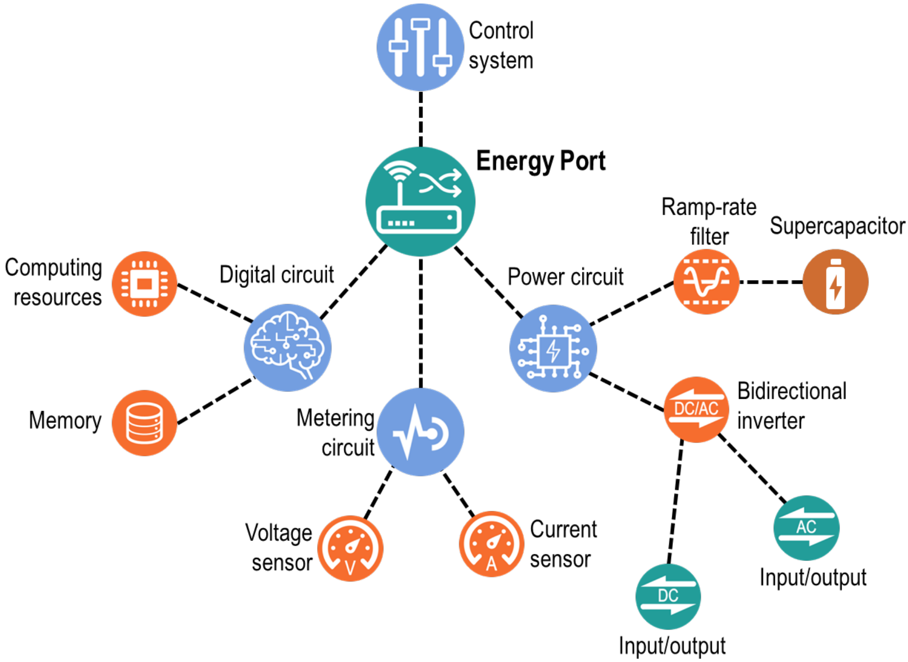


Figure 14: Typical architecture of energy port. Source: Center for Strategic Research North-West.

input range at the DC bus-bar. The inverter ensures operation in asymmetrical conditions in a three-phase network while keeping a low distortion factor. It also contains a ramp rate filter that ensures stable parallel operability of autonomous generators (including RES) that are connected to the port and operate at the point of maximum power takeoff;

Metering circuit — contains voltage and current measurement systems that ensure the electrical mode control;

Digital circuit — contains computing resources that implement the control system; a real-time clock to synchronize metering and actuating signals; data storage to record metrology and control actions.

The energy port has a control system based on the multi-master concept where all the equipment units are equal. This approach helps to reach higher indexes of installed capacity utilization and provides a significantly higher level of system reliability. The control system includes software that implements the following operational modes:

- DC to AC conversion (generator feeding the isolated load);
- AC to DC conversion (generator feeding the isolated load);
- parallel operation with external power generation sources (industrial grid, gensets, power gateway);
- real-time control;
- database management.

Energy ports are the universal modules and therefore they eliminate the need for a custom design of solutions for connecting the power cell to the grid.

Energy router

An energy router is an instrumentation & control complex designed for the control and distribution of electricity within the distribution networks. The energy router can be utilized in medium and low-voltage systems (10/0.4 kV).

The main functions of the energy router are:

- active power and VAR flow control;
- isolation of damaged sections of the grid;
- quality control of the power supply.

The energy router contains several circuits that ensure its functional operability:

Power circuit — contains two energy ports that are connected through a DC converter. The DC converter ensures coordination of voltage levels between the energy ports. The interconnected energy ports provide full control of the power flow through the energy router.

Metering circuit — obtains data from metering systems of energy ports to ensure the control of electric operating modes and to form the control action.

Digital circuit — contains computing resources that implement the control system; real-time clock to synchronize metering and actuating signals; data storage to record metrology and control actions.

The energy router has a control system based on the multi-master concept that ensures the coordinated power flow between two systems of power cell.

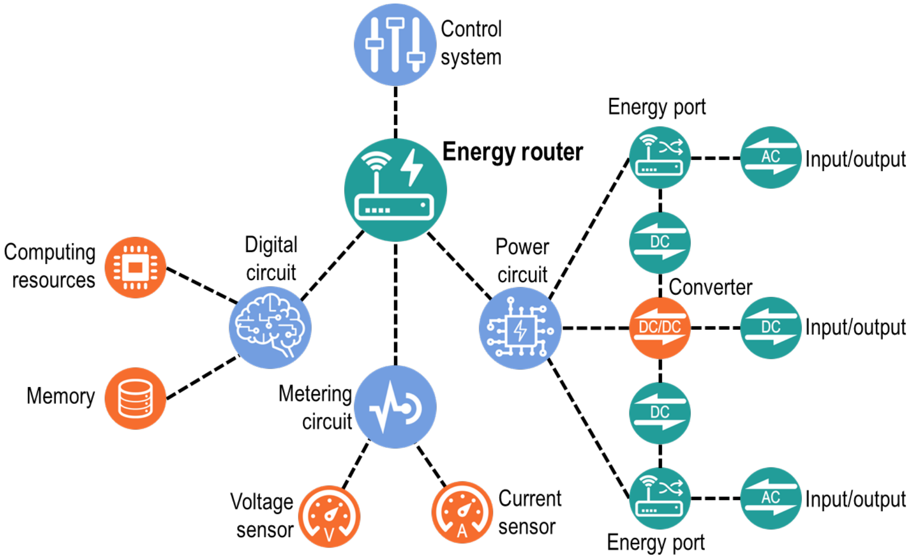


Figure 15: Typical architecture of an energy router. Source: Center for Strategic Research North-West.

The control system includes software that implements the following operational modes:

- grid reconfiguration and restoration;
- active power and VAR control;
- autonomous operational mode;
- real-time control;
- database management.

Energy routers help to configure and build various topologies of power grids, allow the deployment of the operational modes between systems of power cells, and ensure a reasonable level of power supply quality on the interfacial junctions.

3.2.8 SPECIFIC OPTIONAL INTERNET OF DISTRIBUTED ENERGY COMPONENTS

Energy Hub is one of the optional components of the Internet of distributed energy. It is installed at the power cell if the cell can maintain: self-sufficient power balance to support its autonomous operability as power system; self-dependent internal energy balance; static and dynamic stability; functioning of all the sub-cells according to their own optimal and autonomous modes.

An energy hub can be classified as a component of the Internet of distributed energy only if it is controlled by the energy transactions (in addition to its function as an element of the Neural Grid). An energy hub represents a certain type of power cell which performs a specific function for a bigger power cell in which it is located.

An energy hub can be installed on all types of power cells that are able to generate electricity. An energy hub is an RVPB unit that maintains the reference voltage and, if possible, the reference frequency of a power cell; in other words, the real-time primary and secondary control of power balance.

An energy hub maintains the electrical mode by setting the reference frequency and reference voltage, thus keeping the primary power balance within the power grid where it is installed and ensures static and dynamic stability of the energy system.

The main functions of an energy hub are:

- primary control of power balance;
- flexible adjustment to the electrical mode of the load;
- maintenance of a high level of power supply in the digital distributed grid (low nonlinear-distortions coefficient), stabilizing the voltage fluctuations;
- aggregation of DER based on a Virtual Power Plant concept.

An energy hub contains a few circuits that ensure its functionality:

Power circuit — contains two energy ports that can operate in different modes simultaneously (power input and output).

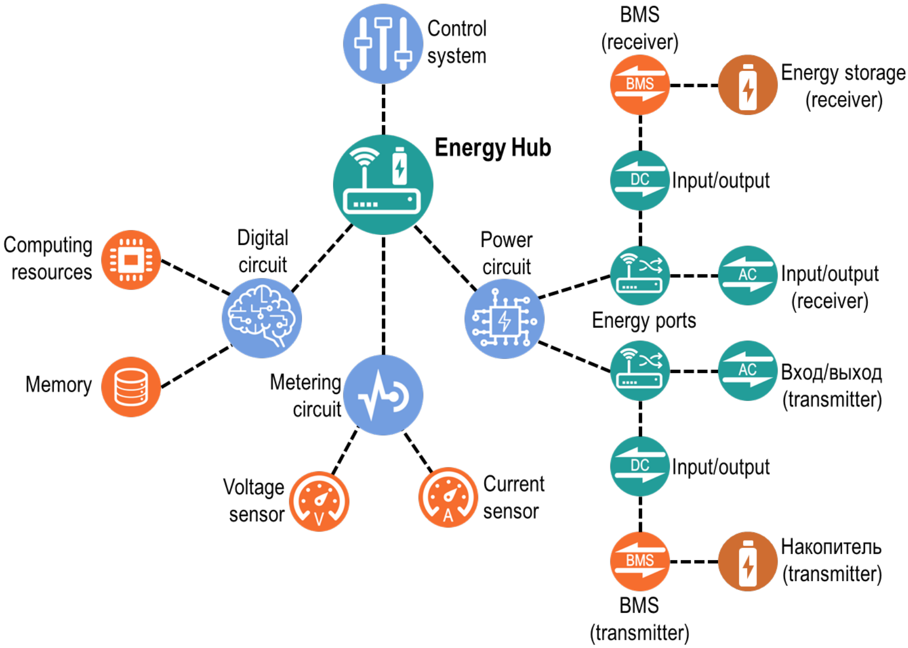


Figure 16: Typical architecture of an energy hub. Source: Center for Strategic Research North-West.

Power storage — contains an energy storage system to accumulate energy and later supply it to the grid. These systems are connected to energy ports via battery management systems.

Metering circuit — obtains data from metering systems of energy ports to ensure the control of electric operational modes and form the control action.

Digital circuit — contains computing resources that implement the control system; real-time clock to synchronize metering and actuating signals; data storage to record metrology and control actions.

An energy hub has a control system based on the multi-master concept. The energy hub sets the power mode of the grid by setting the reference frequency and maintains, when necessary, the capacity output or input when a power grid imbalance is present.

The control system originally contains the software that enables the following operational modes:

- power balance management;
- real-time management;
- aggregation of DER based on a Virtual Power Plant concept;
- database management.

3.3 INTERNET OF DISTRIBUTED ENERGY ARCHITECTURAL PRINCIPLES

The main architectural principles of the Internet of distributed energy are:

- Decentralized nature of the power grid that allocates a vast number of decentralized consumers and producers of electrical energy on the distribution networks level;
- All the processes within the grid are triggered and controlled by direct transactions between users;
- The energy system is built as a network of galvanically isolated cells;
- Formation and maintenance of local power balance and self-sufficient balancing on all levels;
- Presence of two-way power flows and flexible roles of the power grid users;
- Presence of digital communication and collaboration on an IT level along with the electrical interaction between electric power equipment;
- Entirely decentralized smart control, which is achieved by machine-to-machine communication;
- Peer-to-peer contracts for purchase and sale of electrical energy as well as providing various services within a decentralized market;
- Inclusive nature of the system where connections and collaboration are kept with the centralized power grid and its subjects. In this scenario, the users can experience a balanced mix of benefits that both conventional and distributed energy can bring.

3.4 IDEA BASIC MODELS

3.4.1 SPECIFICATIONS OF BASIC MODELS OF IMPLEMENTATION

The basic models of the IDEA implementation are represented by a set of standardized services (Apps) that provide certain value for users of the Internet of distributed energy. These models are designed to enable the following features:

- optimized direct electricity sales between prosumers;
- grid flexibility due to electricity consumption management;
- power grid sustainability.

These features can be achieved if the following basic models are implemented:

P2P electricity trading: finding the matching power cell and optimal contracting party for electricity exchange and following realization of this electricity exchange.

Demand response: matching the electricity demand with its supply, optimization of the electricity consumption curve.

Energy management systems: optimization of electricity consumption within the power cell.

Balancing of autonomous power system: balancing the electric power and capacity in the power system which is not connected to an external power grid.

Integration with the external grid: balancing the electric power and capacity of the system which is connected to an external power grid.

P2P electricity trading

The P2P electricity trading model aims to optimize the market of direct electricity sales among prosumers.

This model includes:

- collecting the data from prosumers (up-to-date parameters of the energy assets, electricity sale offers, orders placed for electricity purchase within a specified schedule, range of admissive deviations in consumption and generation);

- matching the optimal contracting parties based on analysis of generating capacities, the amount of electricity requested by the consumers and the presence of device interconnection between two potential participants of p2p trading;
- p2p energy exchange between prosumers;
- optimization of the matching system based on statistics and operations performed in the past.

Demand Response

The demand response model aims to optimize the power grid by adjusting (lowering or raising) the electricity consumption based on negotiated agreements.

This model includes:

- integration of energy assets (power plants and generation units);
- analysis of a possible decrease in consumption (including analysis of its efficiency);
- calculation of optimal consumption schedule;
- issuing the demand response commands;
- control of execution of commands; performing the necessary calculations.

Energy Management System

The energy management system model aims to optimize the electricity consumption among several power cells if they are operated by a single owner or operator.

This model includes:

- analysis of the energy consumption pattern;
- the optimal pattern of electricity consumption;
- issuing the commands for electricity consumption optimization;
- control of execution of commands;
- analysis of the efficiency of electricity consumption optimization and following correction of the optimization model.

Balancing the autonomous power system

This model aims to ensure technological sustainability and stability of the power grid when the connection to an external (i.e., centralized) power grid is not present. In other words, this model maintains the local balance of electric power and capacity to smooth out the power oscillations in the grid and maintain the quality parameters of electrical energy.

This model includes:

- specifying the configuration of control devices and system parameters management options;
- collecting and analyzing the actual parameters of the power grid;
- specifying the trends of structural transformation of electricity consumption and power generation profiles;
- realization of preventive control actions;
- realization of operative control actions;
- analysis of the efficiency of the grid parameters adjustment and following correction of a control action model.

Integration with an external grid

This model aims to maintain sustainability and stability in the grid that is connected to an external (i.e., centralized) power grid.

The model includes:

- specifying the configuration of control devices and system parameters management options;
- analysis of the channel capacity between the grid and an external power grid;
- collecting and analyzing the actual parameters of the power grid;
- implementation of preventive control actions;
- implementation of operative control actions;
- analysis of the efficiency of the grid parameters adjustment and following correction of a control action model.

3.4.2 REFERENCE PILOT MODEL OF IDEA IMPLEMENTATION

This section will present the case of implementation of a seaport pilot project in Russia based on IDEA reference architecture. The energy infrastructure of the seaport consists of various sources of power generation, transmission networks, elements of grid infrastructure, power storage and industrial consumption units. They include:

- two thermal power plants (18 MW);
- diesel power plants (2 MW);
- external (national) power grid (36 MW of connected capacity);
- internal (local) power grid (30 substations with 150 km of power lines);
- consumers (26 MW of load).

The combination of mentioned elements forms a large energy system in which certain entities may be located within the same area, but are not managed by the single control loop and have little to no connection due to being separated by workshop zones. This leads to low efficiency of power usage – the power generation by local sources never exceeds 17% while the load rate of internal power grid fluctuates around 18%.

The above-mentioned elements represent a distributed energy system. Implementation of the IDEA architecture can significantly optimize this system and address the efficiency challenges it faces. Particularly, the new approach will help to reduce power consumption peaks, raise the efficiency of local power generation usage, reduce the dependency of electric power and capacity purchased from the unified energy system. It was estimated that with the new architecture it will be possible to lower the expenses on seaport power supply by 30% and reduce by four times the need for added capacity.

Let's analyze the IDEA approach based on the given case study. The main economic effects can be obtained through accurate consumption forecasts. Such forecasts are compiled based on measuring data, load managements digital simulation and efficient usage of local power generating sources.

In this case, the key purpose of the IDEA is the dynamic integration of all distributed energy resources and units, which will lead to building of a single unified microgrid. Such microgrid will have an on-site system of technological and financial management and control while ensuring the plug & play interconnection of all elements of the system (including the possible roles of ships and vessels as mobile elements of the grid). The significant capital expenses are not needed to achieve these tasks, as the only crucial component of efficient work is the transparent management and interconnected operation of power system elements based on IDEA principles.

In particular, the following elements should be added to the system:

- Energy router: connects outer (i.e., national, centralized) grids and inner (local) grids, measures the parameters at the point of connection, manages the capacity flow;
- Smart meters: connect passive and active consumers to the grid, measure operational parameters of the grid as well as consumption parameters;
- Energy ports: measure the system parameters on the boundary of a power cell, limits the capacity flow, adaptively supports voltage and frequency levels, maintains the maximum capacity mode.

Each energy equipment unit of the seaport as well as each power receiver equipped with an interface and IoEn platforms represent energy cells. The connection with outer grid is established via an energy router. The applications that maintain the operation of the microgrid providing various energy services are based on two platform systems – Internet of Energy and Transactive Energy.

Figure 17 represents the functional architecture of this pilot project.

This pilot project supports main scenarios and use cases of the Internet of distributed energy:

- p2p-transactions;
- Flexibility as a service (energy system balancing);
- p2o-transactions.

P2p-transactions are utilized to trade electricity among power cells. The p2p contract presumes the sale and purchase of a defined amount of electricity. Fluctuations in electricity consumption occur in the grid on a regular basis due to load inconsistency triggered by new electrical devices being plugged into the electric grid.

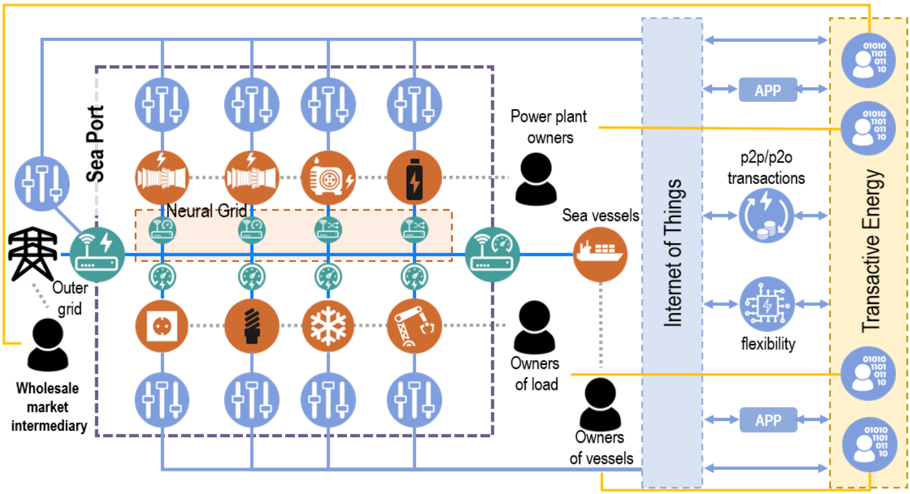


Figure 17: The reference functional architecture on the Internet of distributed energy. Source: Center for Strategic Research North-West.

To balance and smooth out such fluctuations, a flexibility service is provided to maintain the capacity balance in the system. If current generating units are unable to fulfill the electricity demands, the p2o-transactions can be enabled. P2o-transactions are used to purchase the deficient amount of electricity from an operator.

The constant monitoring of current power generation and load is carried out in the system to provide the flexibility service. If excess amounts of electricity are present in the system, they are stored to be transmitted to consumers later when the demand arises.

The amount of power in the system is also monitored during p2o-transactions. If there is an insufficient amount of electricity being fed into the grid from power generating units or energy storage devices, then the purchase request is sent to the operator and the purchased amount of electricity is transmitted into the inner grid via an energy router.

INTERNETOFENERGY