Lappeenranta-Lahti University of Technology
School of Energy Systems
Degree Programme in Electrical Engineering (Industrial IoT)

Juha Närvä

Governance Models for an IoT-based Energy Internet Using a Multi-Agent Approach

Examiners: Professor Juliano Nardelli

Ph. D. Arun Narayanan

ABSTRACT

Lappeenranta-Lahti University of Technology
School of Energy Systems
Degree Programme in Electrical Engineering (Industrial IoT)

Juha Närvä

Governance Models for an IoT-based Energy Internet Using a Multi-Agent Approach

2020

Master's Thesis
Pages: 98, Pictures: 29, Tables: 2

Examiners: Professor Juliano Nardelli
Ph. D. Arun Narayanan

Keywords: IoT, Smart grid, Energy internet, Microgrid, Agent-based model

The existing power grid is designed to transfer energy from high voltage to medium voltage. For historical reasons, it was designed to consider a one-directional electricity feed; thus, it does not properly consider consumer activity. The existing energy supply relies on centralized electricity production. The largest sources of electricity are power plants using nuclear, hydrogen, natural gas, and fossil fuels.

The future household energy will be mainly produced locally by prosumers. De-centralized renewable energy generation and energy-storage systems are expected to change the operation of the existing power grids. The new power grid will support bi-directional electricity flow facilitated by commonly managed fifth generation communication technology. Users' intelligent electronic devices will be actively controlled by internet of things devices. Groups of active users will be organized as physical microgrid communities, in which they will share a pool of energy resources. They will consume jointly, following a commons-based electricity management approach forming an energy internet. Using distributed energy resources, needed energy will be virtually packetized and managed by an energy server. Virtually packetized energy management will maximize the benefits to prosumers of renewable-energy production and consumption inside a microgrid, providing them with electricity self-sustainability. Under this regime, the price of electricity will be zero within the community, while the need for externally produced electricity will be minimal.

In this thesis, the transformation of the existing power grid to create the energy internet is illustrated using three-layer agent modeling. Disruptive change agents are identified, and agent-based governance models are developed to demonstrate a change pathway from the existing system to an energy internet.

TIIVISTELMÄ

Lappeenranta-Lahti teknillinen yliopisto
Energiajärjestelmät
Sähkötekniikan industrial IoT-koulutusohjelma

Juha Närvä

Governance Models for an IoT-based Energy Internet Using a Multi-Agent Approach

2020

Diplomityö
Sivumäärä 98, kuvia 29, taulukoita 2

Tarkastajat: Professori Juliano Nardelli
Tohtori Arun Narayanan

Hakusanat: IoT, Smart Grid, Energy Internet, Microgrid, Agent-model

Nykyinen sähköverkko, sekä sen ohjauslaitteisto on suunniteltu pääsääntöisesti keskitettyyn sähköntuotantoon sekä yksisuuntaiseen sähkönsiirtoon. Verkon suunnitteluaikana ei ollut laajamittaista hajautettua kuluttajien sähköntuotantoa, joka olisi voitu ottaa huomioon. Suurimmat sähköntuotantolähteet ovat ydinvoima, vesivoima, maakaasu sekä fossiiliset polttoaineet.

Tulevaisuuden kotitalouksien käyttöenergia tullaan tuottamaan pääasiassa paikallisesti niiden itsensä toimesta. Kasvava hajautettu sähköntuotanto käyttäen uusiutuvia energian lähteitä edesauttaa nykyisen sähköverkon muutospaineita. Tulevaisuuden sähköverkko tulee tukemaan kaksisuuntaista sähkönsiirtoa, yhteisesti ohjatun viidennen sukupolven langattoman kommunikaatioteknologian avulla. Sähköverkon sekä sähkönkäyttäjien älykkäiden elektronisien järjestelmien mittaamiseen ja ohjaamiseen käytetään esineiden internettiä. Aktiiviset sähkönkäyttäjät voivat muodostaa fyysisiä pienverkkoja, joka mahdollistavat itsetuotetun energian jakamisen. Järjestelmän, joka muodostaa energia-internetin, ohjaa virtuaalisesti kvantisoitua sähkönkulutusta ja -jakamista. Energia-internet maksimoi yhteisössä tuotetun energian hyödyn, saavuttaen energiaomavaraisuuden sekä nollaenergiakustannuksen käyttäen uusiutuvia energianlähteitä.

Tässä työssä kuvataan agenttimallinnuksen avulla energia-internetin tarvitsemia muutoksia nykyiseen sähköverkkoon. Lisäksi työssä esitellään energia-internetin keskeiset tekniset sekä kaupalliset muutosagentit nykytilaan verrattuna, sekä kuvataan tarvittavia muutoksia energia-internetin muodostamiseksi.

PREFACE

This thesis was completed in the Energy Laboratory at the Lappeenranta-Lahti University of Technology (LUT). The study was part of the energy internet project. The project's goal is to build the energy internet as a large-scale IoT-based cyber-physical system that manages the energy inventory of distribution grids as discretized packets via machine-type communications.

I would like to thank my examiners, Professor Juliano Nardelli and Doctor Arun Narayanan, for suggesting this very fascinating topic and giving me the opportunity to learn more about the latest technologies. I would also like to thank my examiners for providing feedback and making this work possible. Special thanks also go to my family for supporting the project and my studies.

Helsinki, April 28th, 2020

TABLE OF CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

3GPP	3rd Generation Partnership Project
6LoWPAN	IPv6 over Low-Power Wireless Personal Area Networks
BESS	Battery Energy Storage Systems
CB	Circuit Breaker
CIoT	Cloud Internet of Things
C-SGN	Cellular Serving Gateway Node
DER	Distributed Energy Resources
DOE	Department of Energy (US)
DR	Demand Response
DSO	Distribution System Operator
eMBB	Enhanced Mobile Broadband
ECN	Energy Consumption Node
ES	Energy Storage
EV	Electric Vehicle
GHG	Greenhouse Gas
GPRS	Global Packet Radio System
GTP-C	GPRS Tunneling Protocol—Core network signaling
GTP-U	GPRS Tunneling Protocol—User-data carrying
ICT	Internet Communication Technologies
IED	Intelligent Electronic Device
IEEE	Institute of Electrical and Electronics Engineering
INF	Information Layer
IoT	Internet of Things
IP	Internet Protocol
IPv6	Expansion of IP protocol
IWMSC	Interworking Mobile Service Switching Center
kV	Kilovolt
L1	Physical Layer (PHY layer)
L2	Data Link Layer
LEG-A	Local Energy Generation Coordination Agent
LPWA	Low Power Wide Area
LPWAN	Low Power Wide Area Network
LTE	Long Term Evolution
LTE-M	Long Term Evolution—Machine Type Communications
LVDC	Low Voltage Direct Current
M2M	Machine to Machine
Market-A	Weather Forecast Agent
MG-A	Microgrid Agent
mMTC	Massive Machine-Type Communication
MTC	Machine-Type Communication
NAS	Non-Access Stratum

NBIOT	Narrowband Internet of Things
NF	Required Network Functions (NF)
NFV	Network Functions Virtualization (NFV)
NPG	National Power-Generation
nZEB	Nearly Zero Energy Building
P2P	Peer-to-Peer
PAN	Personal Area Network
PG-A	Power grid Agent
PHY	Physical Layer
PS-A #1-2	Prosumer Agent’s 1–2
PV	Photovoltaics
RAN	Radio Access Network
RAT	Radio Access Technology
RE	Required Elements
REG	Regulation Layer
RES	Renewable Energy Sources
S1AP	Application Protocol
SCADA	Supervisory Control and Data-Acquisition System
SCEF	Service Capability Exposure Function
SCTP	Stream Control Transmission Protocol
SDN	Software-Defined Networking
SDR	Software Defined Radio
SGAM	Smart-grid Architecture Model
SMSC	Short Message Service Center
SW	Software
TCP/IP	Transmission Control Protocol/Internet Protocol
TSO	Transmission System Operator
UDP	User Datagram Protocol (Transport Layer)
URLLC	Ultra-Reliable, Low-Latency Communication
WAN	Wide Area Network
Wi-Fi	Wireless Fidelity (Alliance trademark)
ZEB	Zero-Energy Building

1. INTRODUCTION

1.1 Background

Climate change is a major challenge facing humans today, which has been studied extensively. For example, Luterbach et al. (2004) studied the long-term temperature increase in Europe since the Industrial Revolution. Their study showed a temperature increase of 0.43°C between 1973 and 2003. The study also showed an increase in weather extremes in the period. A recent study by the IPCC (in August 2019) on climate change and greenhouse gas (GHG) fluxes in land-based ecosystems states: “Since the pre-industrial period, the land surface air temperature has risen nearly twice as much as the global average temperature (high confidence). Climate change, including increases in frequency and intensity of extremes, has adversely impacted food security and terrestrial ecosystems as well as contributed to desertification and land degradation in many regions.” (IPCC Special Report on Climate Change, 2019).

The human contribution to climate change was studied by Scot et al. (2004), who showed evidence of a human contribution to greenhouse gas and other atmospheric pollutant concentrations. Increased environmental awareness is motivating individuals and organizations to choose environmentally friendly options in their actions; replacing fossil fuels with renewable energy sources is a key element in reducing human behavioral effects on global warming by means of carbon emissions.

Multiple actions have been introduced to reduce greenhouse gas emissions. Pacala et al. (2004) presented a strategy and methods to eliminate carbon-emission growth. Carbon dioxide, CO_2, is the dominant anthropogenic greenhouse gas. Pacala et al. showed that if nothing is done to limit the production of CO_2, emissions from fossil fuels will double by 2054. To avoid this growth, their proposal is to keep carbon emissions at the 2004 level. The methods proposed are increasing the use of more efficient vehicles and buildings; improving the efficiency of power plants; capturing CO_2 at power plants; and replacing fossil fuels with wind, solar, and nuclear energy.

Despite numerous actions taken, however, greenhouse gas emissions have continued to rise (IPCC Report, 2019).

Nevertheless, signs of positive prospects for the future are visible. An encouraging trend in public opinion favoring environmentally friendly energy sources, together with an increased use of renewable energy sources, is pushing individuals and organizations to choose environmentally friendly options in their consumption behavior. Consumers are choosing renewable energy sources and requesting that they be made available. The decreasing cost (down 14% from 2018–2019) of photovoltaic (PV) energy sources or solar panels (Solar Power Europe, 2019), combined with increased performance, is making PV energy sources attractive to active users (prosumers).

Localized energy produced by an active consumer is the essential element for triggering a change in power grid infrastructure. Such a consumer, producing energy locally and making it available for others, is called a prosumer. The prosumer has the opportunity to be active in the electricity exchange market. According to the Cambridge Dictionary, a prosumer is “a customer who helps a company design and produce its products.” The term is formed by combining the words “producer” and “consumer.” The U.S. Office of Energy Efficiency and Renewable Energy defines a prosumer simply: “a prosumer is someone who both produces and consumes energy.”

The prosumer will connect himself or herself to a modernized power grid, or more precisely a smart grid, which is a power grid incorporating dynamic optimization of grid operations and resources (Federal Energy Regulatory Commission 2008). Local renewable energy sources will provide self-sustained electricity for prosumers.

Increased renewable sources and energy storage systems connected using modern communication methods would enable demand-shifting and the exchange of energy in a cost-effective manner. In this way, smart energy communities can be formed.

Smart energy communities are potentially forcing electric grid owners and electricity providers to upgrade and modernize power grids.

The energy storage system is important in local energy production because of varying PV and wind-energy generation throughout the daily, weekly and annual cycles. Energy storage capabilities (ES) have increased, potentially, in the form of electric vehicles (EV) and battery energy storage systems (BESS). The amount of ES can be expected to increase, especially in the form of EV, at the same pace as local renewable-energy production. Electric vehicle use becomes increasingly feasible when the energy used is produced locally with no energy fee or energy-distribution fee. Energy storages can also be used for energy-demand shifting. The International Energy Agency stated in their report that during the year 2017 over 3 million EVs were sold globally (The International Energy Agency, Global EV Outlook, 2018). The same report estimated that a total of 125 million EVs will be reached by the year 2030. Sales forecasts for EVs have been increasing every year. The modern EV, in the year 2019, has an operating range of approximately 440 km, requiring a battery size of 100 kWh (EV Statistics of the week, 2018). Thus, in 2030 the ES capacity of EVs alone is expected to be 12.5 TWh.

Existing power plants will remain, providing electricity for industrial customers and ensuring a basic energy supply for smaller customers (Figure 1). In decentralized renewable energy generation, the need to transfer electricity over long distances will be decreased, and transmission and distribution can be proportioned for a smaller energy-transfer capacity. A local network of energy production makes distribution more resilient to weather extremes, and when electricity supply is disrupted the fault can be isolated into a smaller area. Whereas existing power grids star topology is especially vulnerable to weather extremes, such as hurricanes, which can potentially cause a state-wide black-out for the electricity grid. In mesh-protocol the fault area potentially can be isolated to one neighborhood (Koc et al., 2013).

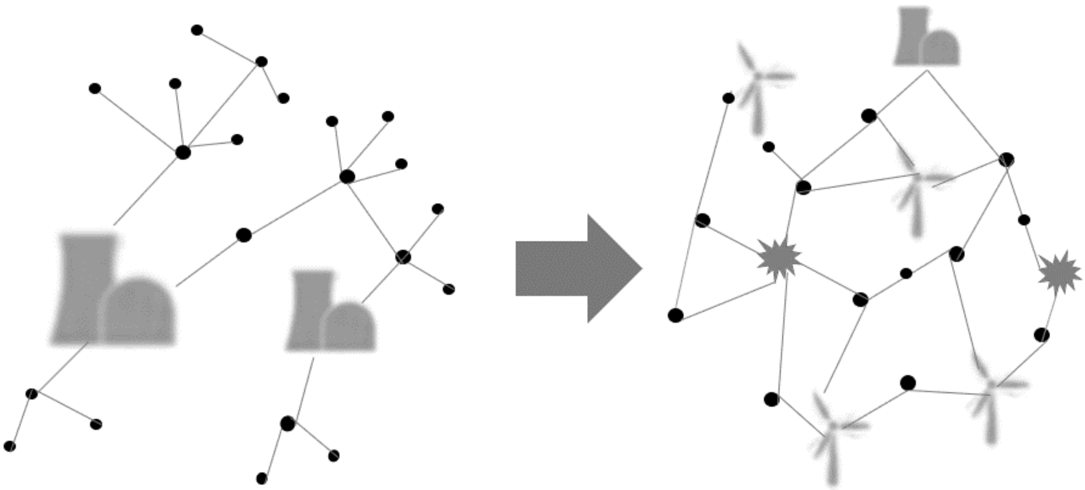

Figure 1. De-centralization of the electric power grid: The centralized network paradigm is replaced by a mesh network paradigm.

The decentralized renewable energy generation exchange requires changes to the existing power grid. Local electricity production, energy storing, and exchange would make the power grid more complex due to the increased number of electricity generation sources and their increased electricity-generation volatility. Power grids require more autonomous functioning, forming a smart grid or power grid by 2050.

A self-accelerated utilization rate for renewable-energy production is expected, due to the decreased costs of renewable energy sources and the consumers autarkic energy model. Local energy producers (prosumers) can form smart communities to exchange energy and balance consumption within the community. Localized renewable-energy production also creates improved power-distribution stability and a decrease in the use of fossil fuels for electricity generation. Decreasing the use of fossil fuels is an important element in fighting human-caused climate change.

The overall energy efficiency of the buildings is similarly important decrease human contribution to climate change. A legislative drive has been introduced by the United States and the European Union for energy-saving measures in buildings' energy efficiency (U.S. Department of Energy, 2015; European Commission, 2010).

Money greatly affects the motivation for change and its speed. Energy market liberalization started globally in the beginning of 1990. In Finland, the energy market was liberalized in 1995. The new energy market legislation decreased regulation and allowed new electricity generation suppliers to sell electricity on the open market. After energy market liberalization, the electricity distribution grid remained in a natural monopoly position, in which the energy market authority created control mechanisms, such as for prices and availability (Suomen energiavirasto, 2019).

The liberalized energy market, the formation of smart grids, and the establishment of energy-sharing communities enabled the creation of independent, local, small grids called microgrids. A microgrid is a localized group of electricity sources (Berkley Laboratory, 2019). The microgrid is defined by the U.S. Department of Energy's Microgrid initiative as follows: "a group of interconnected load and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid" (U.S. Department of Energy, 2012). Virtualized microgrid prosumers may not be physically located close to each other; however, they are interconnected by a management layer. A physical microgrid is a group of active prosumers physically located close to each other.

The prosumer's need for electricity from outside the microgrid could potentially approach zero when annually adjusted. This is possible because of zero-energy buildings, locally produced renewable energy, energy storage, and demand flexibility. Energy exchange and actively managed demand flexibility within a physical microgrid can further decrease the need for external energy transferred from centralized power plants.

Renewable-energy production would enable zero marginal costs of electricity, due the energy's net price would be zero and electricity distribution need is minimum. The value of energy exchange is affected by energy supply and demand, defined by the energy market. The household's electricity demand is greatly affected by seasonality.

The active exchange of energy between prosumers in virtual microgrids creates opportunities for new businesses in the value chain, such as microgrid and prosumer electricity-management operations. The new microgrid management function would operate energy exchange between prosumers in a microgrid. The exchanged energy is based on free renewable energy, so it is free. The free energy is “loaned” between microgrid prosumers, resulting in prosumers having an increased ability to balance energy supply and demand. The prosumer additionally has the option to sell energy actively on the open market, where it is bid on by the independent market aggregator.

An increased number of active prosumers may make physical microgrids possible, in which prosumers are located physically close to each other. They may exchange and balance renewable, free energy consumption inside a physical microgrid in a similar manner as in a virtual microgrid. However, in a physical microgrid distribution fees are minimized due to the close located prosumers.

This thesis discusses governance models for IoT-based Energy Internet, considering the residential sector, small-scale industry, and electrified transportation. The industrial sector is excluded.

1.2 The Energy Internet

The energy internet supports Power grid 2050. The energy internet is plausible if advanced and standardized end-to-end communication technology is utilized. Fifth generation (5G) advanced multi-mode and end-to-end communication technology enables utilization of a large number of internet of things (IoT) devices for measuring and controlling the power grid autonomously with very low-latency communication, connecting power grid to consumers’ intelligent electronic devices (IED) via the IoT.

The energy internet was discussed by Nardelli et al. (2019) in their publication “Energy Internet via Packetized Management and Deployment Challenges”. They proposed a method of managing virtually quantized energy for IEDs in a microgrid by using advanced wireless 5G communication. Virtually packetized (quantized) energy can be autonomously managed in a pre-determined manner to optimize energy consumption, generation, and storage status in microgrids.

A fully electrified energy internet requires a coordinated energy-management structure for managing local renewable-energy production, storage, and demand management (Nardelli et al., 2019). The energy internet combined with zero-energy houses would enable annually balanced net-zero external energy consumption for prosumers. The energy internet would enable adaptation to different users' energy profiles and active control for managing loads locally. Overall power grid management has secured energy generation and distribution in an optimized manner, ensuring energy supply in a grid-fault situation by using a self-healing grid arrangement (European Technology & Innovation Platforms, 2019).

The possibility of net-zero energy consumption makes the energy internet a financially attractive option for the future, causing accelerated interest among traditional consumers. The energy internet would change the operation of the existing energy market and create opportunities for new business models.

The energy internet aims to further improve on the energy self-sufficiency of physical microgrids. The energy used by IEDs is packetized (quantized) for active management in a pre-determined, prioritized manner. The IEDs' operation can be shifted in time to make electricity generation capacity available for more important uses. The virtual energy server handles energy-packet management for prosumers and scheduled exchange inside the microgrid (Nardelli et al., 2019).

Agent-based modelling (ABM) is an illustrative method for describing the complex behavior of the energy internet, the microgrid, and their governance models. An agent can be described as an autonomously behaving element. The agent model is a way to represent agent interaction and the governance of the system (the process model) (Niazi et al., 2011). The energy internet includes complex dynamic socio-technical behavior which can be simulated using ABM. The ABM can be used to simulate the decision-making of real-world autonomous and interconnected elements (Dam et al., 2013).

1.3 The Research Problem

De-centralized renewable energy sources would require changes in the existing power grids. Increasing numbers of electric cars and dedicated ES will make it possible to store energy at larger scales and for longer periods. Stored energy can be used to shift usage time of electrical devices. The load on the power grid would be more balanced due to energy storage. Prosumers who are locally generating electricity may form communities called microgrids. Microgrids may be formed to exchange energy among local households or prosumers.

Distribution networks are owned by private or municipal companies, which may lead to virtual microgrid communities facing challenges in how to transfer energy in a cost-effective manner. The currently existing energy-transfer fee does not directly consider the distance electric energy is transferred. It includes only the quantity of delivered energy. In addition, in liberalized markets such as the Nordic countries, electric power is bought via retailers who usually are not the owners of the physical electricity grid. For residential users, the cost of having electricity available is related to electricity sold via retailers and the network distribution fee.

In this research, future power grid energy is considered to be produced mainly by prosumers with zero marginal electricity costs. Groups of prosumers would be organized as a physical microgrid community in which they share energy resources (generation and storage) and consume jointly following a commons-based management approach (Figure 3). Under this regime, the electricity price within the community would be zero (Lo et al., 2019) while the net energy consumed from outside the microgrid would be minimal.

Rifkin (2014) defines zero marginal costs in connection to the energy internet as follows:

> "*The Energy Internet (a merger of Internet technology and renewable energies) will change the way power is generated and distributed. In the next decades hundreds of millions of people will produce their own renewable energy in their homes, offices, and factories, and share*

> *green electricity with each other on an Energy Internet, just as we now generate and share information online. It will allow billions of people to share energy at near zero marginal cost in an IoT net.”*

The so-called quantum leap forward may occur due to the technology race lowering production costs, while free energy from PV and wind leads to freely exchanged electricity. Rifkin (2014) mentioned the world wide web (www) as an example of a similar industrial revolution, in which a communication medium operates at nearly zero marginal costs. For a www-connection, the consumer can obtain a certain speed within a monthly capacity budget, depending on the consumer’s needs.

Applying a zero marginal cost model to the energy internet could create a model in which energy is exchanged in microgrids with only a marginal network fee. The received and delivered energy is expected to be same, resulting in the net exchanged-energy sum being zero. The price of exchanged energy may be balanced based on market prices at the time of exchange. The exchanged energy may also have a reasonable network fee applied.

If the internet connection pricing model is applied to the energy internet, the base electricity capacity for securing electricity availability is provided by electricity companies, the exceeded capacity would be separately charged. For example, prosumers may make a mid-term contract with a company for a certain amount of energy at a secured price. If this is exceeded, an extra fee is applied. Thus, it is expected that the energy-pricing governance model will include flat-rate pricing for the quantity of energy sourced from outside the microgrid.

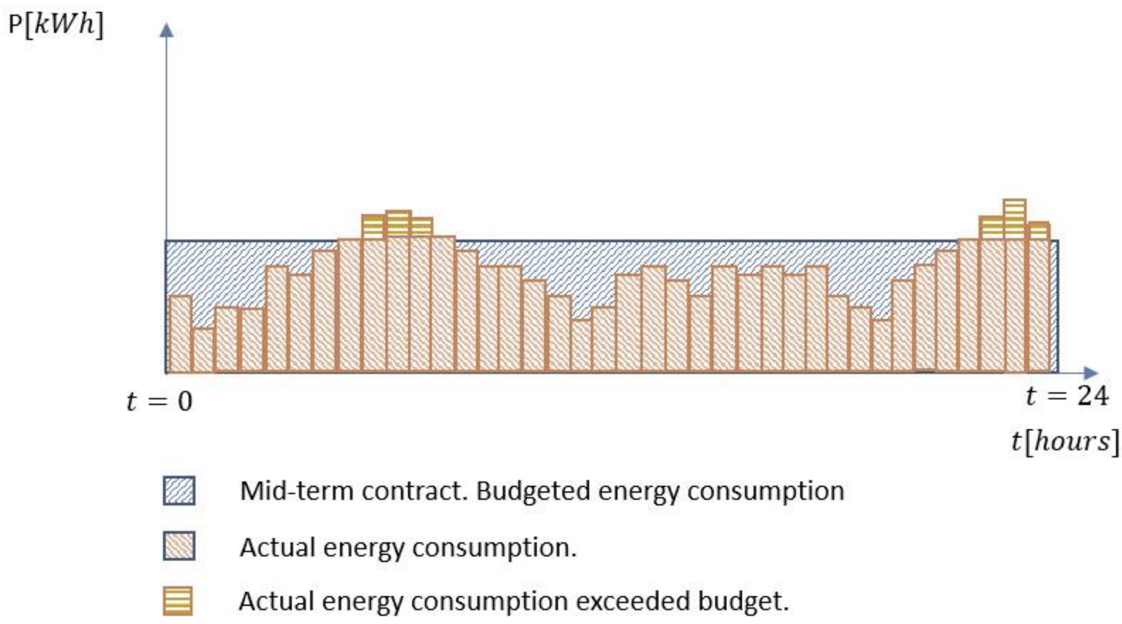

Figure 2. Future pricing governance model for budgeted energy (Nardelli et al., 2019).

Figure 2 provides an example of a centralized electricity-supply agreement, in which hourly actual demand is depicted as . The prosumers' actual consumption ( ) exceeding the mid-term contracted level ( ) attracts an additional energy fee. The mid-term contract is fixed fee, securing price and availability. If the budgeted amount is exceeded, the energy-market fee and network fee is applied. Exceeding the budget can be avoided by having demand flexibility: shifting energy from the period of excessive consumption to another time when there is no danger of exceeding the budget. An alternative way of avoiding exceeding the energy budget is to actively exchange energy with other prosumers.

In the future price governance model, the prosumer is expected to have minimal need for external energy, although the prosumer needs committed external energy delivery capacity for security reasons. This may be achieved using an internet-type of agreement in which the needed capacity is secured in a certain time-window for a fixed fee. The model creates consumer accountability for energy-usage scenarios, allows the power grid design specification to be optimized, and promotes renewable local energy sources.

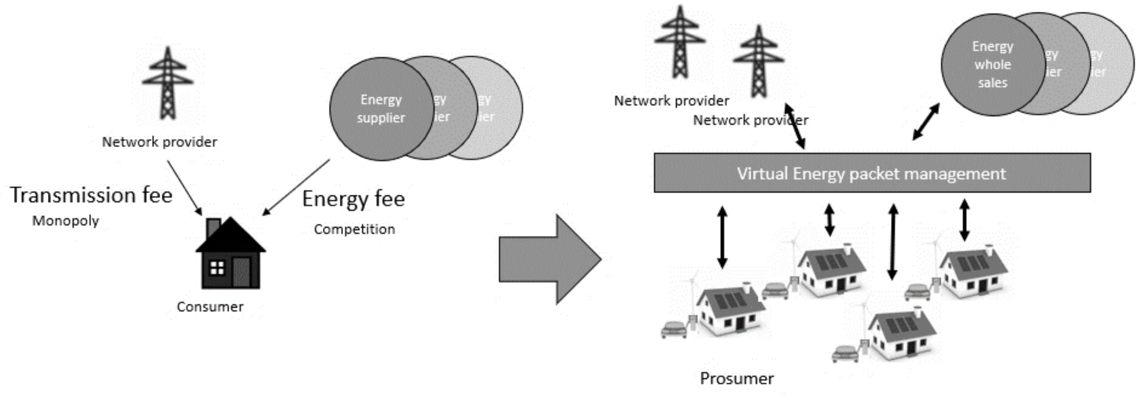

Figure 3. Predicted electricity charging mechanisms: today and 2050 (Nardelli et al., 2019).

If this solution becomes dominant, there will be a strong tendency to have localized microgrids to decrease network costs, leading to the merging of energy generation, distribution, and consumption into pre-determined localities (e.g., cities).

A further step is for physical microgrids to become networked and managed accordingly (Figure 3). This new system—expected to be fully in place in 2050—would be fossil-fuel free and is called the energy internet (European Technology & Innovation Platforms, 2019). The aim of this document is to identify the key agents in the transition from the existing electricity market to the energy internet, from a model that is market-based to a commons-based electricity exchange between prosumers, focusing on changes in governance models.

A necessary condition for the energy internet's existence in 2050 relates to the energy-distribution system. The existing governance model based on liberalized markets does not support virtual microgrids targeting self-sufficiency on larger scales, since markets are designed to deal with scarce commodities with non-zero marginal costs. Future renewable-energy production will utilize a self-sustaining model, in which energy's marginal costs will approach zero. Each prosumer's electricity demand is expected to match with locally produced energy (Figure 4). Prosumer's electricity storage will help to shift demand, if needed. Should a prosumer have excess energy, it could be exchanged between other prosumers (inside the microgrid). Similarly, if a microgrid were lacking energy and other microgrids had an excess of energy, they could exchange back and forth as needed. It can be estimated that, annually adjusted, the sum of energy exchange would approach zero on the prosumer and microgrid levels.

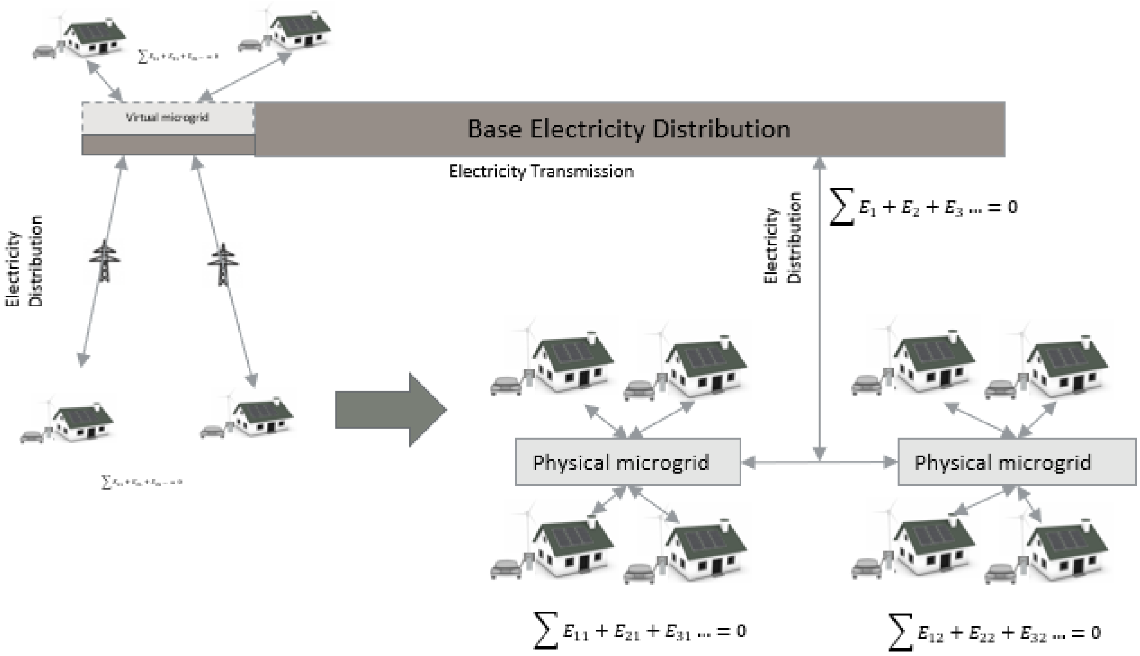

Figure 4. A shift from virtual microgrid to physical microgrid in relation to the power distribution grid (Nardelli et al., 2019).

Virtual microgrid energy may be transmitted rather long distances, straining the power grid. In a physical microgrid, the distribution distances can be significantly shorter. Since the electricity distribution fee is a significant cost element, a physical microgrid is potentially much more cost-effective than a virtual microgrid. When prosumer geographical density is sufficient, they can form physical microgrids (Figure 4).

The existing energy market includes a limited number of energy bidders (centralized energy producers) who, together with energy consumers, define market prices, which creates market-price equilibrium. The main goal of energy-generation companies and energy-distribution companies is to maximize profit on invested capital.

The price of electricity is expected to increase as energy demand continues to increase. Centralized energy-production capacity may not increase at the same rate (due to decreasing use of fossil fuels and limited nuclear power). Electricity transmission and distribution costs are expected to grow due to the need for higher transfer capacity and the increased need to protect the network against extreme weather. The increase in energy and its transfer price, added to possible taxes, will form a major part of consumers' housing costs. The high costs of energy may be the trigger for consumers to seek cheaper and more environmentally sustainable energy options, making the energy internet a viable solution for households.

1.4 Aims of the Research

The virtual microgrid is a forum established by active prosumers exchanging locally generated electricity to maximize their opportunity to be energy self-sufficient and potentially utilize zero marginal electricity costs. The ABM is a method for describing interactions in a non-dynamic prosumer network.

The energy internet brings an additional active element into electricity generation, consumption, and storage control. In the energy internet, intelligent electronic devices are controlled and monitored based on their quantized energy requirements and pre-determined priorities. The upcoming electricity need, electricity-generation information, and storage information are optimized with other physically close prosumers by means of cyber-physical packets, with the goal of zero marginal electricity costs.

To achieve the full benefits of locally generated renewable energy sources, and to allow electricity exchange between prosumers (the energy internet), the power grid needs to support bi-directional power flow with advanced end-to-end communication technologies (5G). These advanced communication technologies support prosumers' active participation in the energy market.

Based on this, the aims of this thesis are as follows:

O1 To develop an ABM for virtual microgrids and create governance models in the existing system.

O2 To develop an ABM of an energy internet consisting of physical microgrids using a commons-based governance model.

O3 To illustrate transition pathways from the existing power grid to the energy internet.

1.5 Methodology

1.5.1 Data

This thesis uses technical reports and research papers to present a clear understanding of the topic.

1.5.2 Research Methods

This research focuses on defining the key agents of an ABM that focuses on the transition from the existing grid to the energy internet, centered on the different governance models and their respective pricing schemes. The method is a literature review relating to technological developments and governance models for distributed energy systems using cutting-edge information and communication technologies (ICT).

1.6 Research Limitations

The research is limited to power grids and solutions used by and for private households.

2. PRINCIPLE OF AGENT-BASED MODELS

2.1 An Introduction to Agents

An agent is commonly described as a decision-body that can make decisions based on information collected from other devices, such as sensors, or from other agents. Agents are commonly used in software-programming languages to describe program behavior. Agents have been defined in many ways in the literature. Shoham (1993) discussed agents in connection to artificial intelligence programming. Shoham expanded the definition of an agent as follows: “A state of an agent consists of components such beliefs, decisions, capabilities and obligations. Agents are controlled by agent programs, which include primitives for communicating with other agents.”

Luck et al. (2001) defined an agent as an “object who is serving a purpose or goal.” They divide agent structure into three parts: the entity agent, the object agent and the autonomous agent. An autonomous agent is a self-motivated agent that pursues its own agenda instead of being under the control of another agent. Agent behavior is described by Tran (2012) as the following operation models: “(1) agent acquiring information, (2) agent forming a proposal, (3) agent making a decision, (4) agent implementing action, and (5) agent conforming the decision.”

Jennings (2000) defines an agent in the context of computer programming as follows: “An encapsulated computer system that is situated in some environment, and that is capable of flexible, autonomous action in that environment in order to meet its design objectives.” The definition is expanded by Dam et al. (2013), in the context of non-linear socio-technical agent models, to describe agents as reactive, proactive, autonomous, and social software entities.

Since traditional mathematical analysis of a static system may not adequately describe systems behaving dynamically, the ABM was created to simulate complex systems, including several interconnected autonomous operations such as traffic jams and stock markets (Bonabeau, 2002). The ABM is an ideal method to describe system behavior when information relates to technology. The agent in a model can inform, instruct, and act.

In complex systems with decision-making and planning capabilities (such as machine learning and artificial intelligence), the ABM is an important method of describing the system's operation for a forum or person who is unfamiliar with the topic (Dam et al., 2013).

There are three advantages to the ABM, as described by Dam et al. (2013):

- The basic idea of the system is easy to understand, even for those who are unfamiliar with the approach.
- Agent-based modelling can deal with complexity.
- The model presents an illustrative description of the system.

The benefits of ABM compared to other modeling techniques can be described as follows: ABM can consider new phenomena in a system, it can provide a natural description of a system, and it can be flexible. Dam et al. (2013) proposed that "a good agent-based model can be relatively 'transparent' to inspection by decision makers." Build agents with operational guides can be compared with actual system behavior in a plausible fashion.

For non-linear dynamic systems, ABM is a tool to describe complex system behavior. The ABM outcome may not be known. In addition to mathematical boundaries, it can have a conceptual worldview or socio-technical model included (Dam et al., 2013).

Agent modeling can be referred as multi-agent system (MAS), where it can be equipped to solve specific problems using agents. As the name indicates, the multi-agent model has multiple agents, in which each agent represents the decision-maker and interacts with other agents. The expected outcome of the MAS is often known. Multi-agent systems are a tool for use in engineering sciences (Balaji et al., 2010).

To provide ABM principles, Dam et al. (2013) introduced the following step-by-step process for building an agent-model to improve decision-making in socio-technical systems:

> "Step 1 Problem formulation and actor identification. What needs to be involved?
>
> Step 2 System identification and decomposition. Data collection and structuring.
>
> Step 3 Concept formalization to create a precise description of the concepts, including the agents, their states, and their properties.
>
> Step 4 Model formalization to establish which agent performs which task and when.
>
> Step 5 Software implementation. Model implementation in an appropriate modelling or programming environment.
>
> Step 6 Model verification to check whether the conceptual model is correctly translated into the model code.
>
> Step 7 Experimentation, which may provide the behavioral insights described in Step 1.
>
> Step 8 Data analysis to explore the data and identify interesting or relevant patterns.
>
> Step 9 Model validation to check whether the outcomes are convincing.
>
> Step 10 Model utilization to explore practical aspects of using models to solve the problem."

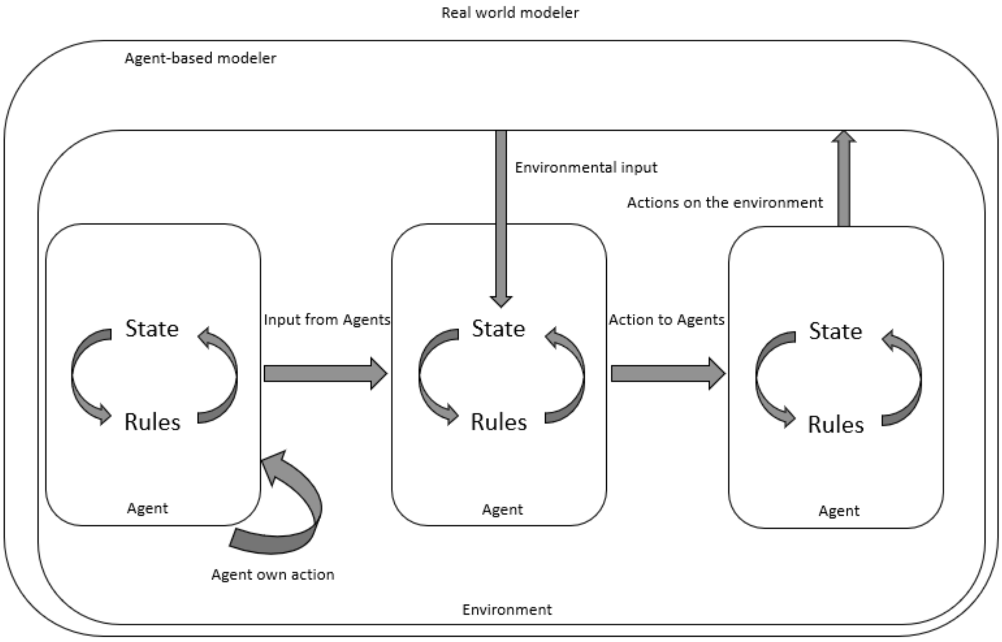

Figure 5. The structure of an ABM. The agent can perform actions autonomously, in discussion with other agents. Agents' autonomous behavior is based on states and rules. Source: Dam et al., 2013.

The step-by-step process described by Dam et al. (2013) provides high-level guidance for building an agent model. Modeling starts with problem identification to form structured data from the collected information. When the structure is in place, agents can be defined, based on their expected states. In the modeling process, it is important to define agents, which agent does what, and in which phase. SW-implementation data and the verification of the model must be checked, to ensure that there are no implementation errors in the building blocks. The exploration step ensures that the system is not showing chaotic behavior, in which small changes cause massive effects or massive changes do not create any effect.

In the model depicted above, the agent can execute actions autonomously, based on its own state. The agent's state considers statuses received from connected agents (Figure 5). The rules control the agent's actions and how other statuses are taken into account when action is executed. Dam et al. (2013) give an example of a rule:

> "A common decision rule might be that agents attempt to maximize some utility, but the agent may or may not have access to information

> about the other agents with which they interact, may or may not be able to record the outcome of previous actions in order to learn, or may have limits on the computation allowed to process any information in order to mimic the limits that human decision makers face. Decision rules specify what an agent will do with the information that they have access to, as well as how they will perform any actions."

Descriptions based on using ABM are an effective tool for analyzing dynamic socio-economic system behavior. However, it is important to understand how measurements are made and what is measured to ensure correct data. Socio-economic modeling may amplify system behavior, so that small changes may cause dramatic effects.

When discussing agents or other elements as part of a system, the word "system" should be defined. Merriam-Webster defines a system as "a group of devices or artificial objects or an organization forming a network especially for distributing something or serving a common purpose." Dam et al. (2013) define socio-technical systems as follows: "Systems are many things to many people." Dam et al. try to clarify the meaning by referring to it as a fuzzy system with "fluid edges," connected to and influencing other systems.

As can be seen from the descriptions of the word "system" by Merriam-Webster and Dam et al., it is very difficult to define a system explicitly. The word "system" is used to describe a complex environment when there is no other word to describe it.

To further clarify ABM complexity and to adapt into practical implementation, the three-layer agent model is introduced

2.2 The Three-Layer Agent Model

While Dam et al. (2013) described an agent as having two elements defining agent operation, Kühlens et al. (2015) presented a three-layer system for agent modeling. The additional third layer they presented represents an essential element of interconnection to other agents. Their publication defines the agent layers as follows: The physical layer represents physical devices like sensors, actuators, or controllable switches, which are controlled by an agent; the communication layer exchanges information by sending and receiving status data with neighbor agents; and the regulatory layer is the core of an agent, making decisions based on all available information (Kühnlenz et al., 2015).

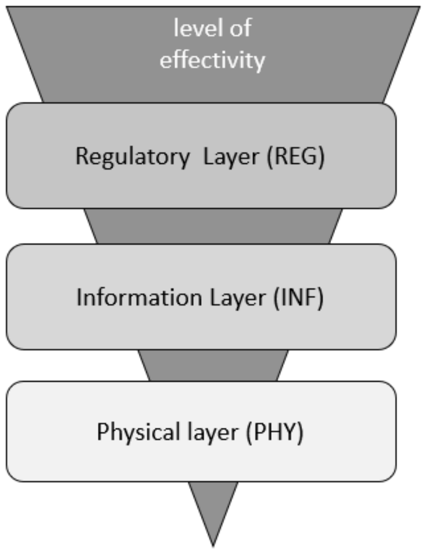

Figure 6. The three-layer model agent’s effectivity levels (Nardelli et al., 2019).

Figure 6 represents how much effect each layer of the agent has on the system’s behavior. The regulatory layer is the layer of the agent with most influence in terms of system behavior.

2.3 Simulating Principles of A Three-Layer Agent Model

Kühlens et al. (2015) simulated the dynamics of a complex three-layer ABM, represented by electronic circuitry designed to maximize power delivered by the agent.

The simulated agent is formed of three layers, in which the physical layer represents the physical infrastructure and executes actions to the external environment. The rules of the agent are defined by the regulatory layer. The agents are connected to other agents via the communication layer. The rules for execution also consider the status of connected agents (Kühlens et al., 2015).

In their simulation, the agent represented a prosumer, whose intention was to maximize their own energy. However, as the system was dynamic and connected agents had the same rule, selfish behavior by the agent would decrease the system's total available energy. The point where an agent's selfish behavior would decrease their own energy supply and that of others is a saturation point. When the agent reached the saturation power, and caused a decrease in system energy, the agent reduced demand to achieve saturation point (Kühnlenz et al., 2016).

The saturation point, or point of equilibrium, forms a prisoner's dilemma situation, in which the agent's decision was to cooperate by removing a load. In this way, the agent improved the system's situation, but worsened its own situation. If the agent added demand (defect), the situation would be reversed: The system's situation would be weakened, but the individual agent's situation would be improved (Table 1) (Kühlens et al., 2016).

Table 1. An agent's behavior at the time *t*, based on the prisoner's dilemma (Kühnlenz et al., 2016)

Physical action	Behavior class	S_i [t]
Add variable by one	defect	1
Remove variable by one	cooperate	-1
do nothing	ignore	0

As shown in a study by Kühlens et al. (2015), the agent under consideration had three options: Agent i can add to the variable by one (increasing demand), decrease the value by one (decreasing demand), or do nothing.

To make the decision (regulatory layer) at time t, the agent considered the state of the previous decision $S_i[t-1]$ to decide the new state $S_i[t]$. The decision for agent i was $\lambda_i[t-1]$. If it was higher than or equal to the system's target minimum, λ_{min} , the agent maintained its strategy at time t. The agent compared its decision to another agent's decision, N_i (Kühnlenz et al., 2016).

Through the communication layer, agent i knew the decisions of the connected agent j with state $S_j[t-1]$. Agents would send their own state at the time $t, S_i[t] \in \{-1, 0, +1\}$. If the topology was ring-type, the agent had two neighbors. For more complex topologies, such as star- or mesh-type, agents might have multiple neighbors (Kühnlenz et al., 2016). Based on the decision process, the agent modified values for the physical layer.

The simulation by Kühlens et al. (2015) demonstrated that the agent model was sensitive to system parameters. Dam et al. (2013) indicated similar behavior. Small changes may cause large changes in outcome. This behavior must be noted when modeling a packetized energy internet, in which an independent market aggregator forms a market-price-based supply–demand balance. If many consumers have price priority to ask for more energy at the same time, the price will increase, which is assumed to decrease demand. Market pricing is based on regional pricing, which may limit the size of the agent system. It must be taken into consideration that a larger agent system may stabilize low hysteresis.

2.4 Conclusions

The energy internet is complex, operating autonomously in a socio-economic environment in which many interactions affect each other. Such complex non-linear system behavior may be described using agents. These autonomous agents are built based on three layers, as follows: A regulatory layer for setting behavior norms, an information layer for sharing agent statuses, and a physical layer to implement concrete actions (Nardelli et al., 2019). Agent-based modeling potentially provides good descriptions of system behavior when the outcome of system behavior may not be known.

3. THE ELECTRICAL POWER SYSTEM

3.1 The Electricity Grid

The electric power grid requires at least two physical elements of electricity, as stated by Erbach (2016):

- Supply and demand in the grid must be balanced; imbalance will cause failures (blackouts).
- Actual flow of electricity in the grid cannot be controlled: The electricity flows in the direction of least resistance.

It may be worth defining the difference between the terms electrical energy (E) and electrical power (P), which is electrical voltage (V) multiplied by electrical current (I). The energy equation can be derived from the previous equation by calculating power used in a certain period of time (dt).

$$P[W] = U[V] * I[A]$$

$$E = \int_{t_1}^{t2} P * dt$$

$$P = Power[W]$$

$$E = Energy\ [J]$$

Equation 1. Equations of energy and power, explaining the difference.

The electricity system consists of physical infrastructure for electricity generation, transportation, and consumption, with a price defined in the electricity market (in countries with a liberalized energy market). The physical grid transfers generated electricity through a long-distance transmission grid and distributes it to residential and industrial consumers (Erbach, 2016).

Electricity quality is defined by its reliability, voltage, and frequency regulation. Alternating current (AC) frequency is an important quality of the electric power grid.

If supply and demand are imbalanced, that is there is too much load compared to supply, the frequency will go down: similarly, excess supply will increase the AC-frequency. The AC-frequency deviating from its nominal values will harm electrical devices connected to the electric network.

Peak energy demands must be covered by the power-generation plants and transmission grid. The transmission grid’s dimensioning must consider peak loads being carried for long distances. Radial feed of the energy is handled by the distribution system operator (DSO) for medium and short distances (Fingrid sähkönsiirtoverkko, 2019).

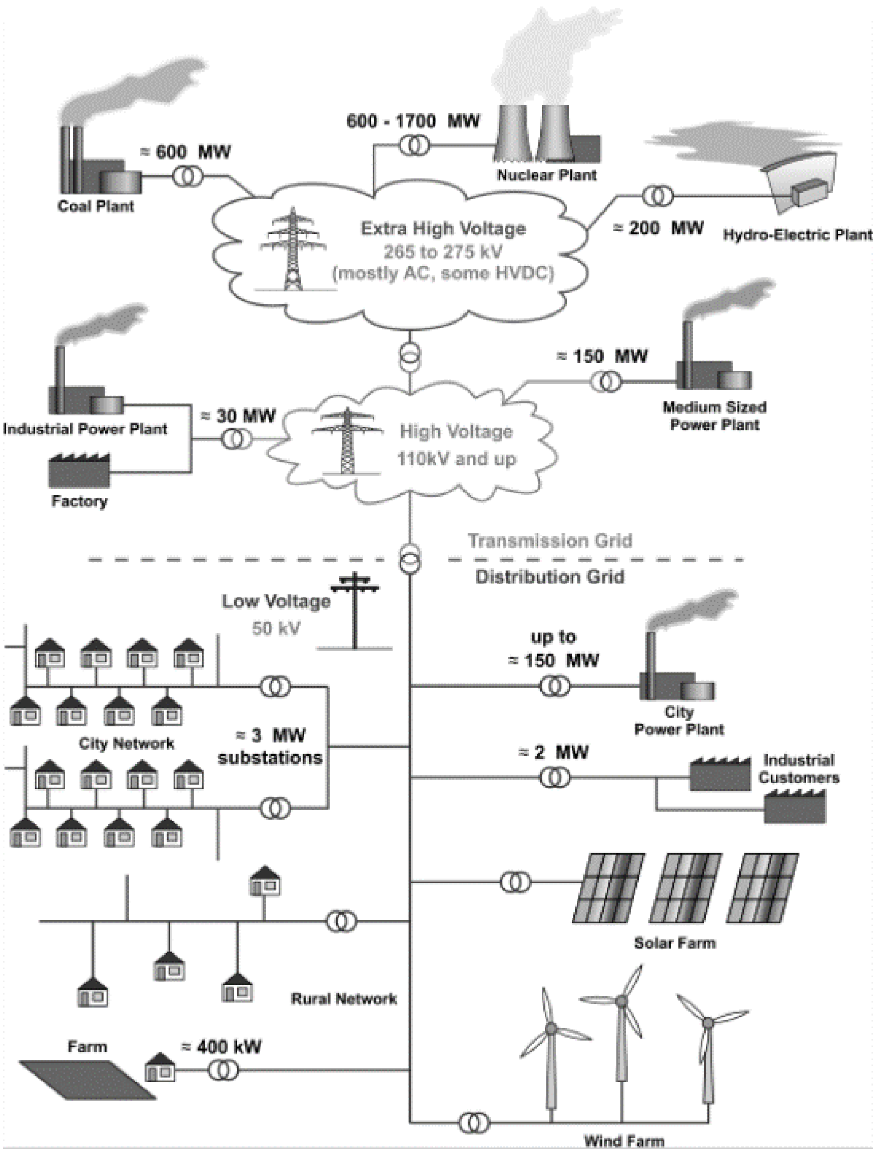

Figure 7. General layout of electricity networks. Source: https://commons.wikimedia.org/wiki/File:Electricity_grid_schema-_lang-en.jpg. https://creativecommons.org/license/by/3.0, from Wikimedia Commons.

A generalized structure for electrical power grids consists of a high-voltage distribution grid and a transmission grid, to which large, nation-wide power-generation plants are connected. The transmission grid operated by the transfer system operator (TSO) is also connected to neighboring countries to sell and purchase electricity abroad (Figure 7). The transmission grid supplies energy over long distances at 400 kV, 200 kV, and 110 kV (Fingrid sähkönsiirtoverkko).

The transmission grid provides electricity to DSOs, which will distribute the electricity to consumers. Substations are used to transform voltage to a lower level and to control electricity-distribution-grid interconnection points using switches and circuit breakers. The voltage level in the distribution network in Finland is 110 kV in municipal areas and 20 kV in rural areas. Transformers are used to change voltage levels. The basic structure of the traditional power grid has similar elements in most countries. For consumers and small-scale industry, electricity voltage is decreased to 400 V in Finland (Fingrid sähkönsiirtoverkko, 2019).

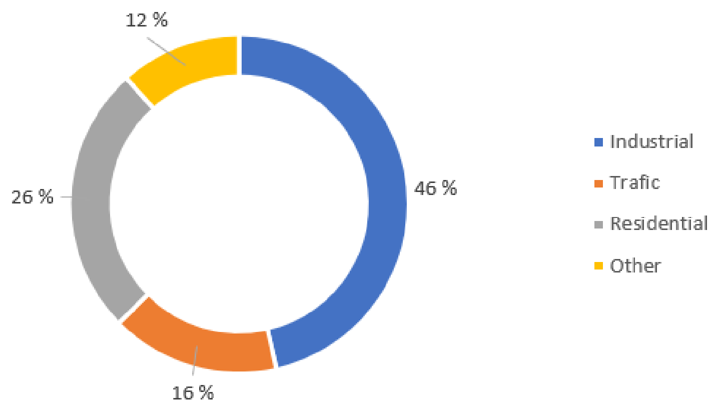

Figure 8. Energy consumption share per sector, 2017 (Suomen virallinen tilasto, 2017).

To avoid power grid black-outs or failures, electricity supply and demand must be balanced at all times. In order to secure supply, additional back-up generators are equipped on top of nominal demand to meet peak demand. The back-up generators have three operational states to connect them into the grid: The primary reserve is equipped to become operational and synchronize with the network in seconds, secondary devices are able to serve the network in a few minutes, and tertiary back-up can support the electricity network in 15 minutes. The back-up generators are not in use most of the time, and thus investments are not in active use (Erbach, 2016).

Transmission and distribution grids typically have radial distribution systems or single looped grids, which makes overload protection simple and easy. However, their disadvantage is a lack of capability to adapt to different load scenarios and their weak ability to support local electricity generation. A possible fault in one large power generator may have a major influence on a large geographical area, due to the existing grid structure and a lack of adequate back-up generators. The distribution grid's quality or status measurement units are typically not very densely installed, or may not provide solid information about the condition of the whole network (Koc et al., 2013).

The power grid control system's functionality is limited to power transmission and distribution-grid elements; thus, it does not properly consider consumer activity. The existing grid is vulnerable due to large distribution areas, in which a fault can cause electricity black-out over a large area (Lakervi et al., 2008).

Power-distribution grids are mainly controlled via a supervisory control and data acquisition (SCADA) system. The SCADA program monitors and measures the TSO/DSO's network status in real time and remotely controls substations, electricity switches, and feeders. The system provides illustrative information regarding electricity-switch positions and network-status information (Lakervi et al., 2008).

The existing energy supply relies on centralized electricity production. The largest sources of electricity are power plants using nuclear, hydrogen, natural gas, and fossil fuels (Figure 9). Power plants using PV and wind turbines are increasing. Wind-power's generation share increased 32% from 2017 to 2018 (Suomen virallinen tilasto, 2018).

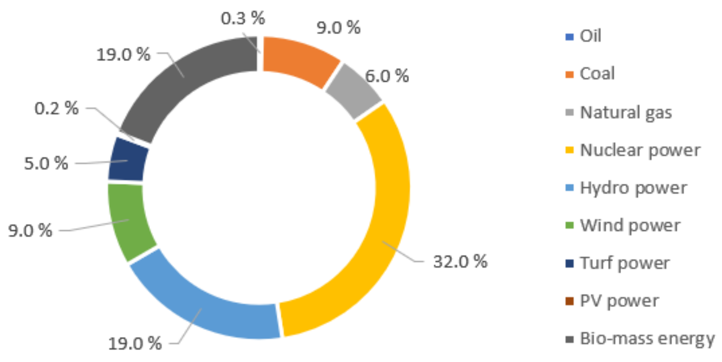

Figure 9. Energy-production sources in Finland (Suomen virallinen tilasto, 2018)

Existing renewable energy sources in Finland are mainly hydro-power and wind-turbine power-generation plants. Wind-turbine power-generator plants are mainly private-owned companies providing energy for energy markets. Their share of total energy production is 28% (Tilastokeskus, 2016; Fingrid energiamarkkinat, 2017; Suomen virallinen tilasto, 2018). Wind-turbines are location sensitive: they are mainly located in windy, high, open areas.

In northern countries, the environment creates extra challenges due to the long, cold winter. During winter, buildings need extra energy for heating, while in the same season PV-production is somewhat limited. In Nordic countries, new buildings have energy-saving requirements, following the European Commission's nearly zero-energy buildings directive (European Commission, 2010).

The power grid is designed to transfer energy from high voltage to medium voltage. For historical reasons, it was designed to consider a one-directional electricity feed. At the time of design, only a limited number of distributed energy resources were available. The DSO collects a consumer's hourly energy consumption by remotely reading metering instruments, where available. The measurement device uses one-way data transfer from the consumer for payment information. The consumer's electricity-consumption information is shared with the selected energy supplier for their energy invoicing. Electricity-consumption information available to the customer is limited to the periodic billing cycle. The consumed-energy information shared with the consumer considers only the total consumption of the building.

The future power grid is expected to rely on decentralized electricity production, in which prosumers generate and store electricity at home. Prosumers can exchange energy with other prosumers using a bi-directional power flow. Hence, better communication protocols, such as the energy internet, are required.

The energy market will disconnect from the industrial and traffic energy market as residential- and electrified-transportation-sector energy is produced, exchanged, and enhanced locally. Based on Finland's official statistical source (Suomen virallinen tilasto, 2016), a major portion of energy consumption in 2017 was shared between industrial, traffic, residential, and other usage. Residential energy consumption compared to other sectors in Finland is approximately 25% of the total energy consumption (Figure 8).

3.2 The Electricity Market

European electricity-market liberalization started at the beginning of 1990, when England and Norway opened their electricity sales and production to competition. In a liberalized electricity market, electricity production is separated from electricity distribution due to its natural monopoly position. The European Union controls the electricity market with directive 2009/28/EC (Erbach, 2016; European Union Directive 2018/944).

The electricity market in Europe operates on various levels. In a liberalized market, different entities are responsible for electricity generation, transmission system operations (TSO) and distribution system operations (DSO). Distribution system operators are required to provide third-party access to their networks (Erbach, 2016). Distributing electricity through distribution grids is a natural monopoly business, in which the private customer is not able to change electricity distributer, due to the physical connection. Markets may be differentiated by geographical scope and retail-market size, from local to transnational wholesale markets. Wholesale markets are organized differently than consumer retail markets. Based on their time scale, wholesale markets range from real-time balancing markets to long-term contracts.

Energy markets in Finland were opened to competition in the year 1995. A consumer can buy electricity from any available energy supplier. In Finland, power-distribution pricing is controlled by the energy authority. A major element in the distribution fee is power grid investments, from which a reasonable profit for the power grid provider is calculated.

The price of energy is divided into three main cost items:

1. The supplier fee, including the energy price
2. The network distribution fee
3. Taxes

The consumer price of electricity in Finland consists of the fee for electricity sold (35%), the distribution fee (29%), the electricity tax (14.5%) and the electricity value added tax (19.5%) (Vattenfall, 2019). The price of electricity is defined in the open energy markets, based on balancing supply and demand.

3.2.1 Energy Price Formation

Electricity is traded anonymously in the electricity market in a centralized manner. The price is formed based on balancing supply and demand. The energy market offers standardized energy products for sale. Countries across Europe (Sweden, Norway, Denmark, Estonia, Latvia, Lithuania, Germany, the Netherlands, Belgium, Austria, Luxemburg, the United Kingdom, and Finland) have joined in an electricity marketplace called Nord Pool. Available products for sale in the market are day-ahead and intraday (Nordic Power Exchange, 2019).

The day-ahead market is a trading place for customers selling or buying energy for the next day (the next 24 hours). The day-ahead market is open for bids until 12:00 CET in the auction for delivery the next day. To match supply and demand, a single price is set for each hour, and the market price point is set at the point of market equilibrium (Figure 10). The algorithm used in the marketplace is EUPHEMIA (EU + Pan-European Hybrid Electricity Market Integration Algorithm) (Nord Pool Day-Ahead Market, 2019). After market-price formation, market participants are informed of the results.

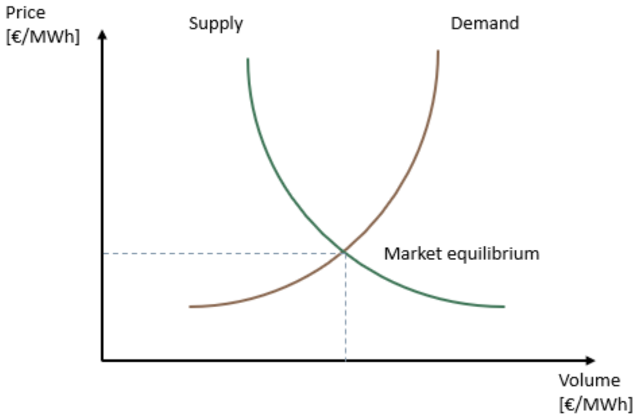

Figure 10. Day-ahead market price formation (Alberta Electric System, 2020).

The intraday market is connected to the day-ahead market to ensure a balance between physical supply and demand after the day-ahead auction. The intraday is an on-going trading market that continues until one hour before actual delivery. It reduces the need for reserves due to changes after the day-ahead demand or supply auction. To set prices, the highest purchase price and lowest selling price are matched (Nord Pool Intraday Market, 2019).

An interesting way of representing price equilibrium considers the source of electricity, its costs, and demand (Figure 11). The demand line is expected to shift towards renewable energy sources (Campillo et al., 2013; Maekawa et al., 2018). If this happens, it will indicate that prices are approaching zero marginal pricing.

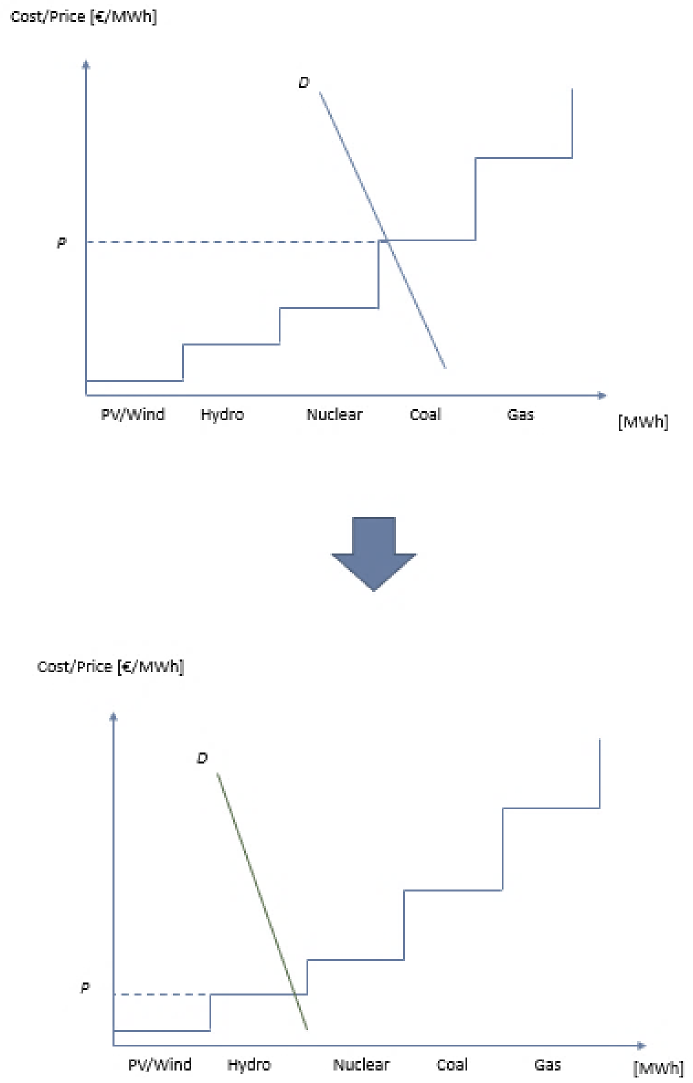

Figure 11. Cost–price equilibrium development due to the increased availability of renewable energy sources in the energy market (Campillo et al., 2013; Maekawa et al., 2018).

Localized energy production by prosumers and nearly zero margin energy costs are shifting the demand curve to a lower price point.

3.2.2 The Electricity Distribution Price

The power grid network fee consists of a transmission grid fee, area distribution fee, and local distribution fee. The local distribution network is owned by private enterprises, and the fee is defined by the grid network operator.

The electricity suppliers are private companies selling electricity to end-users. Their responsibility is to ensure that electricity availability and quality is according to regulations. The suppliers purchase the electricity from the electricity-generation plants or from the energy market (Nord Pool, 2020).

The electricity-distribution pricing model applied is based on charging all similar electricity purchasers equally. The price is not dependent on the distance the electricity is distributed. Electricity distribution is a governmentally regulated, natural monopoly business, in which DSOs are permitted to collect a reasonable profit for electricity distribution. The maximum permitted profit is calculated based on tied-up capital and current interest rates. The fairness of the pricing is controlled by government authorities. In Finland, this authority is Energiavirasto.

As in any privately owned company, a DSO’s main business target is to generate interest on the owner’s investment to maximize profit. In the existing network fee model, if the prosumer (the active consumer who is selling or transferring energy for others) is willing to sell energy, the prosumer is required to pay a local energy distributer a same distribution fee, no matter how long or short the distribution distance is. Similarly, the purchaser is required to pay a distribution fee. As a result, the distribution fee is paid twice for a single transfer. Therefore, it may not be financially economical to sell extra energy in small quantities.

3.3 Conclusions

The existing electrical power system relies mainly on centralized electricity generation, with long electricity transfer and distribution lines. Long-distance electricity distribution makes electricity generation and optimizing its distribution challenging. The centralized electricity system is potentially vulnerable in the case of electricity faults, and the affected geographical area is larger. The existing power grid may not adequately accommodate consumers’ active participation in the energy market, which is expected to increase supply variation in the power grid. This brings additional changes and challenges to the power system, which need to be addressed. Robust ICT is expected to play an important role in creating a new, smart power grid.

4. AN ENERGY INTERNET TO SUPPORT POWER GRID 2050

4.1 Background

The IPCC climate report published in 2019 (IPCC, 2019) indicates accelerated global climate change. It is expected to initialize governmental and organizational action to plan mitigations to prevent environmental effects caused by humans (U.S. Department of energy; European commission, 2010). Electricity production is one focus area, due to its use of fossil fuels that cause greenhouse gas (GHG) emissions (IPCC, 2019; Scott et al., 2004).

The following chapters discuss the semantics of future automated power grids, and the different terms and building blocks needed for a fully electrified, autonomous energy-exchange system between prosumers (Figure 12). The chapters discuss how changing the existing power grid to an energy internet is plausible in terms of enabling technologies and changes needed in the agent structure.

Many initiatives to decrease GHG emissions propose to increase end-to-end automatization of the power grid to enable integration of local renewable energy sources (Goldman et al., 2010; IEA, 2011; Ton et al., 2012). Proposals are differentiated from each other based on their proposed power grid autonomy level and the technological implementation. It is likely that the future solution will happen by market pull, not push: the solution is attractive enough to consumers for them to demand it. Consumers tend to make decisions based not only on green values but also on the financial effect on them.

The following presents an incomplete list of proposed future power grid models to give an idea of the research resources available.

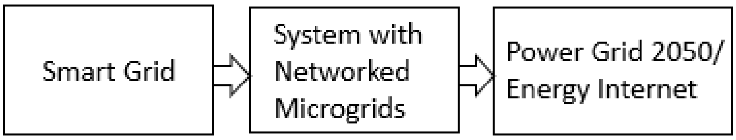

Figure 12. Electricity power grid development phases towards power grid 2050

The existing power grid is expected to evolve towards a fully autonomous, end-to-end transfer and distribution grid incorporating locally produced and actively exchanged electricity in the energy market (Figure 12).

4.2 The Smart grid

The definition of the smart grid is widely discussed in connection with the future power grid; thus, it is worth reviewing some studies of the smart grid. Goldman et al. (2010) simply define a smart grid as a system linking the power source, distribution, and customer together with communication. This integrated system fulfils four objectives (Goldman et al., 2010):

1. The customer has the option to select the energy source based on price and technology.
2. The electricity distribution's reliability is improved compared with a traditional power grid.
3. Renewable energy sources and energy storage are integrated as elemental parts of the distribution grid.
4. The smart grid architecture model (SGAM) is applied (Mashlakov et al., 2018).

According to Goldman et al., the smart grid is designed so that electricity management fully supports electricity flow in two directions, compared with the traditional power grid, in which power-flow is designed to flow mainly towards the customer. Bi-directional electricity distribution enables locally generated electricity to be traded actively in the energy market.

The International Energy Agency (IEA), defines the smart grid in their report "Technology Roadmap—Smart grids" as follows:

> "an electricity network system that uses digital technology to monitor and manage the transport of electricity from all generation sources to

meet the varying electricity demands of end users. Such grids are able to co-ordinate the needs and capabilities of all generators, grid operators, end users and electricity market stakeholders in such a way that they can optimize asset utilization and operation and, in the process, minimize both costs and environmental impacts while maintaining system reliability, resilience and stability" (IEA, 2011).

The intergovernmental authority IEA calls smart grids virtually isolated grids that are able to minimize distribution costs and enable fault-area isolation by using local renewable energy. It also indicates that smart grids take into consideration all stakeholders' financial interests.

Considering the future large number of local energy sources and ES systems, grid management and demand balancing will be more complex. Thus, digitalized common electricity management of the full demand–supply chain is essential.

Broadly available smart-grid definitions present the concept on a general level, as do Goldman et al. and the IEA. The smart grid concept is generally expected to produce the following results:

- Reduced energy-production costs (because of the use of renewable energy sources).
- Reduced energy losses and operational costs in transmission and distribution grids.
- Decreased reserve-capacity costs, and reduced management costs.
- Emissions of carbon dioxide, NO_x and Sulphur dioxide will be reduced.
- Security of supply can be improved as there will be fewer electricity disruptions due to the distributed electricity generation.

4.3 EU Energy System 2050

The European Union funded a group study conducted by the European Technology and Innovation Platform for Smart Networks for Energy Transition (ETIP SNET) to propose a vision of European energy systems for the year 2050: “A low-carbon, secure, reliable, resilient, accessible, cost-efficient, and market-based pan-European integrated energy system supplying all of society and paving the way for a fully carbonneutral circular economy by the year 2050, while maintaining and extending global industrial leadership in energy systems during the energy transition” (European Technology and Innovation Platform, 2018).

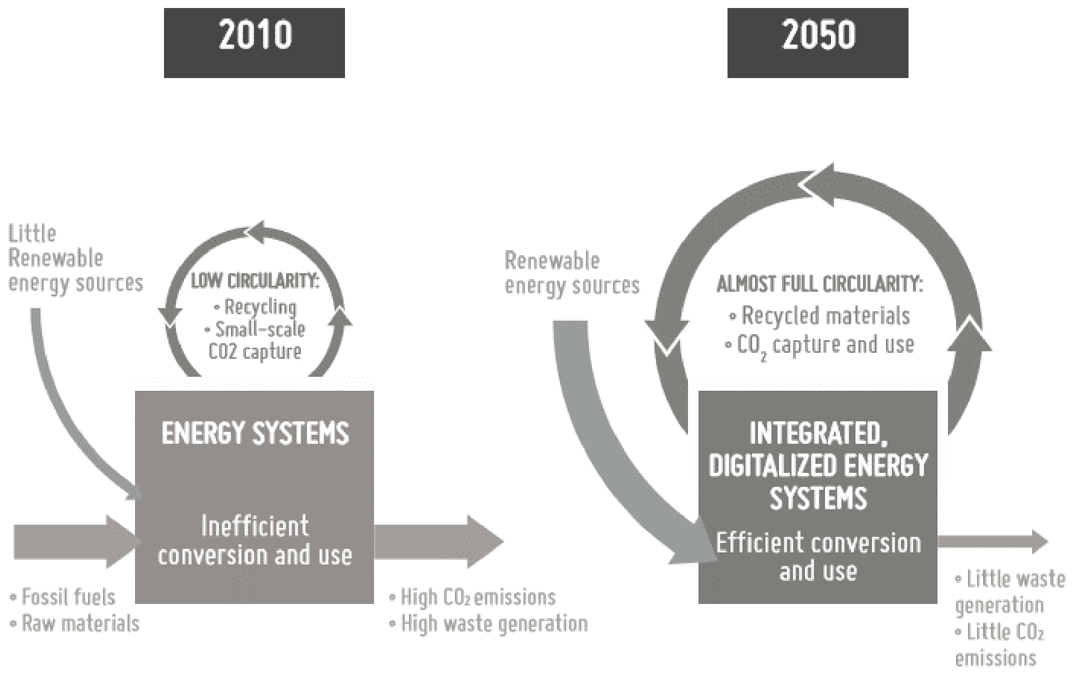

Figure 13. The EU working group’s vision of changes in the energy system (European Technology and Innovation Platform, 2018).

The ETIP SNET study proposes full circularity of carbon dioxide emissions, achieved by increasing use of renewable energies that utilize an integrated digital platform (Figure 13).

The working group has summarized the EU objectives for the energy system in 2050 as follows (European Technology and Innovation Platform 2018):

- Protecting the environment by decreasing GHG emissions
- Creating affordable and market-based energy services
- Ensuring the security, reliability, and resilience of electricity supply

Improvements proposed by the working group rely greatly on power grid digitalization to provide tools for user-friendly services for all kinds of customers. The targeted services are planning, maintenance and operational services, fostering information, analytics, and connectivity (European Technology and Innovation Platform, 2018).

As regards digitalization, the working group listed the following requirements: real-time demand response, smart charging for EVs, and peer-to-peer (P2P) technologies for local-community energy trading. Digitalization is expected to support interconnected services to enhance the system's balance in different time scales (European Technology and Innovation Platform, 2018).

The main components of digitalization are as follows (Balaji et al., 2010):

1. Information generated and collected by the IoT. A large amount of data is provided by smart meters and sensors for real-time monitoring and control.
2. Analytics for data mining and machine learning.
3. Connectivity allowing a massive amount of data to be transferred between humans, devices, and machines.

Power grid 2050 can be considered to consist of networked microgrids. Microgrids can be further differentiated into virtual microgrids and physical microgrids. Prosumers inside a virtual microgrid may not be physically close to each other, even though they are in the same group on the system management level. Physical microgrid members are located close to each other, minimizing electricity network losses and other related costs. Physically located microgrids form a physical area which can be isolated in electricity fault situations.

4.4 Microgrids

The microgrid is a considered as a building block for the smart grid or energy internet. Ton et al. (2012), as a part of U.S. Department of Energy's Microgrid Initiative (DOE), defined the microgrid as follows: "a group of interconnected load and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid." This definition states how a microgrid is a single entity from a management perspective but it can also operate separately and independently from the rest of the distribution grid.

The microgrid model can provide the benefit of integrating multiple microgrids together, in which they can operate as a large group of entities to commonly optimize electricity storage, load, and generation.

4.4.1 The Virtual Microgrid

A virtual microgrid does not necessarily consider prosumers' physical location. When locally generated renewable energy becomes dominant, it is expected that the energy market price for prosumers will approach zero marginal energy costs (Figure 11). Prosumers may form a virtual microgrid to benefit from near-zero margin prices compared to existing consumer energy markets. With fully automated prosumer and power grid data management, the prosumer is permitted to exchange energy inside the virtual microgrid with the target of needing zero energy from outside the microgrid. External (outside the microgrid) energy demands are exposed to energy market pricing controlled by the independent market aggregator, which balances the regional energy supply and demand.

The benefit of forming a microgrid for the prosumers is that they are able to exchange energy at its production cost, which in the case of renewable energy generation is approaching zero. To exchange energy, an active microgrid management structure is required.

4.4.2 The Physical Microgrid

As locally generated electricity becomes more popular, prosumers located physically close to each other are able to form physical microgrid communities. The energy exchange between prosumers inside a physical microgrid aims for zero energy needed from outside the microgrid, in a similar manner to the virtual microgrid. Due to short electricity-distribution distances between prosumers, the electricity-distribution fee can be minimized or potentially even removed, which makes the model more attractive for the prosumers. The physical microgrid by definition forms physically small, self-sustained energy communities. This increases the ability to isolate and secure electricity availability in case of a fault, assuming the distribution grid supports end-to-end automation. The physical microgrid's active energy exchange in the energy market is identical to that of the virtual microgrid.

While existing legislation may not support short-distance distribution fees, studies have been published that aim to minimize the distribution fee, in which the microgrid is separated from the existing distribution grid structure. A low-voltage direct current (LVDC) technology for microgrids has been presented by Nuutinen et al. (2014), which proposes to use LVDC instead of existing AC networks. The microgrid using LVDC-technology is connected to the distribution network using a transformer to drop the voltage to ±750 V and rectify it for direct current.

The proposal by Nuutinen et al. (2014) makes microgrid development independent from the decisions of the distribution network operator, which may not be motivated to open its network to bi-directional electricity transfer with reasonable distribution costs without legislative actions.

4.5 The Energy Internet

4.5.1 Introduction

The energy internet is a proposed communication model for a fully electrified solution to enable local energy exchange between prosumers. In the model, prosumers use and generate energy actively in an optimized manner to maximize available energy (Nardelli et al., 2019). The energy used by each prosumer's IEDs (producing, storing or consuming) is quantified (virtually packetized) and their electricity exchange is planned with other prosumers. When prosumers form microgrid communities of sufficient size, the probability of prosumers having a demand peak at the same time will decrease. The community formed is potentially energy self-sufficient and thus more resistant to power grid faults. The energy internet creates a way of managing energy supply and demand through a virtual energy server.

A similar model is studied by Saitoh et al. (1995). In their study of an “open electric energy network” (OEEN), electricity is physically routed via energy routers to consumers. In an OEEN, the electric energy packets have sender and receiver information stored by the electric energy router, which acts as the control system for the process. The electric energy router controls energy flow from energy storage to customer based on a demand schedule and address information. Physically routing energy to individual consumers from different energy suppliers presents an implementation challenge for the existing distribution network. The proposal by Saitoh et al. would require massive and expensive changes in the existing power grid’s mechanical systems.

The energy internet concept received increased publicity from The Economist publication (2004) which presented it as a way to prevent future power grid failures like the failure in the U.S. in 2003 (The Economist, 2004). The power grid failure in 2003 caused North America’s largest blackout, in the northeastern U.S. Fifty million people lost power for up to two days. The cause of the fault was a tree on the power line and a failure in the electricity alarm system (Minkel et al., 2008). The Economist proposed that one solution to the problem would be to have intelligent, localized electricity production instead of centralized production.

Tsoukas et al. (2008) proposed a management solution for the failure-sensitive power grid by having a multi-agent environment in the power grid distribution components, allowing them to communicate with each other and re-configure themselves in the case of grid failure. Tsoukas et al. also defined the major difference between the data internet and the energy internet as follows: “Data networks can store data, while energy can’t be stored in large quantities.” Tsoukas et al. presented the energy internet as a solution to improve the security and stability of the power grid through local energy generation. When Tsoukas et al. presented the idea of storing electricity (in 2008), energy-storage technologies were not available in large quantities. To manage complex energy-internet systems, Nardelli et al. (2019) presented the concept of an energy internet via packetized management, in which IED energy consumption is quantized into cyber-physical energy packets for active control to maximize prosumers' electricity self-sustainability in physical microgrids.

4.5.2 Energy Internet Requirements

In order to be able to define the requirements of the energy internet, its key drivers need to be set. The energy internet needs to solve the following problems:

- The energy internet should improve the security of the power grid. It will need to provide continuous electricity availability with a self-healing mechanism.
- The energy internet should promote locally generated energy.
- The energy internet should use renewable energy sources.
- The energy internet should enable bi-directional electricity supply.

The energy internet's requirements sound very much like Power Grid 2050. Power grid 2050 is supported by an energy internet in which energy exchange is achieved using virtually packetized energy utilizing end-to-end data management.

For the prosumer to fully benefit from distributed energy resources (DER), active device and data management is required. Active management would consider the planning of electricity generation, storage, and demand. The management would utilize quantization of all energy generated and consumed by IEDs. Prosumers' quantized energy would be prioritized and managed actively based on pre-determined rules.

This virtually packetized (quantized) energy demand or consumption could be managed in a randomized manner, referred to as an "internet manner" (packetized data packets) (Nardelli et al., 2019). Each prosumers' IED data is collected using Machine-type communications (MTC) and sent to each microgrid energy server. The energy server balances the microgrid's supply and demand based on the planned demand of the IEDs.

The energy server forms a virtual storage system to manage energy allocation. The management of the energy packets can be balanced inside the microgrid and between microgrids (Nardelli et al., 2019). The energy internet is a fully electrified end-to-end system, managing the demand–supply balance between prosumers inside the microgrid and eventually to the distribution grid.

4.5.3 Demand Flexibility

Demand flexibility is an important operational concept used in connection to Power grid 2050. When it is combined with prosumers' active energy management, it will create a basis for the virtually packetized energy internet. Demand flexibility is a concept in which energy demand is shifted to be used another time to avoid a peak in electricity consumption, or if the time of electricity generation does not match the time of electricity demand.

The Brattle Group (2019) estimated in their report that the net national savings enabled by load flexibility could exceed $15 billion a year by 2030. The annual value in 2030 will be comprised of 57% avoided generation capacity, 29% avoided energy costs, 12% avoided transmission and distribution capacity, and 2% ancillary services, the "cherry on the sundae" as the Brattle Group calls them.

The IEDs need to have pre-set priorities to ensure demand is not shifted from the node, as this cannot be done without compromising safety, compromising security, or creating a financial impact. Figure 14 shows an example of shifted demand, in which EV loading (the red bar) would exceed the budgeted energy consumption (the blue solid area) if no demand shifting were implemented. The system estimates needed time for sufficient EV charging to cover journeys needed before the next charging. The EV charging is shifted into the morning hours when the electricity base load is low enough to cover EV charging.

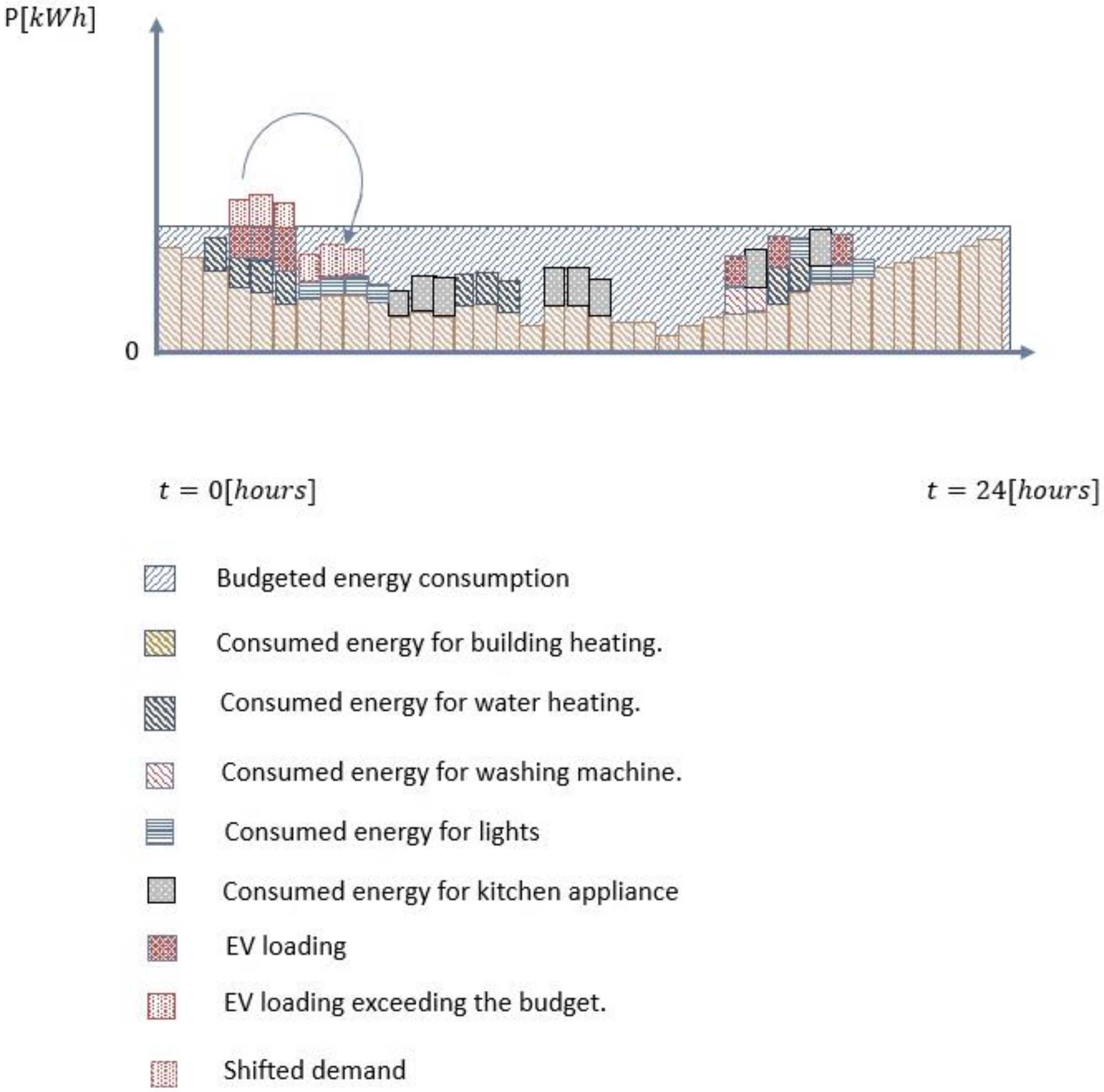

Figure 14. An example of flexible demand: a shifted load (Nardelli et al., 2019).

Electricity storage combined with demand flexibility would increase the system's ability to adjust demand to a more convenient time. Electric vehicles can potentially be used as ES. Full demand flexibility can be extended to cover other prosumers in a microgrid. Virtually packetized energy offers a way to manage prosumers energy in a proactive manner. A system organized and coordinated in this way would be considered an energy internet.

4.5.4 Packetized Energy

Packetized energy is a model in which “analog” energy is quantized into “digitalized” energy packets to manage exchanged energy between prosumers in close connection with the independent market aggregator. Saitoh et al. (1995) presented a packetized energy idea by introducing the OEEN, in which physical electricity distribution is controlled by router devices.

To avoid a complex power-grid structure based on Saitoh et al., a proposal for a virtually packetized energy system was introduced by Nardelli et al. (2019). They described the virtualization of the energy management of the power grid, forming an energy internet, or EnergyNet. The publication defined EnergyNet as a “cyber-physical system, managing virtually discretized energy packets.” In their publication, electricity generation and loads are discretized and actively managed by an energy server. The electricity is managed based on its amount, usage time, and pre-determined priorities. Energy stores (ESs) are actively used for demand shifting, by supplying energy when renewable energy generation availability otherwise would be low, such as at night, to help balance demand (Nardelli et al., 2019). The exchange of virtual electric packets between prosumers in microgrids is managed by the energy server.

Consumed energy can be defined as a cyber-physical energy packet that has a usage time, power of the device (power x time = energy), and priority. In a similar manner, prosumers’ locally produced electricity can be packetized and shared with other prosumers based on time, amount, and priority. Priority will be set based on timescale and the effect on the prosumer. The total energy in the energy internet is compiled based on the IED’s energy amount, start-time, and end-time, along with the priority. In this manner, collected total energy defines the energy clock diagram for the day, week, month, and year. Priority is defined by personal preferences, personal safety, or health. Building requirements are also a possible priority, in connection with national or municipal policies. Preferred energy sources for supply are similarly prioritized: renewable sources, ES, microgrid exchange, or externally purchased energy (Nardelli et al., 2019).

$$Total\ Energy_{hour\ 1} = \sum_{00:00}^{01:00} E_1(500w * 0{,}5h(00:10 - 00:40) \ldots + E_2(1500w * 0{,}2h(00:00 - 00:20) + E_3(750w * 1h(00:00 - 01:00)$$

Equation 1. Example of calculation of total discretized energy for one hour based on energy amount and clock time.

Figure 15 illustrates the simplified packetized energy consumption of different electrical appliances (IEDs) for each hour.

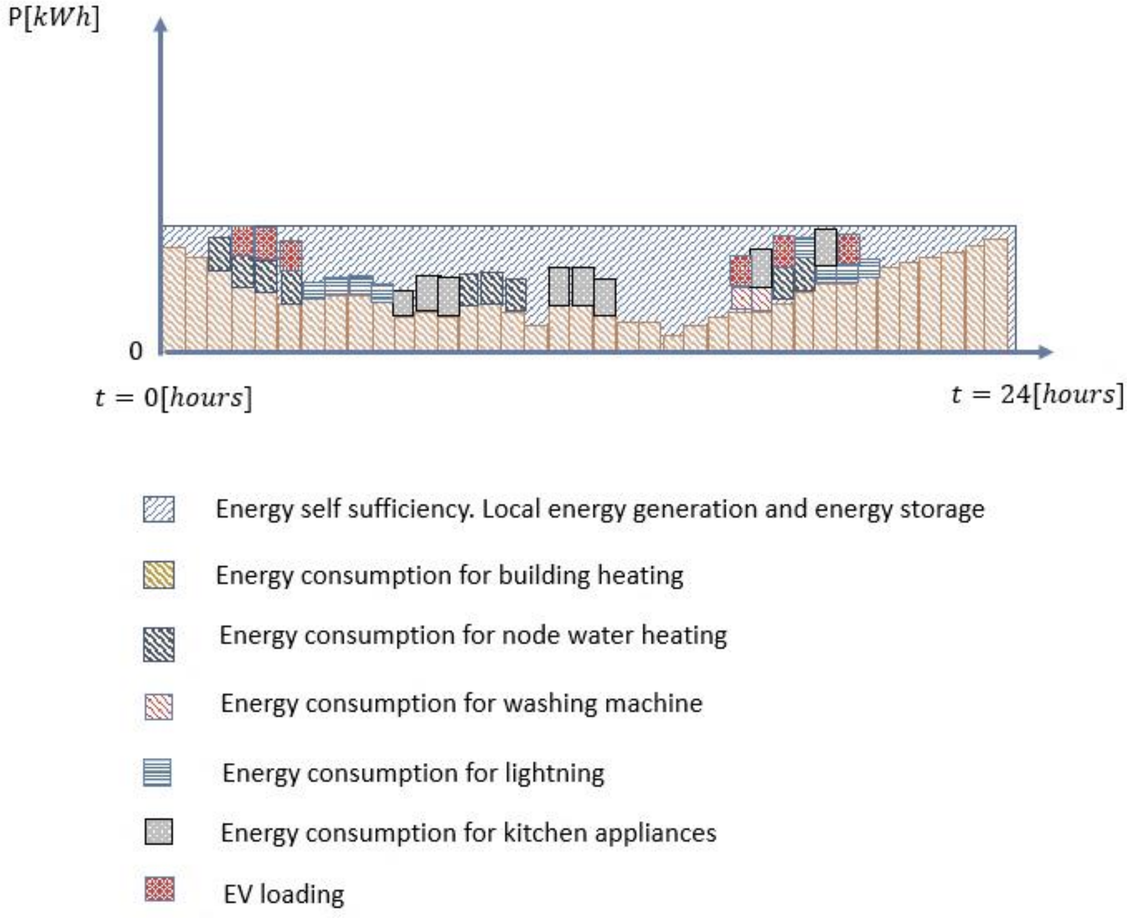

Figure 15. An example of packetized energy based on IEDs (Nardelli et al., 2019).

Discretized cyber-physical energy packets are a key management method for coordinating prosumers’ and microgrids’ supply and demand accurately in the energy internet at IED level. The managed IED can be a washing machine, water heater, building heater, and so on. The demand diagram is pre-planned based on historical information, actual weather, the weather forecast, PV- or wind-energy availability, and planned schedules (such as personal preferences or presence at home).

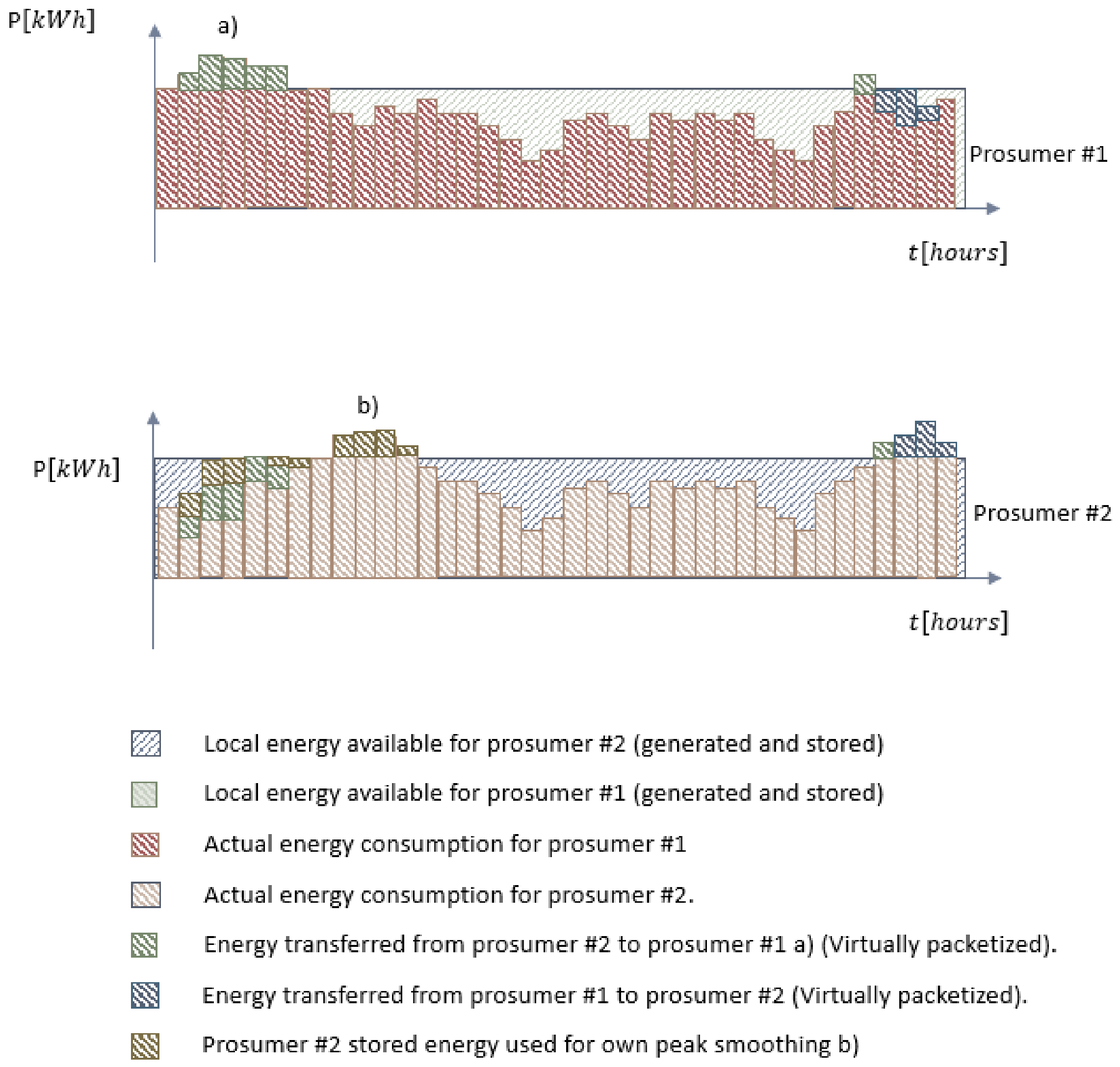

Figure 16. Virtually packetized energy exchange between prosumers (Nardelli et al., 2019).

Figure 16 illustrates the virtually packetized energy exchange between two prosumers inside a microgrid. The prosumers' energy capacity (generated and stored) are depicted by green (Prosumer #1) and blue (Prosumer #2) back-hatched areas. If the demand of prosumer #1 exceeds its capacity (a) and demand shifting cannot solve the issue, the needed energy can be shifted from prosumer #2 (b).

In an ideal situation, the entire energy consumption of different prosumers can be balanced inside the microgrid. However, that may not always be possible if prosumers' demand profiles are too similar. Locally produced energy may have similar energy-generation profiles (i.e., PV) in the case of physically closely located prosumers. The virtually packetized energy exchange between microgrids follows same process as that between prosumers (Figure 16). If microgrid #1 lacks capacity (a), it can transfer it from microgrid #2.

4.6 Energy Internet–Enabling Technologies

4.6.1 Introduction

In order to make the energy internet concept plausible, several advanced technologies and regulations must be in place. Key enablers for the energy internet are as follows:

- IoT–connected devices for sensing, measuring, and acting as actuators.
- 5G end-to-end communication technology to connect massive numbers of IoT devices, to provide channels for high data amounts, and to provide ultra-reliable, low-latency connections.
- A self-healing automatized power distribution network (microgrid) with a 5G low-latency connection.
- A packetized energy-management structure to coordinate the energy-management process in detail.
- Energy storage systems for storing energy and demand shifting.

The energy internet requires end-to-end communication channels between IoT devices, microgrids, and smart-grid actuators. The advanced internet communications technology with ultra-reliable, low-latency service (URLCC) and massive machine-type communications (mMTC) services provided by 5G mobile technology makes the energy internet technically plausible. The 5G services will provide needed time-critical operations (via URLCC) and connections to hundreds of sensors and actuators (via mMTC) for systems management of the energy internet (GSMA Mobile, 2019; Obiodu et al., 2017).

Environmental legislation is required to decrease the use of fossil fuels and create a preference for the use of renewable energy sources. The energy internet will be plausible when renewable-energy production becomes popular among ordinary electricity customers, and when it is supported by 5G communications technology.

The European Commission has issued a directive (2010) for European Union member countries to comply with nearly zero energy building requirements. Each European Union country ratifies requirements and actions based on their own national and local needs. The directive sets energy-saving requirements and a requirement to increase the use of renewable energy sources. Based on these requirements, all new private houses should be nearly zero energy houses by the end of 2020 (European Commission, 2010).

When considering the energy supply and demand of several households, energy demand is averaged, and electricity flexibility is improved. In this kind of microgrid community, electricity can be actively managed and exchanged so that the need for externally sourced energy can be minimized or avoided. In the optimal situation, the sum of electricity transfer is zero from outside the microgrid community. This model would challenge the existing centralized energy-generation model and the natural monopoly position of the DSO in power distribution grids.

The electricity transmission network and large electric power plants are the backbone of the power grid, securing electricity availability when local renewable energy supply is insufficient, or in fault situations.

4.6.2 The Internet of Things

The control elements in the energy internet are a massive number of connected sensors, actuators, and measurement devices. The connected devices and actuators provide vital information and a controlling resource for energy-internet management.

Wirelessly connected internet devices form an Internet of Things. The IoT is defined by the ITU-T 2060 (2012) as “a global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies” (ITU Standardization, 2012).

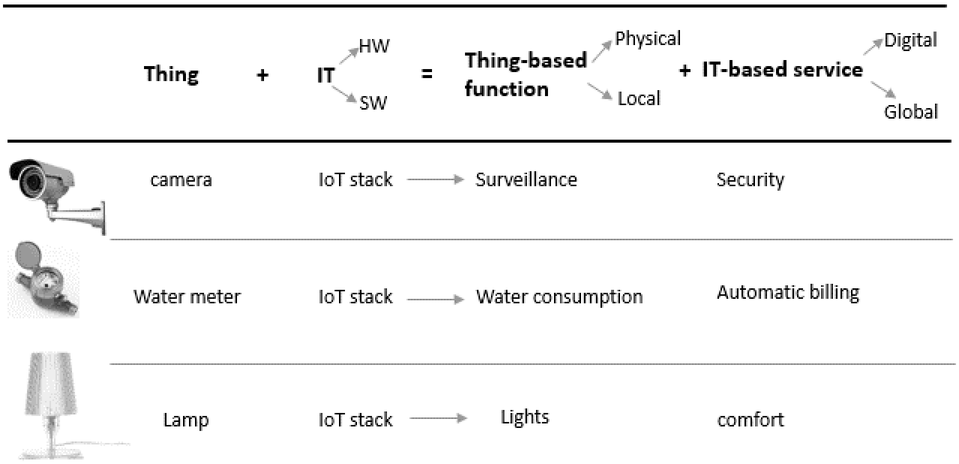

Figure 17. IoT–product–services logic (Fleisch et al., 2014)

The IoT enables various remotely operated applications and solutions, extending their presence to all available areas. The IoT wirelessly connects different things into the global internet (IPv&6) and provides wireless connectivity for devices. With the connected things, information can be gathered from a very wide geographical area and from various applications. With the aid of the collected information concerning certain functions or processes, system management can be automatized. Potentially, this smart sensor network can solve problems independently without human interaction.

The IoT uses wireless technology for data transfer. The IoT technology design makes various important properties possible, creating multiple use cases. The IoT device features cover a wide range of applications and features, from low current consumption, wide network coverage, large data quantities, fast reaction times, and low total cost of ownership. Some of the listed properties have tradeoffs with each other, such as network coverage and current consumption.

Commonly used IoT network topologies are point-to-point topology, star-, and mesh-topology. Point-to-point topology is a simple way to connect two devices together, in which a device has a direct link with another device. Star-topology has one hub, which communicates with all devices. Point-to-point topology or star-topology may not allow IoT devices to communicate directly with devices that are not neighbors. The mesh-topology allows connected IoT's to pass messages through other devices. Messages will travel in the network using IP-addresses. One broken network device will be bypassed by other connections. Thus, one broken device does not paralyze the whole network. However, message traffic can be higher compared to the first topologies mentioned.

4.6.3 Communication Technologies

Data transfer in an IoT network's communication channel is here divided into two main groups, depending on the device's distance capabilities: a personal area network (PAN) is for short connectivity, and wide area networks (WAN) are for longer distance connectivity.

Personal area network technology is commonly used in very short distance IoT networks, such as inside buildings or in small-scale industrial applications. Commonly used data-transfer technology is based on the IEEE 802.15.4 standard. This standard is ideal for the low-power, short-distance transfer of limited data. The standard does not allow data transfer between other devices, nor it does not have TCP/IP address capability. To overcome these limitations an IPv6 over low-power wireless personal area network (6LoWPAN) was developed, which allows devices to communicate with each other within different networks. The technology allows IPv6 data-packet sending and receiving (ITU, June 2018).

Wide area network technology uses several different data transfer technologies. Most common data connectivity technologies are: Wireless IP-networks (through the third generation (3G) and fourth generation (4G) mobile networks), NarrowBand IoT (NB-IoT), and low-power WAN (LPWAN).

Low power WAN technology was developed to improve the 3G-4G mobile network's ability to support low-power IoT-devices. The topology used is star-topology, in which IoT devices are connected directly to the network. Some examples of LPWAN technology providers are SiGFox and LoRA. They use simplified data-transmission technology, in which calculation processes and actions are performed on the servers. The server-based data processing makes it possible to design cost-efficient sensors and gateways. Both SiGFox and LoRA utilize a license-free, industrial frequency band. The frequency bands used in Europe are in the rage of 863–870 Mhz. The data-transfer speed is 0.3–50 kb/s, and network coverage is potentially up to 50 km (Lora Alliance, 2019; Rohde&Schwartz, 2019; Actility, 2019).

The 4G mobile network included an extension (third Generation Partnership Project (3GPP) standard release 13) to support IoT devices using narrow-band IoT (NB-IOT) and long-term evolution category M1 (LTE-M) technologies. They share a similar design and architecture. Functionalities can be differentiated by software changes in the baseband functionality. The LTE-M is for low-latency application requirements and NB-IOT is used when there is a large number of connected devices (GSM Association, 2019; Rohde&Schwartz, 2019).

The NB-IoT has a reduced bandwidth of 200 kHz (downlink and uplink), achieved using a half-duplex protocol. As the NB-IoT is intended for machine-type communication, it has lower processing capabilities and uses less memory compared to the LTE-M (Lora-alliance, 2019; Sharma et al., 2017, Diaz et al., 2015). Unlike LTE-M, NB-IoT does not operate in a licensed LTE band, which increases the cost for technology providers, since the existing technology is not fully standardized. However, it does not need a gateway, which reduces some costs (ITU, 2018).

The LTE-M uses a licensed spectrum with an LTE bandwidth in the range of 700–900 MHz. The data throughput is a maximum of 1 Mbps (uplink and downlink), with a maximum coverage of 11 km when using half-duplex as the protocol (Rohde&Schwartz, 2019). Both NB-IoT and LTE-M can be placed into sleep mode to save power and woken up periodically. The LTE-M has an improved data throughput speed for secure, lower-latency connections (GSM Association, 2019).

Fifth-generation mobile technology (5G) combines ultra-reliable low-latency services (URLCC) and massive machine-type communications (mMTC) services. In addition to URLLC and mMTC services, 5G provides enhanced mobile broadband (eMBB) services, extending traditional personal-data, phone and messaging services (GSMA publication, 2018).

The 3GPP standard describes the requirements for mMTC. MMTC is used for automated data communication directly between machines or data communication through a management server. Based on International Telecommunication Union requirements, the minimum connection density is one million devices per square kilometer. The distance that data is transferred though mMTC is usually short, and data is sent sporadically: thus, only low data-rates from one to 100 kb/s are supported. For asynchronous and power-saving modes, the radio interface technology has support for sleep mode for the network and for the IoT-devices. Message-communication frequency is either random or periodic, depending on the application. The IoT-device battery life is a maximum of 10 years (ITU, 2017). The mMTC is intended for stationary, low-data-rate and low-power IoT-devices. Devices utilizing mMTC are typically measurement instruments, information-status devices, and control actuators (ITU, 2017).

The URLLC service is intended for critical processes, in which low latency and high reliability are required. According to the International Telecommunication Union (2017), the minimum requirement for user-plane latency is 1 millisecond, and the minimum reliability requirement is $1*10^{-5}$ (probability of success). Low latency is achieved by using multiple antennae to transmit and receive data, mobile-edge computing, and direct device-to-device communication (ITU, 2017). The URLLC service ensures fast and secure information transmission, while data rates are usually low. The URLLC was developed for applications requiring high data reliability and very low data-transfer latency. The URLLC was developed for new applications such as autonomous car operation, traffic control, externally controlled medical operations, and power grid operations for smart cities.

The third 5G service, eMBB, is intended for broadband services with high data rates. According to the International Telecommunication Union (2017), the minimum downlink peak data rate is 20 Gbit/s, and the uplink peak data rate is 10 Gbit/s. The eMBB is an extension for existing 4G radio services. Applications for eMBB are existing mobile audio/video applications and applications with simulation or gaming (ITU, 2017).

All three services overlap to provide seamless end-to-end solutions, allowing different services to coexist in the same network. The integrated services are implemented in 5G using a network-slicing technique.

Network slicing makes the 5G service overlap possible. The slicing ensures the network's end-to-end performance and interference-free communication between different services. The slicing technology enables the co-existence of different operative services and different radio-access technologies (RAT). For security reasons, they are also able to operate in isolation (Sherma et al., 2017).

The 5G slicing architecture is built on modes using a three-layer cloud service (Figure 18). The modes support multiple RAT-modes, such as Wi-Fi, 5G, or LTE, to implement the radio access network function (Huawei, 2016). The high-level principle of network slicing is described in Figure 18, in which different physical radio protocols are mapped by software-defined radio (SDR) and function virtualization. The network slicing allows virtual networks on top of the physical infrastructure, enabling a customer to select only the needed service (Sherma et al., 2017).

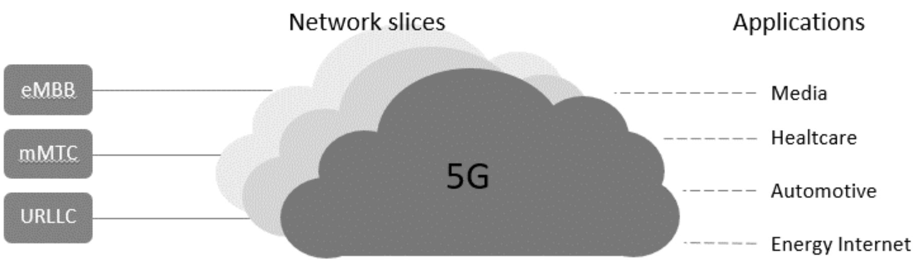

Figure 18. The high-level operation principle of 5G network slicing (Rost et al., 2016).

Unlike earlier mobile communication standards (3G to 4G), 5G technology can combine communications channels, mobile broadband, the mobile IoT, the massive IoT, and low-power wide-area (LPWA) technology. Applications can vary from multimedia, artificial intelligence data, IoT connectivity, and low latency connections for power grids. Thus, 5G-technology is the enabling solution for the energy internet, providing communications technology and end-to-end solutions throughout the system, from the user through to the smart grid's management.

4.7 Conclusions

Increased utilization of household renewable-energy sources, such as PV and wind turbines, is gradually converting consumers to electricity self-sufficiency. Such a transformation is expected to trigger changes in the existing power-transfer grid by transforming it from centrally generated electricity to locally generated electricity. The decentralized system supports bi-directional electricity flow, improving electricity availability in power grid fault situations and enabling prosumers to be active in the energy market. Advanced end-to-end 5G communication technologies enable the management of prosumers' local electricity generation, consumption, and storage in an optimized manner. By using the energy internet, prosumers' intelligent electronic devices can be actively monitored and controlled to further optimize their electricity demand and storage. Prosumers located close to each other will eventually form physical microgrids in which energy is exchanged using the energy internet to gain zero marginal electricity costs (Nardelli et al., 2019).

5. TRANSITIONING TO THE ENERGY INTERNET

The power grid affiliates' motivations and change drivers play a key role in enabling the energy internet to be created. Some operative functions may require regulative initiatives, such as a distance-based fee for distribution-grid transfer.

The existing power grid will gradually change through virtual microgrids to form the energy internet. It should be noted that consumers are a subset of prosumers, since a consumer is basically a prosumer with an energy production of zero. Therefore, they will have access to zero-production-cost electricity. However, the number of those in a distribution grid in the future who will be consumers only is unclear. Moreover, the exact allocation of electricity to the consumers and the costs for the consumer require separate research. The key elements of the power grid's transition are illustrated using agents and their behavior, described with ABM.

5.1 Change Drivers

In order for change to be implemented, various parties or authorities require a motive to implement changes. In the market economy, the financial aspect has a major influence on people's behavior. Political and other authorities, together with public opinion, are important shapers of the market economy. It is evident that solutions such as the energy internet would create a greener environment for all. Following chapters discuss what stimulus is motivating the general public, companies, and organizations to initiate changes?

5.1.1 Environmental and Social Drivers

Greenhouse gas emissions are causing climate change, in which fossil-fuel energy generation plays a significant role (IPCC special report on Climate Change, 2019; Scot et al., 2004). Green values are expected to be important decision criteria guiding consumers to choose renewable energy sources (RES) instead of fossil-fuel energy sources. The electricity generated by prosumers will be based on RES, and thus environmentally friendly.

Rifkin (2014) estimated zero marginal prices to follow a second industrial revolution after improved workflow by having mass production 1870-1914. During industrial revolutions, the cost of goods decreases due to cheaper manufacturing costs per unit. The energy internet with zero marginal electricity price is assumed to follow the same procedure as improvements in the manufacturing process for goods: necessary electricity costs consume a smaller portion of people's incomes (Figure 19).

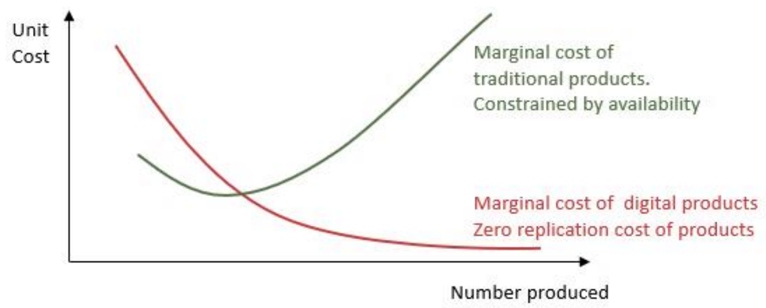

Figure 19. Production costs of traditional and digital products (Rifkin et al., 2014).

With increasing productivity and decreasing marginal costs, the cost of goods eventually decreases. In this manner, economic welfare is expected to spread.

5.1.2 Financial Drivers

Financial benefit is a strong driver for a human or organization to change their behavior. When active consumers form sufficiently dense groups, they can form physical microgrids, in which electricity-distribution distance and its related costs are minimized. In a physical microgrid, prosumers IEDs can be actively managed via the energy internet using virtual energy packets, bringing substantial financial benefits. A prosumer connected to the energy internet will benefit from self-sustainable electricity availability, with zero marginal energy fee and marginal distribution fee. The prosumers vulnerability to TSO or DSO grid failures will be decreased because of their access to locally self-produced electricity.

Operation of a power grid is a heavily investment-oriented business. For the TSO and the DSO, locally generated renewable energy creates opportunities to optimize transfer-grid and distribution-grid dimensioning. In a situation in which the transfer grid or the distribution grid's capacity is at its limits, the distributed energy sourced may allow the TSO or DSO to delay distribution-grid expansion investments (International Energy Agency, 2002). However, the new automation needed may increase non-recurring costs. The 5G technology makes end-to-end management of the transmission and distribution grid possible. Power grid modernization would improve its reliability and enable support for bi-directional electricity exchange over the distribution grid. Financially, there may not be strong motivation for the TSO or DSO, as they are expected to lose a large portion of turnover. However, society as a whole requires a change. The energy internet may bring additional business opportunities to DSOs: the energy internet's value chain will require a management function for virtually packetized energy exchange.

The energy market is expected to follow market needs by adapting its support for locally generated electricity exchange. Also, the energy market is expected to be more volatile due to changes in renewable electricity production and an increased number of active electricity suppliers. The supplier gains a greater active market, with the financial benefit of increased electricity sold. In a similar manner, the retailer can benefit from increased activity and the increased number of transactions in the energy market.

5.1.3 Technical Drivers

The 5G communication technology makes smart-grid end-to-end management possible. It can utilize massive amounts of information through the IoT, enabling autonomous behavior by distribution feeders in power grids to improve the network's ability to react in different situations. The 5G connected IoT devices will actively coordinate DERs through the energy internet, enabling zero marginal costs for electricity. IoT devices will eventually become inexpensive and they will spread everywhere to connect machines, cars, households, and businesses in an intelligent manner.

5.1.4 Governmental drivers

Distribution grid owners rely on steady profit generation, which is regulated by the government. The existing natural monopoly does not support a liberalized market system, in which the customer would freely choose the local energy distributer, or the distribution fee would be charged based on transfer distance. Government action would be required to enable more intelligent pricing regulations.

If the existing governmental model of transmission fees for the network grid is not changed, alternative operational models may be created. A local energy producer may create innovative ways of sharing energy in microgrids to avoid using existing distribution grids. An alternative power-distribution grid could come into existence, using a low-voltage distribution grid between microgrids, in parallel with the existing distribution grid. This would create a lose–lose situation, in which DSOs lose turnover, and prosumer communities need to invest in a small-scale grid. This situation would also increase unnecessary controlling bureaucracy, for safety and compatibility reasons.

The government is expected to follow public opinion by removing fossil-fuel energy sources. The government benefits from local energy generation, as it enables the removal of fossil-fuel energy sources and the avoidance of GHG emissions.

5.2 Describing the Existing Power Grid Using Agents

The existing power grid was illustrated by means of agents to highlight its differences from the smart grid or energy internet. The agent structure of the existing power grid was considered to include household consumers, EV, and small industrial consumers. The market aggregator agent was simplified to consider day-ahead and intra-day market operations.

An agent is defined by its ability to execute actions independently and autonomously, based on pre-determined rules which take into consideration the statuses of connected agents (Catterson et al., 2012). When the agent model is applied to the existing power grid structure, it is worth noting that many automatically operative elements are not, in practice, fully autonomous, as they need to be partially manually operated from grid-monitoring centers (Catterson et al., 2012).

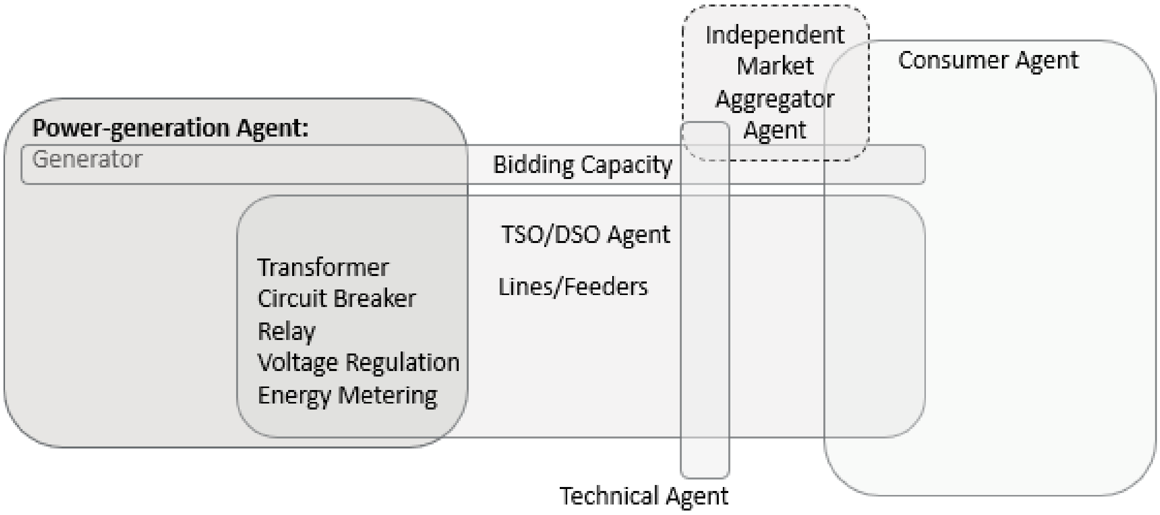

Figure 20. Agents in the existing power grid

Figure 20 depicts the structure of the existing power grid, using an “agent” model. The power-generation agent aims to maximize its revenue by offering or bidding capacity into the market. This will be published in the marketplace by the independent market aggregator agent, which will combine consumers’ consumption data. The DSO agent ensures that the power grid’s physical elements are able to carry the electricity load and secures the availability of electricity to the consumer.

The power-generation agent

The power-generation (PG) agent bids capacity into the market. To secure demand–supply balance, the PG agent adjusts frequency by reducing or adding electricity generation, based on market information (intra-day). An AC frequency is an indication of demand–supply balance (in 1–15 minutes reaction time). For the day-ahead market, the PG agent offers capacity to the market by bidding (30 minutes reaction time). A total capacity investment is planned, based on market information (1–25 years) (Nardelli et al., 2018).

The transmission and distribution system operation agent

The DSO agent manages electricity transmission, its synchronization, switching-gear operations, and re-routing electricity based on need (0.5 seconds to one minute). The transmission capacity investment is implemented based on market information (40–50 years) (Partanen et al., 2012). The DSO agent's response time to changes in the environment is defined to secure electricity availability in changed situations. In case of a network-fault situation, schedules are set from one second to one minute so that feeders and circuit are able to switch electricity routing to bypass the faulty area and minimize down-time. Planning for investments in transmission capacity is company-dependent, and this is usually planned annually.

The technical agent

The technical agent monitors electricity quality (AC frequency, protection circuitry, grid safety, and possible faults).

Objectives

- To monitor the overall situation in the distribution grid
- To protect the safety of the transmission and distribution grids
- To sustain electricity quality in the distribution grid

Constraints

- An unreliable electricity supply
- Unreliable communications technology and errors in information messages

The independent market aggregator agent

The independent market aggregator (IMA) agent exposes electricity supply and demand into price equilibrium to set the electricity hourly price (30 minutes to one hour). The algorithm used for setting the market price is EUPHEMIA, which maximizes the most competitive price and ensures efficient capacity allocation (Figure 21) (Nord Pool Group, 2018).

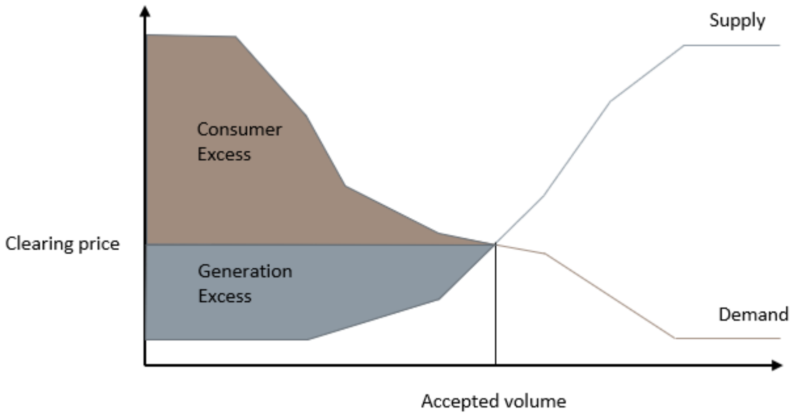

Figure 21. Market price formation by EUPHEMIA (Nord Pool Group, 2018).

EUPHEMIA uses network data, orders, and topology as input data to set the price in each bidding area (Nord Pool Group, 2018).

The consumer agent

The consumer agent aims to minimize users' electricity costs. In the existing power grid, the consumer has the option to agree to either a flat price throughout the day or week, or a day–night electricity product, in which some IEDs (for example, an electrically heated concrete floor) may be turned off during higher-priced periods. The agent is neither automated, nor autonomous. The system uses the time to determine when to switch extra heating elements on or off.

The key elements of the existing power grid model are as follows:

- The PG agent bids on electricity capacity and ensures a demand–supply balance.
- The energy transmission and distribution agent aims to secure energy delivery by maintaining the network's condition and re-routing distribution in fault situations.

- The IMA is the key agent for bringing supply and demand together, thus creating market-price equilibrium. Demand is influenced by consumer loading, which is dependent on the weather and seasonal consumption profiles. Supply may depend on, for example, hydro-power availability (water levels and so on).

5.3 Virtual Microgrid Agents

The prosumer who is active in the energy market is expected to generate a high number of supply events in the energy market: thus, market volatility is expected to increase. A microgrid agent was introduced into the model to collect information from prosumer IEDs and manage prosumers' demand–supply balance inside the microgrid.

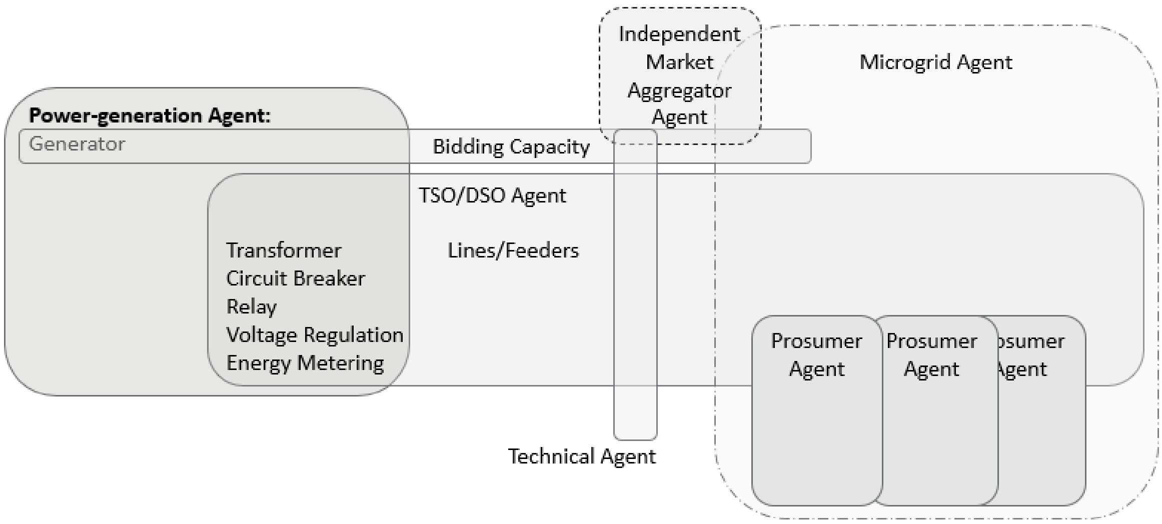

Figure 22. Virtual microgrid agent structure

In the virtual microgrid community, active prosumers could exchange electricity without energy fee. The prosumer can make electricity available to other prosumers. The virtual microgrid members may not be located physically close to each other, so an electricity distribution fee will be applied by the DSO.

5.3.1 New agents introduced

The microgrid agent

The microgrid agent collects supply and demand information from prosumers' IEDs. The microgrid (MG) agent exchanges the prosumer information collected with other microgrids and, importantly, with the IMA agent for regional demand–supply balance and market pricing (Figure 22).

Objectives

- To maximize utilization of prosumers self-generated electricity inside the microgrid, thus minimizing electricity costs for prosumers

Constraints

- Prosumers having similar DER-profiles, preventing effective load balancing

The prosumer agent

The prosumer agent aims to maximize energy generation and storage. The agent considers energy availability and projections based on, for example, the weather forecast, ES status, and prioritized-demand information. The microgrid agent collects the prosumer's supply and demand information and makes it available for the market aggregator. If the prosumer's electricity generation is not deemed to cover their own demand, the microgrid agent can manage the discrepancy by exchanging energy inside the microgrid. The prosumer's target is self-sustained electricity availability (15 minutes to one hour).

Objectives

- To minimize the prosumer's electricity costs
- To minimize disturbances to the prosumer's normal use of electronic devices due to electricity load shifting

- To exchange extra available electricity with other prosumers in the microgrid

Constraints

- Low availability of renewable electricity generation
- Higher actual electricity demand compared to the estimate
- Technical limits, such as voltage regulation and safety

5.4 Energy Internet Agents

In the power grid, electricity consumption and supply need to be balanced. However, they are not usually very stable. Demand varies in short time periods (15 minutes to one hour) and there is longer variation on a daily, weekly, and seasonal basis. As demand varies, electricity generation capability needs to adapt to changing demand. As renewable energy sources form the future basic electricity source for households and small enterprises, electricity-generation output variation will likely increase. This is because local renewable energy sources are mainly based on PV and wind-turbine sources, and their supply relies on the availability of sun and wind energy. Availability will vary in short cycles (15 minutes to one hour), intermediate cycles (daily), and in longer periods, such as weekly, monthly and seasonally.

When power grid electricity supply and demand are in balance, the AC frequency is in its nominal value (in Finland, this is 50 Hz). If demand exceeds supply, the frequency will be dropped. The over-supply situation follows the same principle, so frequency will be increased (Fingrid, 2019).

The energy internet can be seen as a complex system, combining machine-learning and massive information collection, in which a multi-agent system can make decisions, plan, and learn from mistakes. The Three-Layer Agent model is applied to agent representation, to model agents’ interfaces, regulations, and physical activity (Kühlens et al., 2015).

In the following section, virtually packetized energy internet agents are described and compared to agents in the existing power grid structure.

5.4.1 Agents modified

The PG agent, microgrid agent, and DSO agents need to be modified to have a centralized and autonomous capacity to balance locally exchanged energy using virtually packetized energy. The capacity balancing includes autonomous fault isolation and fast re-routing to secure the availability of electricity. The distribution grid would manage two-way electricity transfer between physical microgrids. The agents are connected via 5G communications technology, enabling low latency and reliable grid communication to a massive number of prosumers IEDs.

The power-generation agent

To adapt to rapidly varying electricity-supply situations, the PG agent's modification requires fast common communications technology (5G) and a cloud database with URRLC to balance supply situations.

The distributed system operator agent

The DSO agent's modification ensures automated synchronization, switching gear, and electricity feeder. Common communications technology and a cloud database with URRLC are needed to ensure fast re-routing in fault, safety, and grid-protection situations.

The technical agent

The technical agent monitors electricity quality (AC frequency, protection circuitry, grid safety, and possible faults). The agent proposes DSO distribution routing changes, isolation, and power-generation changes according to collected information. The agent is part of the common URRLC communication cloud database, alongside the DSO, IMA, and PG.

The independent market aggregator agent

The independent market aggregator (IMA) agent's changes are needed for it to be connected into the same common communication technology cloud database with URRLC as the DSO, and the PG agent.

5.4.2 New agents to be introduced

The energy server agent

The energy server agent (ESA) would be a disruptive agent for the existing power grid (Figure 23). The agent coordinates energy supply and demand for the physical microgrid by means of virtual energy-packet management. The ESA virtually stores exchanged energy to build a visualization of the DER's current status and future planning horizon. The virtually packetized energy is managed and coordinated between prosumers in a physical microgrid by the energy server. The energy server considers prosumers' load priorities, energy generation profiles, and ES status. The energy server aims to ensure the physical microgrid is self-sufficient in energy. If one microgrid is not self-sufficient, balancing can be managed between microgrids' ESAs (see Chapter 4.5.4).

Objectives

- To achieve zero demand for energy from outside the microgrid, that is, energy self-sufficiency
- To optimize IED demand and DER storage so that prosumers inside the microgrid achieve zero marginal electricity costs

Constraints

- In the case of equal load- and DER-profiles among microgrid prosumers, the following occurs:
  a. Prosumers are not able to exchange electricity
  b. External electricity is needed

- Poor electricity quality due to the following:
    a. An unreliable electricity supply
    b. High latency in controlling devices
    c. Insufficient voltage regulation

The agent needs to consider the following variables:

1. Microgrid prosumers' DER status and their projections for short, medium, and long periods. The short period is from an hour to a day's operation; the medium period is for a day, a week or a month; and the long period is for a year (Nardelli et al., 2019). Functions' time projections are as follows:
    a. Local control (1–30 seconds)
    b. Coordinated control (1–30 seconds)
    c. Short-term market resolution. Weather and DR resolution (15 minutes to one hour)
    d. Day/night, battery storage (one hour to one day)
    e. Weekday/weekend/holidays (one day to one week)
    f. Mid-term contracts (one week to one year)
2. The DER status of connected microgrids
3. Electricity market information. Demand–supply information is exchanged with the IMA agent and shared with the TSO and DSO agents and PG agents.

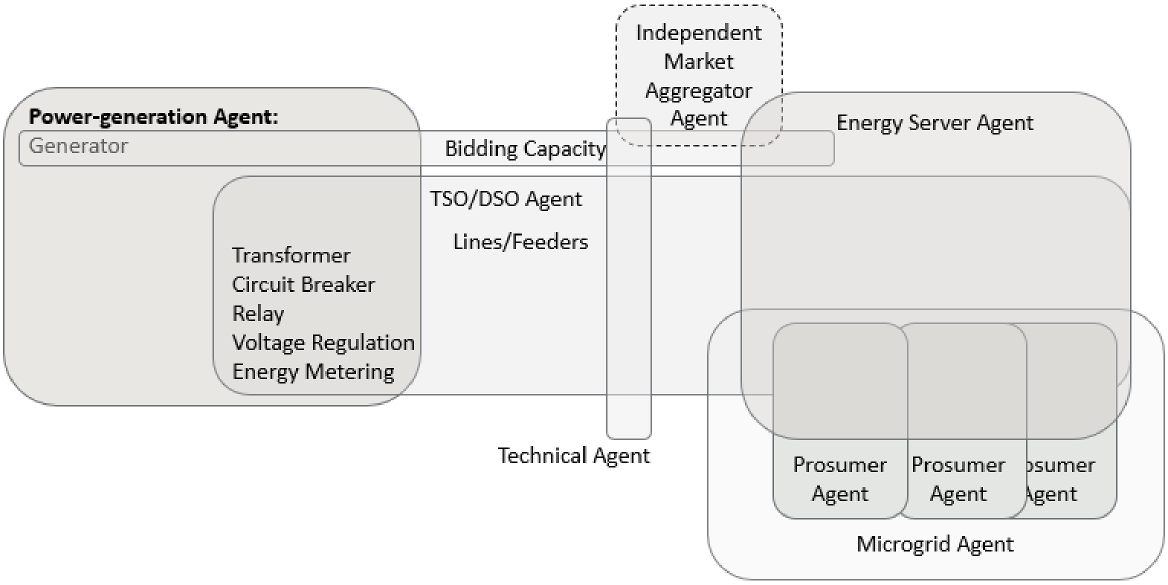

Figure 23. Agents in a virtually packetized energy internet.

In a virtually packetized energy internet, the IoT devices collect, actuate, and communicate DER information to the ESA inside the microgrid. The ESA virtualizes energy packets. Each microgrid has a similar communications system implemented (Nardelli et al., 2019).

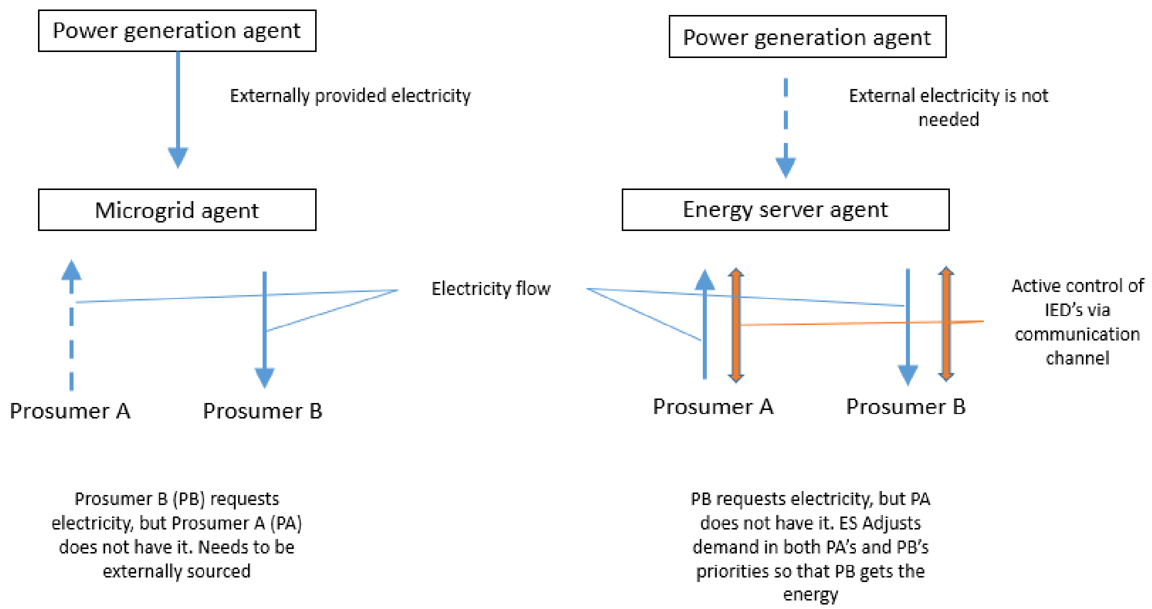

Figure 24. The difference between the virtual microgrid and energy internet models when a prosumer's demand cannot be met (Nardelli et al., 2019).

The operational difference between the virtual microgrid and the energy internet is described in Figure 24. The starting position is the same for both models. Prosumer B requests electricity since his or her own production or storage is not enough to meet demand. In the virtual microgrid, the microgrid agent checks if any connected prosumers have any extra energy. If no extra energy is available, Prosumer B needs externally sourced energy. In the case of the energy internet, the ESA monitors prosumers' IEDs through the prosumer agent and knows that Prosumer A has low-priority demand that can be shifted without risking future electricity availability. The ESA turns off the lower priority IED to liberate a virtual energy packet to be transferred to Prosumer B.

5.5 Agent-Based Model Principles

A virtually managed microgrid will not be dependent on location. Prosumers connected to the virtual microgrid can be physically distant from each other. They share a common interest in producing and storing renewable energy locally, and a willingness to exchange energy within a microgrid. The prosumers' motivation is to actively exchange energy for which the production price is nearly zero. The microgrid agent collects the information from prosumers' IEDs, forming a demand–supply horizon. The prosumer can prioritize his or her own production and load. Based on the prosumers' agreement, the microgrid agent can propose a prosumer agent to deliver electricity to other prosumers and balance the situation at the microgrid level. The aim of the microgrid agent is to optimize energy supply and demand at the microgrid level so that external-energy need is minimized. The microgrid agent is a book-keeping agent for energy exchange, balancing demand–supply for each prosumer.

The prosumer's agent aims to optimize energy demand and electricity supply to achieve self-sufficiency. The prosumer agent can implement demand, supply, and storage optimization, using demand flexibility to eliminate energy consumption spikes by turning on or off household IEDs. The virtual microgrid set-up will have the electricity-distribution fee as a burden, if prosumers inside the microgrid are not closely located.

5.5.1 A Three-Layer Agent Model Operational Example

For illustrating each layers in the three-layer agent model operation (Figure 25), the Prosumer agent *i* aims to minimize electricity costs (in the Rules or Regulatory layer). If the DER situation of prosumer *i* is not self-sufficient at some point of time with a priority A IED, the demand request is escalated to the microgrid agent (in the Status or Information layer), which knows that prosumer *j* has extra electricity available at the requested time. The microgrid agent proposes electricity exchange (in the Physical layer) from prosumer *j* to prosumer *i*. As a return, prosumer *i* has extra capacity later and can propose exchanging electricity back to prosumer *j*.

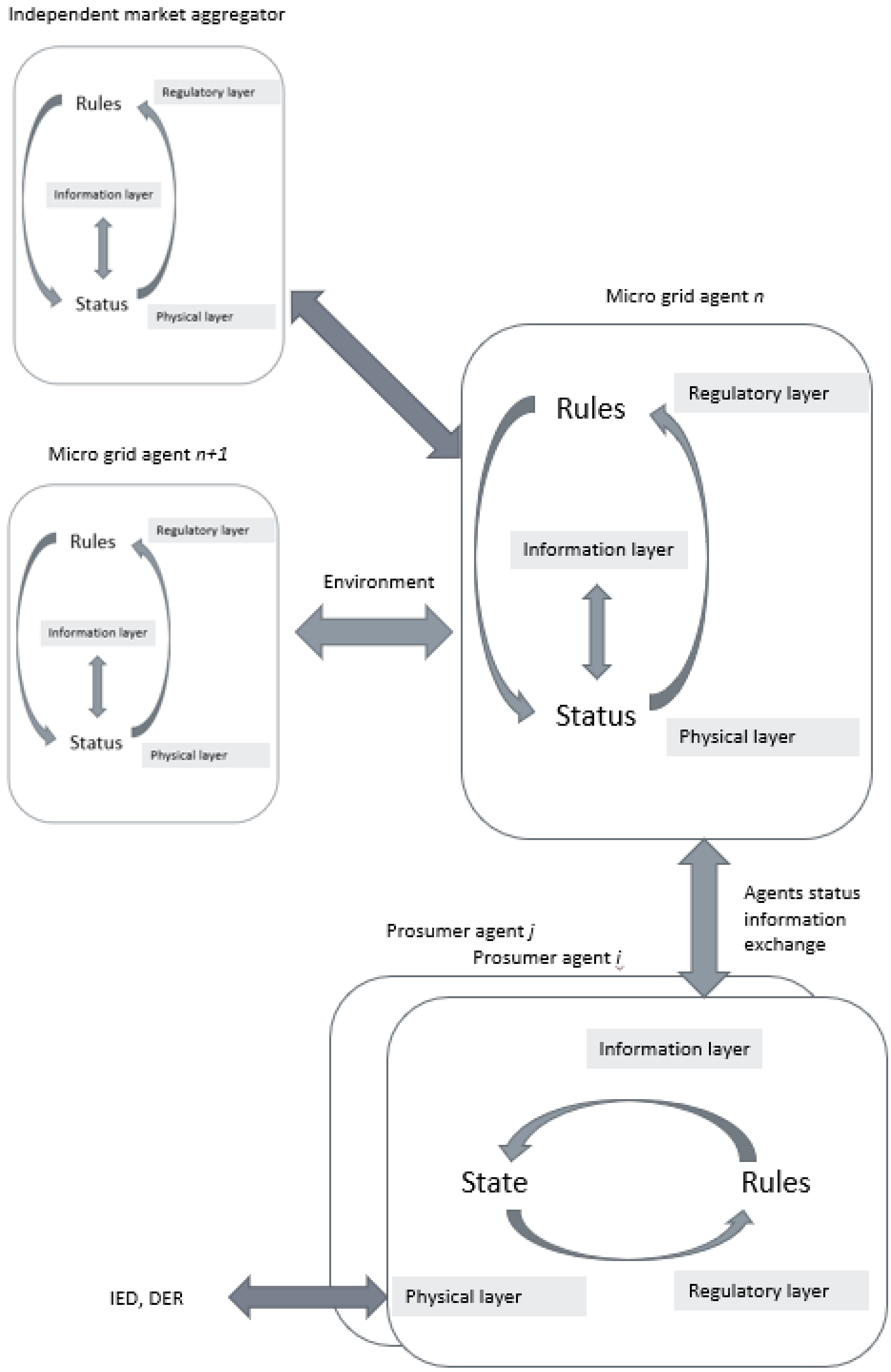

Figure 25. A three-layer agent-based model for a virtual microgrid (Nardelli et al., 2019; Dam et al., 2013)

The microgrid agent connects prosumers into a virtual microgrid and manages energy exchange (Figure 25). Depending on prosumers' priorities (for example, to optimize zero energy exchange or optimize for market sales), the prosumers' information is escalated for the microgrid agent. The aim is for energy supply and demand to be optimized at the microgrid level. If this does not succeed, demand–supply balancing is escalated for microgrid agent resolution (between microgrids) and eventually to the IMA agent. The external energy is invoiced using the market-price at the time of transfer and managed by the microgrid agent.

The ABM for a physical microgrid is similar to that of a virtual microgrid. A new technical agent is needed to ensure needed grid protection and power-grid safety. As a natural evolution from the virtual microgrid, the microgrid may be organized so that prosumers are physically located close to each other. Prosumers who are located close to each other ensure short electricity distribution chains, which minimizes distribution costs and creates the smallest possible area for isolation in case of an electricity fault. The physical microgrid makes it possible to achieve zero marginal energy costs by exchanging energy with a minimal distribution fee.

In addition to virtual and physical microgrid models, the energy internet provides active control of prosumers' IEDs to achieve an optimal demand–supply status inside the microgrid. To optimize IEDs, the energy needs and energy supply of each DER are virtually packetized. This energy quantization makes management of each IED more transparent for each connected agent. The packetized energy of each IED is combined in the energy server to enable the sharing of supply and demand in a fair and pre-prioritized manner (Figure 26) (Nardelli et al., 2019).

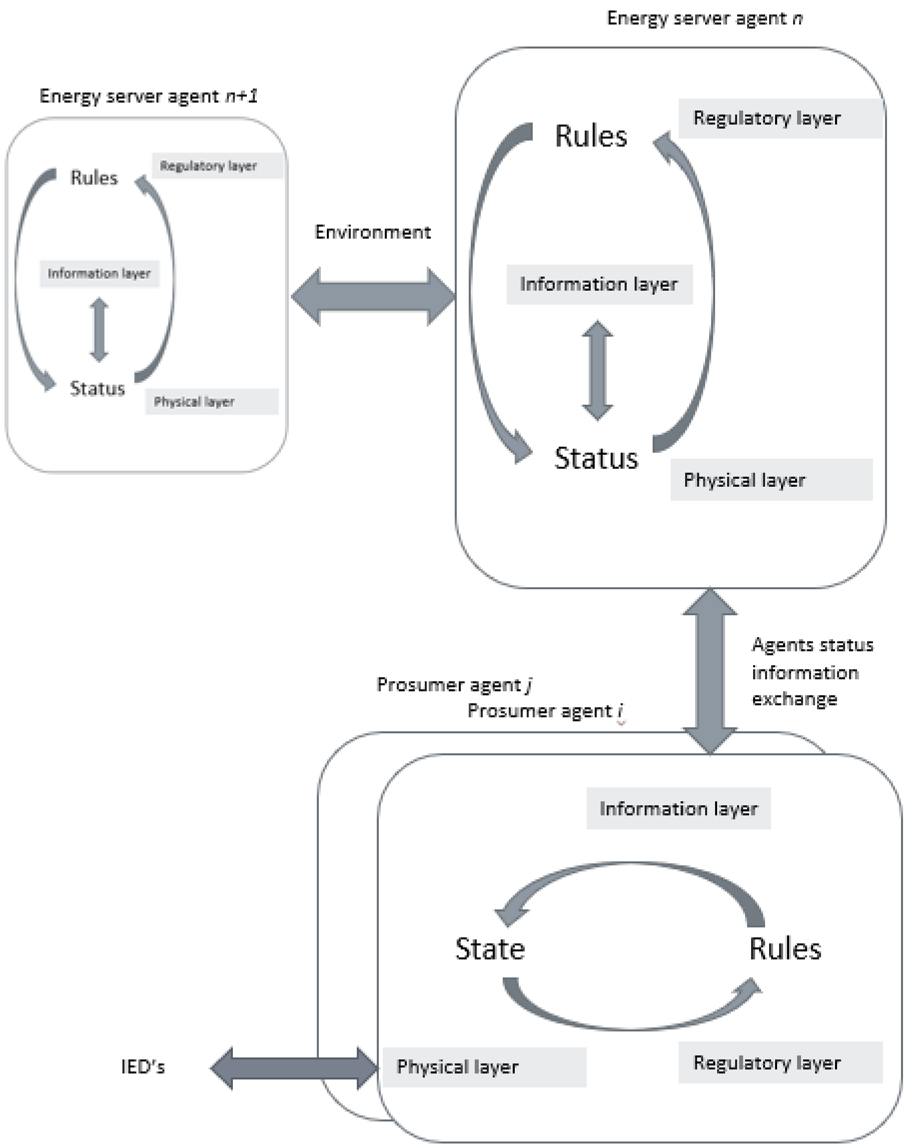

Figure 26. An Agent-Based Model for the energy internet (Nardelli et al., 2019; Dam et al., 2013)

The energy server will undertake most of the microgrid's event management, liberating IMA capacity for demand–supply balancing between microgrids and other electricity-generation sources. The IMA balances regional supply and demand.

5.6 An Agent-Based Model for Energy Internet Market Operations

The operation of the energy market is expected to become more complex compared to the existing energy market due to the increased number of energy-capacity bidders. New bidders will be more volatile in nature, due to fast-changing PV and wind energy availability.

The energy server collects IED information from all connected prosumers. The server balances prosumers demand and planned consumption inside the microgrid by exchanging energy based on priorities. The energy is exchanged using virtually packetized energy for each IED.

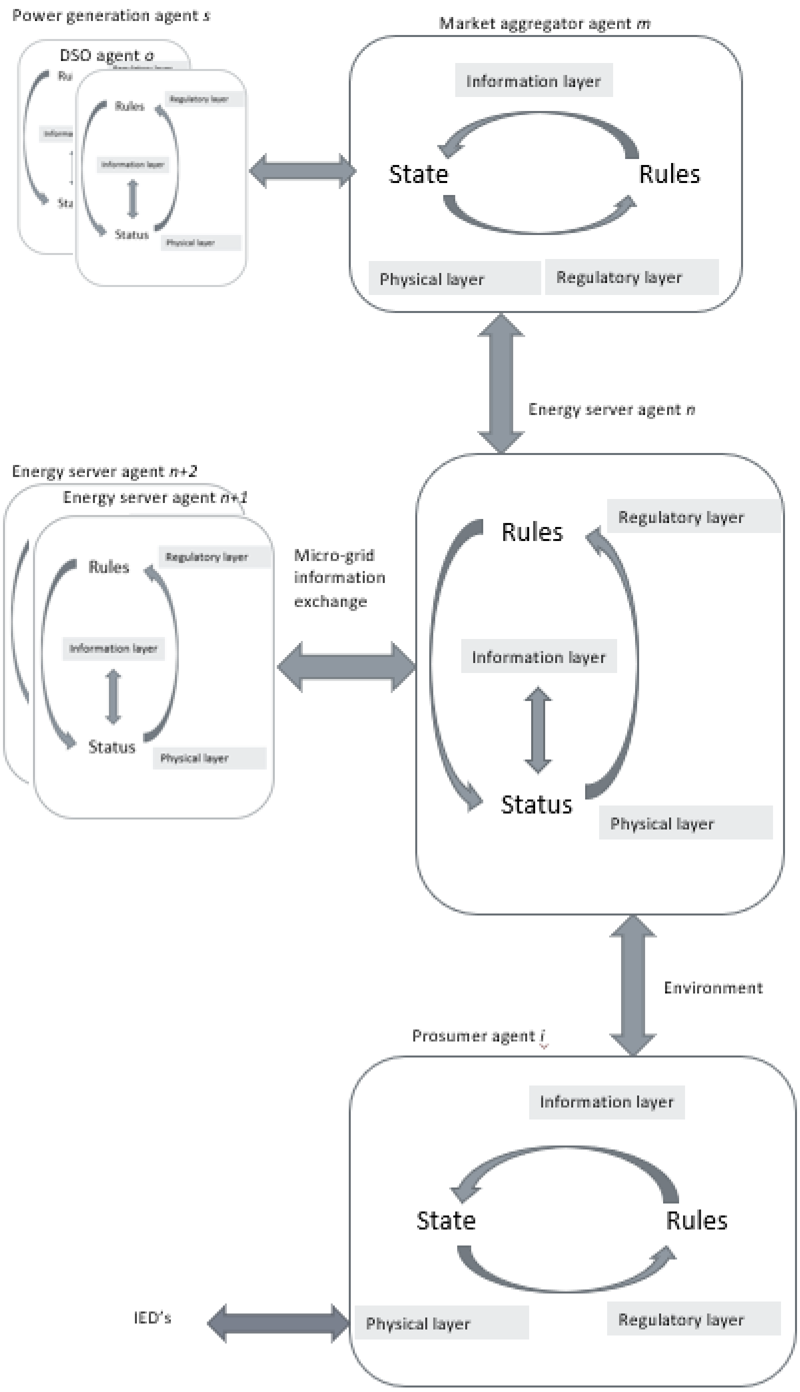

Figure 27. An Agent-Based Model for the energy internet, including the connection to the energy market (Nardelli et al., 2019; Dam et al., 2013).

The energy server agent updates the real-time demand–supply situation for the market aggregator, in addition to providing short-, medium-, and long-term demand–supply horizons to enable capacity reservation. When the model proves to have a clear cost benefit to prosumers, due to energy self-sufficiency, the model is expected to become popular with accelerated speed.

5.7 Key Elements for Transition

As renewable energy sources become more popular, prosumers will start to seek opportunities to utilize low-cost energy options and potentially exchange it. Prosumers will form community targets to exchange zero-priced energy. The exchange is expected to create new business opportunities in managing the exchange operations. The prosumers' communities would exchange zero-margin electricity using existing distribution grids. Distribution costs would be changed by the DSO separately.

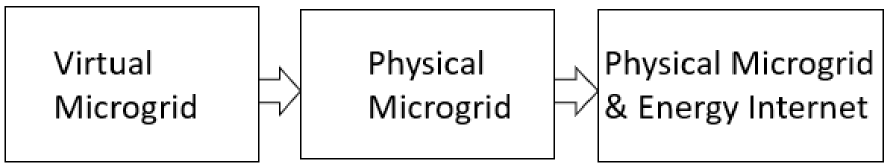

Figure 28.Transition steps from a virtual microgrid to the energy internet.

The first step: a virtual microgrid

At this point, renewable energy exchange is becoming popular and friendly prosumers agree to exchange energy. A business opportunity is created to manage and share the group's information with the market aggregator. The 5G communication channel is used to share prosumer supply and demand information for the microgrid and market aggregator. Target for step one: Prosumers pay only the energy transfer fee.

The second step: a physical microgrid

Closely located prosumers form communities. In a physical microgrid, short physical distances between prosumers minimize their distribution costs compared to the virtual microgrid model (the first step). For cost minimization to occur, governmental action is needed to change DSO invoicing principles. The existing electricity distribution fee model needs to be changed from flat-rate pricing to distance-based pricing. Target for step two: Prosumers are not paying for energy and pay a very minimal fee for distribution.

The third step: The energy internet

To further maximize benefits to prosumers, active IED and DER management is needed. Accurate IED information collection and control requires IoT devices communicating through 5G with the distribution grid and market aggregator. The power grid requires low-latency information communication (5G URLLC) to operate promptly, with grid actuators reacting to the rapidly changing grid environment. Efficient and active management of prosumers' energy requires quantization of energy loads and stored energy. The collected and packetized energy information from each prosumer is managed by the virtual energy server, which allocates demand–supply inside the microgrid based on pre-determined priorities. In addition to the previous steps, an energy server management layer is needed to collect IED data, packetize it, and share it in an optimized manner between prosumers. Target: Active optimization of energy supply and demand inside the microgrid by exchanging and shifting energy, based on DER information.

5.8 Summary of Transition Findings

The energy server agent will be a disruptive agent. It will be a game-changer, making large-scale, virtual energy flow management between prosumers and microgrids possible. Energy exchange management using virtual energy packets enables active and detailed IED and DER management to achieve maximum energy self-sufficiency, making zero marginal pricing plausible. The prosumer agent is a key agent for managing prosumers' own IEDs. The prosumer agent's operation enables scheduled energy exchange between other prosumers. For a physical microgrid the ESA supports energy exchange between prosumers. The virtual energy server stores virtually packetized energy and shares it according to scheduled priorities for prosumers within the community.

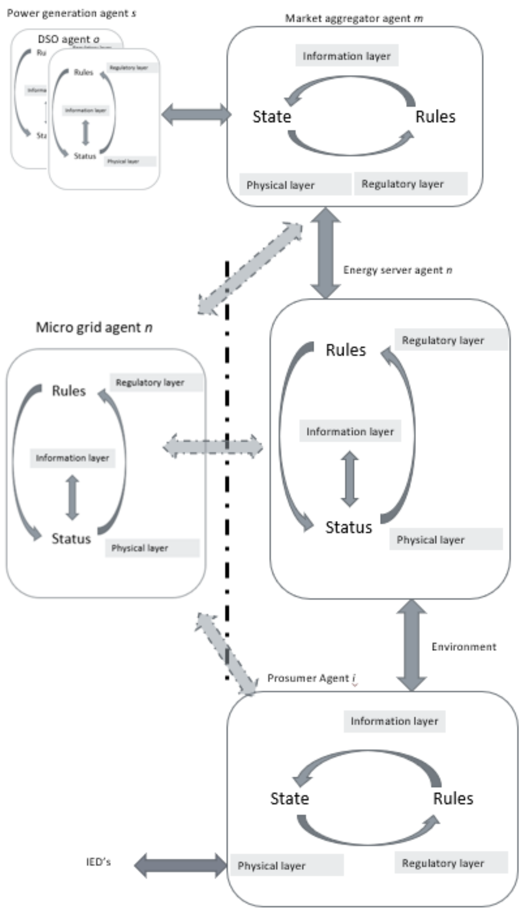

Figure 29 The virtual microgrid, energy internet and market agent models combined to illustrate their differences and similarities (Nardelli et al., 2019; Dam et al., 2013).

The main difference between a virtual microgrid and the energy internet is the energy internet's ability to actively control prosumers' IEDs (via ESAs), managing the overall DER situation in an optimized manner (Figure 29). The energy internet prosumers are located physically close to each other to minimize electricity distribution charges. Thus, the energy internet further optimizes system flexibility to gain zero margin energy.

Table 2. Summary of agents' objectives, their constraints and relations (Nardelli et al., 2019).

Existing power grid	**Objectives**	**Constraints**	**Agent relations**
PG agent	max (sold energy)	demand, fault	DSO, IMA
	max (quality)	capacity, latency	DSO
DSO agent	max (profit)	demand, reliability	PG, Consumer, IMA
	max(Electricity quality)	supply variation, latency	PG, Consumer
IMA	max (profit)	supply variation, demand-supply, grid/generation fault	Consumer, PG, IMA
Consumer agent	min (cost)	max (demand)	DSO, IMA
Virtual micro grid			
MG agent	min (external eletricity)	prosumer supply, DER, equal (load profile)	PG, Prosumer, IMA
Prosumer agent	min (cost)	supply, demand, comfort	MG, IMA
Energy Internet			
ESA	min (external energy)	high demand, low generation, same demand profile	Prosumers, IMA
	min (latency)	bandwidth capacity, signal distance	DSO, PG, prosumers
	min (information loss)	bandwidth capacity, signal distance	DSO, IMA, Prosumer
Technical agent	max (quality)	Electricity distortion, protection, safety, electicity demand-supply imbalance	DSO, PG, prosumers

6. CONCLUSIONS

The existing power grid is designed to transfer energy from high voltage to medium voltage. For historical reasons, it was designed to consider a one-directional electricity feed; thus, it does not properly consider consumer activity. The power grid control system’s functionality is limited to power transmission and distribution-grid elements; thus, it does not properly consider consumer activity. At the time of design, only a limited number of distributed energy resources were available. The existing energy supply relies on centralized electricity production. The largest sources of electricity are power plants using nuclear, hydrogen, natural gas, and fossil fuels.

The future household’s energy is mainly considered to be produced locally by prosumers which is triggering a change in power grid infrastructure. The future localized renewable electricity production is using PV and wind turbines.

The research question is how model IoT-based energy internet, a complex autonomously operating a socio-economic environment in which many interactions affect each other. This thesis illustrates agent-based modeling and governance models for the operation of the existing power grid, physical micro grid and energy internet. The agent-based model is defined by using three-layer system, where three layers are: regulatory layer, information layer and physical layer.

The motivation for the thesis is encouraging trend favouring environmentally friendly energy sources in connection to energy internet and advanced communication technologies. The local renewable electricity management and its exchange in micro grids requires coordinated energy management structure – the energy internet. A fifth-generation communication technology enables utilization of a large number of IoT -devices for measuring and controlling power grid autonomously to support energy internet.

The financial justification is an essential motivational change driver towards energy internet. Centrally generated electricity and long-distance distribution will increase overall electricity prices, while improved competitiveness in local renewable energy sources will make their investment payback time shorter. Thus, locally produced, renewable energy will be increasingly beneficial. Similarly, usage of electric cars is expected to become an increasingly attractive solution for economic travel. The equation will financially favor the use of EV even more when energy is produced locally, with no energy-distribution fee applied. The EV potentially provides ES, enabling demand flexibility for prosumers and active energy exchange between prosumers. Physical microgrid communities exchanging free renewable energy between prosumers make zero marginal electricity pricing plausible and financially attractive.

Artificial intelligence and massive data collection using IoT devices are referred to as the fourth industrial revolution. This industrial revolution is expected to increase productivity, which traditionally lowers production costs and increases demand and employment. High demand and productivity may spread into other industries, improving social welfare.

The objective of the thesis is to conduct literature review of simulating principles of three-layer agent modeling, advanced end-to-end communication technologies to support future smart grid. Also, thesis aims to develop agent-based governance model for the energy internet as a virtual energy management method for prosumers, microgrids and energy markets, and to illustrate transition pathways from existing power grid to the energy internet.

A mathematical framework to simulate IoT-communication combined with power grid operation is one subject for further studies. An ABM of the dynamics of the energy internet is another possible subject.

7. REFERENCES

Actility, 2019. Actility LoRA technology description. [Online document]. [Accessed 19.6.2019]. Available at https://www.actility.com/.

Alberta Electric System Operator, 2019. Guide to understanding Alberta's electricity market. [online document]. [Accessed 2.1.2020]. <https://www.aeso.ca/aeso/training/guide-to-understanding-albertas-electricity-market/>

Balaji, P.G., and Srinivasan, D., 2010: An Introduction to Multi-Agent Systems. Innovations in MASs and Applications – 1, SCI 310, pp. 1–27.

Berkley Lab, 2019. About micro-grids. [Online document]. [Accessed 25.9.2019]. <https://building-microgrid.lbl.gov/about-microgrids>

Bloomberg, 2016. Here's How Electric Cars Will Cause the Next Oil Crisis [online document]. [Accessed 17.6.2019]. Available at: https://www.bloomberg.com/features/2016-ev-oil-crisis/

Bonabeau, E., 2002. Agent-based modeling: Methods and techniques for simulating human systems. Proc Natl Acad Sci U S A. 2002;99 Suppl 3 (Suppl 3):7280–7287. doi:10.1073/pnas.082080899

Bonabeau, E., 2002: Agent-based modeling: Methods and techniques for simulating human systems**.** Proceedings of the National Academy of Sciences of the United States of America 14 May 2002, Vol.99(3), pp.7280-7287

Brattle Group, a research consultancy, 2019. Using electricity at different times of day could save us billions of dollars. [online document]. [Accessed 28.8.2019]. Available at: https://www.vox.com/energy-and-environment/2019/8/7/20754430/renewable-energy-clean-electricity-grid-load-flexibility

Buildings Performance Institute Europe, 2015. Nearly zero energy buildings definition across the Europe. [Online document]. [Accessed 27.6.2019]. Available at: http://bpie.eu/uploads/lib/document/attachment/128/BPIE_factsheet_nZEB_definitions_across_Europe.pdf.

Campillo, J., Wallin, F., Vassileva, I., Dahlquist, E., 2013: Economic impact of dynamic electricity pricing mechanisms adoption for households in Sweden. Conference publication, World Renewable Energy Congress. Research Gate 254864389

Cappers, P., Goldman, C., Hofmann, R., Partridge, D., Kast, M., McParland, C. Grid-Modernization technology Webinar: Energy Technology Area. Berkley Lab.

Available at: https://emp.lbl.gov/sites/default/files/grid-mod-tech-webinar-slidesandnotes.pdf

Catterson, V. M., Davidson, E. M., McArthur, S. D. J., 2012. Practical applications of multi-agent systems in electric power systems. European Transactions on Electrical Power March 2012, Vol.22(2), pp.235-252

Dam, K. H., Nikolic, I., Lukszo, Z., 2013: Agent-Based Modelling of Socio-Technical Systems. ISBN 978-94-007-4932-0

Díaz Zayas, A., Merino, P., 2015: The 3GPP NB-IoT system architecture for the Internet of Things, University of Málaga, Andalucía Tech, Málaga, Spain, 29071. ICC2017: WS06-Convergent Internet of Things- On the synergy of IoT systems.

Economist, 2004. Building the Energy Internet. [Online document]. [Accessed 17.6.2019**.** Available at: https://www.economist.com/technology-quarterly/2004/03/13/building-the-energy-internet

Energiavirasto. Information on the purchasing of electrical energy and the pricing of electricity network services. [online document]. [Accessed 12.6.2019]. Available at: https://energiavirasto.fi/en/consumers

Erbach, M., 2016. Understanding electricity market in the EU. European Parliament Briefing, 2016. [Online document]. [Accessed 15.8.2019]. EPRS |European Parliamentary Research Service, PE 593.519. Available at: http://www.europarl.europa.eu/RegData/etudes/BRIE/2016/593519/EPRS_BRI(2016)593519_EN.pdf

European Commission, 2010, Directive: Energy performance of the buildings. Document 32010L0031. [Online document]. Available at: http://data.europa.eu/eli/dir/2010/31/oj

European Commission, 2010. Energy performance of buildings (EPBD 2010/31/EU. [Online document]. Available at: https://ec.europa.eu/energy/en/topics/energy-efficiency/energy-performance-of-buildings

European Commission, 2013. Towards Nearly Zero-Energy Building. Definition of common principles under the EPBD, Final report BESDE10788. [Online document]. Available at: https://ec.europa.eu/energy/sites/ener/files/documents/nzeb_full_report.pdf

European Technology & Innovation Platforms. Integrating Smart Networks for the Energy Transition: Serving Society and Protecting the Environment. [Online document]. [Accessed 24.4.2019]. Available at: https://www.etip-snet.eu/etip-snet-vision-2050/

European Technology and Innovation Platform for Smart Networks for the Energy Transition working group, 2018: Integrating Smart Networks for the Energy Transition. [online document]. Available at: https://www.etip-snet.eu/wp-content/uploads/2018/05/VISION2050-v10PTL.pdf

European Union Directive 2019/944. Common rules for the internal market for electricity and amending Directive. [Online document]. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019L0944&from=EN

EV Statistics of the week, 2018. Range, price and Battery size of currently available BEV's. [Online document]. [Accessed 17.6.2019].Available at: https://evadoption.com/ev-statistics-of-the-week-range-price-and-battery-size-of-currently-available-in-the-us-bevs/

Federal Energy Regulatory Commission, 2008. Assessment of Demand Response & Advanced Metering. United States Federal Energy Regulatory Commission. [online document]. Available at: https://www.ferc.gov/legal/staff-reports/12-08-demand-response.pdf

Fingrid oy Towards the future electricity system - Smart grid. [Online document]. [Accessed 15.8.2019]. Available at: https://www.fingrid.fi/en/electricity-market/the-future-of-the-electricity-markets/development-projects/smart-grid/

Fingrid sähkömarkkinat 2017. Wind-turbine energy production on year 2017. [Online document]. [Accessed 24.6.2019]. Available at: https://www.fingrid.fi/sahkomarkkinat/kulutus-ja-tuotanto/tuulivoiman-tuotanto/

Fingrid sähkönsiirtoverkko. Suomen sähkönsiirtoverkko. [Online document]. [Accessed 10.8.2019]. Available at: https://www.fingrid.fi/kantaverkko/suomen-sahkojarjestelma/fingridin-sahkonsiirtoverkko/

Fingrid, Suomen sähköjärjestelmä. [Online document]. [Accessed 30.9.2019]. Available at: https://www.fingrid.fi/kantaverkko/suomen-sahkojarjestelma/kulutuksen-ja-tuotannon-tasapainon-yllapito/

Fleisch, F., Weinberger, M., Wortmann, F., 2014. Business models for the internet of things. Bosch lab white paper. Available at:http://www.iot-lab.ch/wp-content/uploads/2014/09/EN_Bosch-Lab-White-Paper-GM-im-IOT-1_1.pdf

Goldman, C., Levy, R., Feb 2010**.** An Introduction - Smart grid 101. Lawrence Berkley National Laboratory, Smart Grid Technical Advisory Project. Accessed 15.8.2019. https://emp.lbl.gov/sites/default/files/chapter1-3.pdf

GSM Association., LTE. [Online document]. [Accessed 24.6.2019]. Available at: https://www.gsma.com/iot/long-term-evolution-machine-type-communication-lte-mtc-cat-m1/

GSMA, mobile IoT. [Online document]. [Accessed 16.6.2019]. Available at: https://www.gsma.com/iot/mobile-iot-5g-future/

GSMA publication, 2018. Road to 5G Introduction and Migration. [Online document]. [Accessed 19.8.2019]. Available at: https://www.gsma.com/futurenetworks/wp-content/uploads/2018/04/Road-to-5G-Introduction-and-Migration_FINAL.pdf

Gui, E. M., Diesendorf, M., MacGill, I., 2017: Distributed energy Infrastructure paradigm: Community microgrids in a new institutional economics context. Renewable and Sustainable Energy review 72, pp. 1355-1365

Hirvonen R, Sulamaa P, Tamminen E, 2003: Kilpailu sähkömarkkinoilla: Sähkömarkkinoiden keskeiset piirteet ja toiminta**.** ETLA Discussion Papers, The Research Institute of the Finnish Economy (ETLA), No. 879. Available at: http://hdl.handle.net/10419/63960.

Huawei, 2016. 5G Network Architecture, A High-Level Perspective. [Online document]. [Accessed 26.9.2019]. Available at: https://www.huawei.com/minisite/hwmbbf16/insights/5G-Nework-Architecture-Whitepaper-en.pdf

International Energy Agency (IEA) Paris, 2002. Distributed Generations in Liberalised Electricity Markets. ISBN:9789264175976

International Energy Agency (IEA) Paris, 2011. Technology Roadmap Smart Grids. [Online document]. Available at: https://webstore.iea.org/technology-roadmap-smart-grids

IPCC special report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse gas fluxes in Terrestrial Ecosystems addresses greenhouse gas (GHG) fluxes in land-based ecosystems on August 2019. [Online document]. [Accessed 17.8.2019]. Available at: https://www.ipcc.ch/site/assets/uploads/2019/08/4.-SPM_Approved_Microsite_FINAL.pdf

ITU Standardization, 2012. Internet of Things Global Standards Initiative, ITU-T Y.2060. [Online document]. [Accessed 12.8.2019]. Available at: https://www.itu.int/en/ITU-T/gsi/iot/Pages/default.aspx

ITU, International Telecommunication Union, 11/2017. Minimum requirements to technical performance for IMT-2020 radio interface. Report ITU-R M.2410-0.

ITU, International Telecommunication Union, June 2018. ITU-R studies in support of the Internet of Things. [Online document]. [Accessed 9.6.2019]. Available at: https://www.itu.int/en/ITU-D/Regional-

Presence/Europe/Documents/Events/2017/Spectrum%20Management/Philippe%20IoT%20in%20ITU-R%20Study%20Groups%20(May%202017)_PhA.pdf

James, P., 2002. Peer-to-Peer Network. Computerworld Apr 8, 2002, p52, <https://search-proquest-com.ezproxy.cc.lut.fi/docview/215991160/fulltextPDF/CE908A62F94D4A84PQ/1?accountid=2729>

Jennings, N. R., 2000. On agent-based software engineering. Elsevier Artificial Intelligence 117, pp 277–296.

Kärkkäinen, S., Lakervi, E., 2001: Liberalisation of electricity market in Finland as a part of Nordic market. IEEE Article 2001, Vol 148(2) pp.194-199.

Kermack, W. O., McKendrick, A. G., 1927: A Contribution to the Mathematical Theory of Epidemics. Proceedings of the Royal Society of London Vol 115, No. 772, pp.700-721.

Koc, Y.¸ Warnier, M., Kooij, R. E., Brazier, F. M. T., 2013**:** Structural Vulnerability Assessment of Electric Power Grids. Cornwell University, arxiv:1312.6606.

Kolen, S., Isermann, T., Dähling, S., Monti, A., 2017: Swarm Behavior for Distribution Grid Control. Conference paper, Institute for Automation of Complex Power Systems. RWTH Aachen University. IEEE 978-1-5386-1953-7/17/

Kühnlenz, F., Nardelli, P. H. J., 2016. Dynamics of Complex Systems Built as Coupled Physical, Communication and Decision Layer. PLos ONE, Volume 11, Issue 1, 5 January 2016, Article number e0145135

Kühnlenz, F., Nardelli, P. H. J., 2016: Agent-based Model for Spot and Balancing Electricity Markets. Cornell University, arXiv:1612.04512v1

Kühnlenz, F., Nardelli, P. H. J., and Alves H., 2018: Demand Control Management in Microgrids: The Impact of Different Policies and Communication Network Topologies. IEEE system journal, vol. 12, no. 4, Dec 2018 pp.3577-3584

Kühnlenz, F., Nardelli, P. H. J., Karhinen, S., Svento, R., 2017. Implementing Flexible Demand: Real-Time Price vs. Market Integration. Energy 15 April 2018, Vol.149, pp.550-565

Lakervi, E. and Partanen, J., 2008. Sähkönjakelutekniikka. ISBN 9789516723597. pp. 235–236)

Lo, H., Blumsack, S., Hines, P., Meyn, S., 2019. Electricity rates for the zero margin cost grid. The electricity journal 32, pp. 39-43.

Lora-alliance, about lorawan. 2019. [Online document]. [Accessed 24.6.2019]. Available at: https://lora-alliance.org/about-lorawan

Luck, M., D'Invenrno M, 2001: A Conceptual Framework for Agent Definition and Development. Computer Journal 2001, Vol.44, pp.1-20.

Luterbacher, J., Dietrich, D., Xoplaki, E., Grosjean, M., Wanner, H., 2004: European Seasonal and Annual Temperature Variability, Trends, and Extremes since 1500. Science 303, pp. 1499-1503.

Maekawa, J., Hai, B. H., Shinkuma, S. and Shimada, K., 2018: The Effect of Renewable Energy Generation on the Electric Power Spot Price of the Japan Electric Power Exchange. Energies 2018, Vol.11(9), p.2215.

Mashlakov, A., Tikka, V., Honkapuro, S., Lehtimäki, P., Repo, S., Keski-Koukkari, A., Aro, M., Abdurafikov, R., Kulmala, A., 2018. SGAM use case definition of an information exchange architecture. Cired workshop Ljubljana 2018 Paper 0503. Available at: http://www.cired.net/publications/workshop2018/pdfs/Submission 0503 - Paper (ID-20994).pdf

Massoud, A., Schewe, P. F., 2017: Preventing Blackouts: Building a Smarter Power Grid. [Online document]. [Accessed 17.6.2019]. Available at: https://www.scientificamerican.com/article/preventing-blackouts-power-grid/

Ministry of Economic affairs in Finland, 2018. Final report by Smart Grid Working Group A Flexible and Customer driven Electricity System. [Online document]. Available at: https://tem.fi/documents/1410877/2132296/Smart_Grid_WG_proposals_241018/97f47b31-71df-868c-ab10-e24ff9bc9e0f/Smart_Grid_WG_proposals_241018.pdf

Minkel, J. R., 2008, Accessed 17.6.2019. The 2003 Northeast Blackout – Five years later. Scientific American. [Online document]. Available at: https://www.scientificamerican.com/article/2003-blackout-five-years-later/

Nardelli, P. H. J., Alves, H., Pinomaa, A., Wahid, S., De Castro Tomé, M., Kosonen, A., Kühnlenz, F., Pouttu, A., Carillo, D., Jan 2019: Energy Internet via Packetized Management and Deployment Challenges. IEEE access, Vol 7 pp. 16909-16924

Nardelli, P. H. J., and Kühnlenz, F., 2018: Why Smart Appliances May Result in a Stupid Grid. IEEE Systems, Man, and Cybernetics Magazine October 2018, Vol.4(4), pp.21-27

Niazi, M. and Hussain, A., 2011. Agent-based computing from multi-agent system to agent-based models: a visual survey. Springer Scientometrics, 89(2), pp479-499. DOI:10.1007/s11192-011-468-9

Nokia Technology report, white paper, 2016: 5G for Mission Critical Communication: Achieve ultra-reliability and virtual zero latency. [Online document]. Available at: https://es.scribd.com/document/364424493/Nokia-5G-for-Mission-Critical-Communication-White-Paper

Nord Pool Group, day-ahead market. [Online document]. [Accessed 28.10.2019]. Available at: https://www.nordpoolgroup.com/the-power-market/Day-ahead-market/

Nord pool group, intraday market. [Online document]. [Accessed 28.10.2019]. Available at: https://www.nordpoolgroup.com/the-power-market/Intraday-market/

Nord pool group, 2018: Euphemia: Description and functioning. [Online document]. Available at: https://www.nordpoolgroup.com/globalassets/download-center/pcr/euphemia-public-documentation2.pdf

Nord pool group, market members. [Online document]. [Accessed 04.04.2020]. Available at: https://www.nordpoolgroup.com/the-power-market/The-market-members/

Nuutinen, P., Kaipia, T., Peltoniemi, P., Lana, A., Pinomaa, A., Mattsson, A., Silventoinen, P., Partanen, J., Lohjala, J., and Matikainen, M,. 2014. Research Site for Low-Voltage Direct Current Distribution in a Utility Network—Structure, Functions, and Operation. IEEE Transactions on Smart Grid Vol. 5 , Issue 5 , Sept. 2014 pp.2574-2582

Obiodu, E., Giles, M., 2017. The 5G Era, GSMA intelligence. [Online document]. [Accessed 19.8.2019]. Available at: https://www.gsmaintelligence.com/research/2017/02/the-5g-era-ageofboundless-connectivity-and-intelligent-automation/614/

Ostrom, E., Janssen, M. A., Anderias, J. M., 2017: Going beyond panaceas. PNAS.0701886104

Pacala, S., Socolow, R., 2004. Stabilization Wedges: Solving the Climate Problem for the next 50 years with Current Technologies**.** Science 305 pp. 968-972.

Partanen J., Lassila J., Kaipia T., Haakana J., 2012: Sähkönjakelun toimitusvarmuuden parantamiseen sekä sähkökatkojen vaikutusten lieventämiseen tähtäävien toimenpiteiden vaikutusten arviointi. Vaikutusarvioselvitys TEM:n muistiossa 16.3.2012 ehdotetuista toimenpiteistä sähkönjakelun varmuuden parantamiseksi sekä sähkökatkojen vaikutusten lieventämiseksi. Lappeenrannan teknillinen yliopisto. Available at: https://www.lut.fi/documents/10633/138922/S%C3%A4hk%C3%B6njakelun+toimitusvarmuuden+parantamiseen+sek%C3%A4%20s%C3%A4hk%C3%B6-+katkojen+vaikutusten+lievent%C3%A4miseen+t%C3%A4ht%C3%A4%C3%A4vien+toimenpiteiden+vaikutusten+arviointi/bf021a58-24fc-47bd-a893-1804ad813f08

Pouttu, A., Haapoja, J., Ahokangas, P., Xu, Y., Kopsakangas-Savolainen, M., Porras, E., Matamoros, J., Kalalas, C., Alonso-Zarate, J., Gallego, F. D., Martin, J.

M., Deconinck, G., Almasalma, H., Clayes, S., Wu, J., Cheng, M., Li, F., Zhang, Z., Rivas, D., Casado, S., 2017: P2P Model for distributed Energy Trading, Grid Control and ICT for Local Smart Grids. IEEE 978-1-5386-3873-6/17.

Praca, I., Ramos, C., Vale, Z., 2003. MASCEM: Multiagent System: That simulates Competitive Electricity Markets. IEEE 1094-7167/03

Rifkin, J., 2014. Zero Marginal Cost Society. The Internet of Things, The Collaborative Commons, and the Eclipse of Capitalism, Palgrave Macmillan, New York, 2014: 356, ISBN 978-1-137-27846-3

Rohde&Schwarz GmbH. LTE-M test requirements. [Online document]. [Accessed 24.6.2019]. Available at: https://www.rohde-schwarz.com/us/solutions/test-and-measurement/wireless-communication/iot-m2m/lte-m/lte-m-theme_234034.html

Rost, P., Banchs, A., Berberana, I., Breitbach, M., Doll, M., Drostem H., Mannweilerm C., Puente, M., Samdanis, A. K., Sayadi, B., 2016: Mobile Network Architecture Evolution toward 5G. IEEE Communications Magazine May 2016, Vol.54(5), pp.94-91.

Saitoh, H., Toyoda, J., 1995: Flexible Electric Power Distributor for Smart Use of Dispersed Generation Plants in Metropolitan Area. Science direct, IFAC Proceeding volume 28, issue 26, pp 353-358.

Scott, P. A., Stone, D. A., Allen, M. R., 2004. Human contribution to the European heatwave of 2003. Nature 432 (ISSN 1476-4687), pp. 610-614.

Sharma, S., Miller, R., Francini, A., 2017: A Cloud-Native Approach to 5G Network Slicing. IEEE Communications Magazine, August 2017. 10.1109/MCOM.2017.1600942.

Shoham, Y., 1993: Agent oriented programming. Elsevier ARTINT 931. Artificial intelligence, Vol 60, pp 51-92.

Sigfox, 2019. IoT-radio technology. [Online document]. [Accessed 24.6.2019]. Available at: https://www.sigfox.com/en/sigfox-iot-radio-technology

Singh, A. K., Sood, Y. R., Singh, H., Gagrai, S. K., 2013. Smartgrid: An Introduction. International Journal of Advanced Computer Research; Bhopal Vol. 3, Iss. 4, (Dec 2013): pp. 53-57.

Solar Power Europe, 2019. Global Market outlook for Solar Power 2019-2023. ISBN NUMBER 9789082714326

Sousa, T., Soares, T., Pinson, P., Moret, F., Baroche, T., Sorin, E., 2018: Peer-to Peer and community-based market: A comprehensive review. Research gate qualification/328474757.

Suomen virallinen tilasto (SVT). Energian kulutus ja hankinta. [Online document]. [Accessed 12.8.2019]. Available at: http://pxnet2.stat.fi/PXWeb/pxweb/fi/StatFin/StatFin__ene__ehk/

Tabbane, S., 2016. International Telecommunication Union ITU, IoT Network planning. [Online document]. [Accessed 19.6.2019]. Available at: https://www.itu.int/en/ITU-D/Regional-Presence/AsiaPacific/SiteAssets/Pages/Events/2016/Dec-2016-IoT/IoTtraining/IoT%20network%20planning%20ST%2015122016.pdf

Ter-Martirosyan, A., Kwoka, J., 2010. Incentive regulation, service quality, and standards in U.S. electricity distribution. Journal of Regulatory Economics 2010, Vol.38(3), pp.258-273

International Energy Agency, Global EV outlook 2018 report. [Online document]. [Accessed 17.6.2019]. Available at: https://www.iea.org/newsroom/news/2018/may/strong-policy-and-falling-battery-costs-drive-another-record-year-for-electric-ca.html

The Nordic Power Exchange, Nordpool market information. [Online document]. [Accessed 15.8.2019]. Available at: http://wwwdynamic.nordpoolspot.com/marketinfo/

Tilastokeskus, energian kokonaiskulutus Suomessa 2016. [Online document]. [Accessed 13.6.2019]. Available at: https://www.stat.fi/til/ehk/2016/04/ehk_2016_04_2017-03-23_tie_001_fi.html

Ton, D. T., Smith, M. A., 2012. The U.S. Department of Energy's Microgrid Initiative. Science Direct, Vol.25, pp. 84-94. Available at: http://dx.doi.org/10.1016/j.tej.2012.09.013

Tran, M., 2012. Agent-behavior and network influence on energy innovation diffusion. Communications in Nonlinear Science and Numerical Simulation September 2012, Vol.17(9), pp.3682-3695

Tsoukas, L., H, Gao R, 2008. From Smart Grids to and Energy Internet: Assumptions, Architectures and Requirements. IEEE 10.1109/DRPT.2008.4523385, pp. 94-98

Työ- ja elinkeinoministeriö, julkaisu 48/2018. Sähkönsiirtohinnat ja toimitusvarmuus. [Online document]. Available at: http://julkaisut.valtioneuvosto.fi/bitstream/handle/10024/161178/43_18_Sahkonsiirtohinnat_ja_toimintavarmuus.pdf

U.S. Department of energy. A common definition for zero energy building, 2015. [Online document]. Available at:

https://www.energy.gov/sites/prod/files/2015/09/f26/A%20Common%20Definition%20for%20Zero%20Energy%20Buildings.pdf

U.S. Department of Energy. Microgrid Initiative, 2012. [Online document]. Available at: https://www.energy.gov/sites/prod/files/2016/06/f32/The%20US%20Department%20of%20Energy%27s%20Microgrid%20Initiative.pdf

Vattenfall, sähkön hinnan muodostuminen, Formation of Energy costs. [Online document]. [Accessed 24.6.2019]. Available at: https://www.vattenfall.fi/asiakaspalvelu/aihe/sahkosopimukset/sahkon-hinnan-muodostuminen/

Ympäristöministeriö, Sitra ja Tekes, 2012: Suomen kansallinen suunnitelma lähes nollaenergiarakennusten lukumäärän kasvattamiseksi. Rakennusten energiatehokkuusdirektiivin (2010/31/EU) 9 artiklan mukainen raportointi Euroopan komissiolle. [Online document]. Available at: https://ec.europa.eu/energy/sites/ener/files/documents/finland_fi_version.pdf.

Yu, X., Xue, Y., 2016: Smart grids: A Cyber-Physical Systems Perspective. IEEE 0018-9219, 2016.