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AI AND DIGITALIZATION AS ENABLERS OF FLEXIBLE POWER SYSTEM

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INDUSTRIAL ENGINEERING AND MANAGEMENT
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ABSTRACT

AI and digitalization as enablers of flexible power system

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The Paris climate agreement obligate energy and power sector to reduce greenhouse gasses even though at the same time the global power demand increases. This leads to need to increase emission-free power generation with renewable energy sources (RES). Wind- and solar power technologies have developed significantly and price of power generated by them has decreased clearly in recent years. These factors have led to large-scale installations globally. However transitioning towards RES, such as wind and solar power, poses a challenge, since supply and demand in the electric power system must be equal at all times, but wind- and solar power are non-adjustable. These factors leads to need of finding flexibility from elsewhere e.g. from demand side, but also from storage systems.

Purpose of this thesis is to analyze electric power system's flexibility and how it can be increased by employing digital technologies including artificial intelligence (AI). This research was done by using qualitative conceptual research method, where data is collected until saturation point is reached. Data was collected from scientific journals and relevant sources to form conceptual understanding of current state and future possibilities.

With digital technologies and artificial intelligence, companies can create new types of products, services and business models, which create more value for the customer. At the same time, these new solutions can improve the electric power system and create needed flexibility. The thesis studied these novel solutions and discussed practical implementation of three example cases in more detail. Digital solutions are rising into more significant role and they act as enablers for greener electric power system.

Keywords: Digitalization, artificial intelligence, electric power system

TIIVISTELMÄ

Tekoäly ja digitalisaatio joustavan sähköjärjestelmän mahdollistajana

Ville Jokiniemi

Oulun yliopisto, Tuotantotalous

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Työn ohjaajat yliopistolla: Pekka Kess, Jukka Majava

Pariisin ilmastosopimus velvoittaa energia- ja sähkösektorit rajoittamaan kasvihuonepäästöjä, vaikka samaan aikaan sähkön kysyntä globaalisti kasvaa. Tämä johtaa tarpeeseen lisätä päästötöntä sähköntuotantoa uusiutuvilla energialähteillä. Tuuli- ja aurinkovoimateknologiat ovat kehittyneet ja niillä tuotetun sähkön hinta on laskenut selvästi viime vuosina. Nämä seikat ovat johtaneet niiden laajamittaiseen käyttöönottoon maailmanlaajuisesti. Siirtyminen näihin energiamuotoihin tuottaa haasteita sähköjärjestelmälle, sillä sähköjärjestelmässä tuotannon ja kulutuksen tulee olla tasapainossa koko ajan, mutta tuuli- aurinkovoiman sähköntuotantoa ei pystytä säätämään. Nämä seikat ovat johtaneet tarpeeseen löytää joustavuutta sähköjärjestelmän muista osista mm. kysynnästä, mutta myös varastoinnista.

Tämän tutkimuksen tavoitteena on tutkia ja analysoida, miten sähköjärjestelmän joustavuutta voidaan lisätä digitaalisten teknologioiden, erityisesti tekoälyn avulla. Tutkimus on tehty laadullisella konseptuaalisella tutkimusmenetelmällä, jossa datan keräystä on jatkettu saturaatiopisteen saavuttamiseen asti. Data on kerätty tiedejulkaisuista ja muista tutkimuksen kannalta merkityksellisistä lähteistä, joiden pohjalta on voitu muodostaa konseptuaalinen ymmärrys tämän hetken tilasta ja tulevaisuuden mahdollisuuksista.

Digitaalisten teknologioiden ja tekoälyn avulla yritykset voivat luoda uudenlaisia tuotteita, palveluita ja liiketoimintamalleja, jotka tuottavat aikaisempaa enemmän arvoa asiakkaalle. Samalla nämä uudet ratkaisut pystyvät parantamaan sähköjärjestelmää ja luomaan tarvittavaa joustavuutta. Tässä työssä tutustuttiin näihin uusiin ratkaisuihin ja tutkittiin myös niiden käytännön toimivuutta analysoimalla kolmea esimerkkitapausta tarkemmin. Digitaaliset ratkaisut ovat nousemassa merkittävään osaan sähköjärjestelmää ja niillä, kuten monella muullakin digitaalisiin teknologioihin pohjautuvilla ratkaisuilla voidaan mahdollistaa ympäristöystävällisempi sähköjärjestelmä.

Asiasanat: Digitalisaatio, tekoäly, sähköjärjestelmä

FOREWORD

First of all, I would like to thank VTT Technical Research Centre of Finland, for this opportunity. This research has been educating journey and I have learned a lot since I started. Studying digital technologies, AI and energy sector was engaging way to gain insights of future.

Special thanks belongs to my supervisor from VTT, research professor Heikki Ailisto, who offered guidance during this process and offered advices when needed. In addition, I would like to express my gratitude to D.Sc. Jukka Majava and professor Pekka Kess, from University of Oulu, who supervised and aided during this research process.

Finally, largest thanks belongs to my family and friends who supported me during my university studies.

Oulu, 13.11.2019

Ville Jokiniemi
Ville Jokiniemi

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LIST OF ABBREVIATIONS

AI	artificial intelligence
AMR	automatic meter reading
ANN	artificial neural network
BMG	Brooklyn microgrid
BRP	balance responsible party
CHP	combined heat and power
CPS	cyber-physical system
CSP	concentrated solar power
DAC	direct air capture
DCF	discounted cash flow
DER	distributed energy resources
DLT	distributed ledger technology
DR	demand response
DSM	demand-side management
DSO	distribution system operator
EE	energy efficiency
EMTS	energy management system
EPAD	electricity price area difference
ESS	energy storage systems
EV	electric vehicle
FCR	frequency containment reserves
FRR	frequency restoration reserve
GHG	greenhouse gasses
HVAC	heating ventilation and air conditioning
IoT	Internet of things
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
LACE	levelized avoided cost of energy
LCOE	levelized cost of energy
LIB	lithium-ion battery
MG	microgrid
ML	machine learning

MW	megawatt
MWh	megawatt hour
PHS	pumped hydro storage
PV	photovoltaics
P2X	power-to-X
SIB	sodium-ion battery
SNG	synthetic natural gas
RES	renewable energy sources
RFID	radio frequency identification
RR	replacement reserve
SR	spinning reserve
SVM	support vector machine
TOU	time of use
TSO	transmission system operator
TW	terawatt
TWh	terawatt hour
VPP	virtual power plant
VRE	variable renewable energy
V2G	vehicle to grid
WACC	weighted average cost of capital
WSN	wireless sensor network

1 INTRODUCTION

1.1 Background

Concern about climate change is influencing countries, companies and individuals to change current behaviour. To mitigate climate change, 195 countries have signed and 186 ratified the Paris Agreement. The Paris Agreement requires countries to:

“ a) Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change;

(b) Increasing the ability to adapt to the adverse impacts of climate change and foster climate resilience and low greenhouse gas emissions development, in a manner that does not threaten food production; and

(c) Making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development. “ (United Nations, 2015)

The goal of this agreement is to keep global warming lower than 1.5 Celsius degrees by lowering greenhouse gases (GHG). The Paris Agreement affects the energy and power sector due it being one of the largest sources of GHGs globally.

In addition to lower GHG emissions, the power sector faces other changes as well. Power demand is expected to increase in the coming years due population growth and the electrification of transportation and other sectors. (McKinsey, 2019) Changes are expected to occur in power generation. Traditional large power plants are replaced by decentralized renewable energy sources (RES).

The agreed goal for the energy sector is to replace more polluting fossil fuels with RES. Due to the fluctuation of the power supply, actions must be taken to ensure a safe and functional electric power grid at all times. Currently, the problem is solved by demand-response, increasing energy efficiency and small-scale energy storage. Adding an increasing amount of renewable energy to the mix will require more to flexibility.

Productions of current RES rely heavily on weather conditions, and for this reason electricity supply to the grid will fluctuate. Fluctuation will happen between days, months and seasons.

Digital transformation is predicted to improve the electricity system. Digitalization, artificial intelligence (AI) and other technologies are emerging and improving. This thesis studies how AI can improve the current electricity system.

1.2 Research problem, goals and questions

This thesis was done for the Technical Research Center of Finland (VTT). The purpose of this work is to study and discuss the future of the electric power system. AI and other digital technologies have high priority in this study. These technologies will have a presumably high impact on the power system by enabling it to work more efficiently. The aim of these research questions is to form a clear picture of the current electric power system. Based on this information, analysis and requirements for transition towards new systems can be made.

1. **How do renewable energy sources affect the electric power system?**

To understand how future power systems might look like, current systems must be studied. Implementing a high amount of RES leads to problems balancing supply and demand of electricity. Therefore, the first research question focuses on this important aspect.

2. **How can digital technologies and AI help transition to a power system with a high integration of renewable energy sources?**

The second research question focuses on how AI and other digital technologies can enable a transition towards a cleaner system, without jeopardizing either economical or security aspects of the system.

3. **What are most suitable pilot projects using digital technologies to enable renewable energy systems?**

The third research question focuses on current state-of-the-art project cases. The purpose of this research question is to find proof concepts and demonstrate how AI and other digital technologies have been successfully implemented to improve the electric power system.

1.3 Research methodology

This dissertation was conducted with a conceptual literature study. In the conceptual research, data was collection with qualitative methods. Conceptual research can collect more data compared to empirical research. In addition to this, conceptual research is able to collect data more widely from different perspectives. Historical research uses this method, but conceptual research does not only limit the past. With a larger database, conceptual research can form concepts from collected data, which can be used to describe the phenomenon. (Xin, Tribe, & Chambers, 2013)

The benefit of conceptual research comes from describing the larger, holistic phenomenon. This research's study area is wide and the scope is large. The electric power system is one of the most complex systems humans have made and the prospect of complex future developments add to this challenge. Therefore, conceptual literature study was suitable to conduct this research. Xin et al., (2013) conducted study conceptual literature study on tourism. Even though study field differs to study on electric power system, similarities are notable. With this method they were able to form conceptual framework of their study. (Xin et al., 2013)

With massive amounts of data available in relative studies, reports and websites, defining the end of research and analysis might prove a difficult task. In this study, research was done following the principles of the concept of saturation. Saturation has wide acceptance in qualitative research and was first introduced by Glaser and Strauss in 1967. (Saunders et al., 2018).

With widespread of acceptance, saturation has gained popularity as an approach in qualitative research. However, to clearly define saturation might prove to be a difficult task. When deciding a saturation point, a researcher should make three key questions such as: *What? Where and why? When and how?* (Saunders et al., 2018). In this dissertation, the answers for these key questions are:

- *What?* Saturation was defined as "no new data has novel information relevant for this study".
- *Where and why?* This qualitative research sought a large-scale picture, to answer questions that have large impacts and relevance on the electric power system.
- *When and how?* In this research, the study ended when no new data was found that was novel information relevant for this study. When this point reached, results were assessed based on collected data.

However saturation point depends on subjectivity and some arguments can be made that saturation point cannot be reached in vast topic as this. One definition of saturation can be a point where data collection becomes counter-productive and emerging data does not add to the final theory (Saunders et al., 2018).

1.4 Structure of the thesis

This master's thesis is done by qualitative research methods, illustrated in Figure 1. The first chapter presents the background for this study, objectives, goals and research questions. Chapters 2 and 3 are part of the literature review. Chapter 2 describes the current electric power system and answers research question 1. Chapter 3 provides a theoretical background for digital technologies.

Chapter 4 consists of results. This chapter answers research question 2 and illustrates current usage of AI digital technologies in the electric power system. Additionally, this chapter also answers research question 3 by demonstrating cases where digital technologies have been used to improve the electric power system.

In the discussion, results of this dissertation are evaluated. Based on the results, the future of electric power systems is discussed. Finally, conclusion synthesize this research.

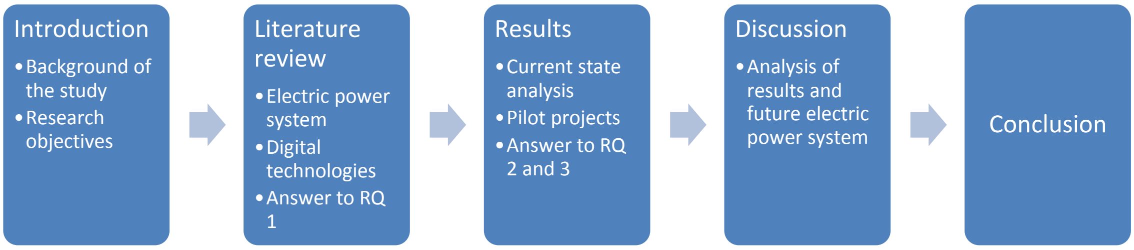

Figure 1. Research process.

2 ELECTRIC POWER SYSTEM

The electricity system has three major requirements: 1) cost-effectiveness 2) environmental sustainability with low greenhouse gases and 3) secure supply of energy (Huttunen, R., 2017). These aspects must be taken into account when planning to make changes in a power system.

Key parts of the electricity value chain are presented in this chapter. Briefly, this system consists of power producers, consumers and infrastructure between them. The grid that connects producers and consumers consists of a nationwide transmission grid as well as regional and distribution networks. Transmission system operator (TSO) is responsible for the nationwide grid’s infrastructure and distribution system operators (DSOs) are accountable for distributing networks (Fingrid, 2019a). Multiple different companies, and increasingly individuals, produce power to the grid. Power flow in the system is shown in Figure 2.

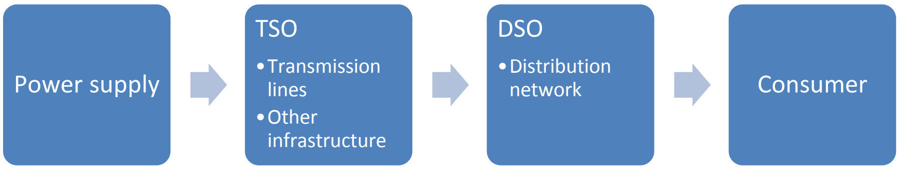

Figure 2. Power flow in electric power system.

This chapter presents production and consumption of electricity in Finland. Electricity is vital for countries and their citizens. People are dependent on electricity and it is a basic need for modern life. Due to the importance of electricity, large blackouts and long lasting power shortages can have devastating impacts on society.

2.1 Electricity production and consumption in Finland

Balance between supply and demand of electricity is essential to have a working grid. This is one fundamental difference between electricity and other products and services. In addition to grid balancing, storing electricity is a difficult task. Electricity production follows just-in-time principles, where electricity is supplied exactly when it is needed. In this ecosystem, there are many actors working together assuring a stable grid and electricity to customers when needed. (Energiateollisuus, 2019)

Power systems can be adjusted two ways: decreasing demand or increasing power supply. Increasing the power supply has been mainly accomplished by produced hydro or thermal power, which can be adjusted on short notice. These power plants are called load following power plants. Load following power plants are adjustable and can produce electricity when needed. (Energiateollisuus, 2019) Large power users can also agree to lower power demand, when needed.

Most of the load following power is generated with hydropower in Finland or in other Nordic countries. This power is then transferred to Finland. Hydropower plants can store energy by holding water in pools. When load following power is needed, water is directed to turbines to produce electricity. The importance of load following power and demand-side management (DSM) increases when total power consumption and share of renewable energy sources (RES) increases. Therefore, load following power is an essential supplement to volatile and unpredictable wind and solar power. (Energiateollisuus, 2019)

2.1.1 Production

Finland produced 67 TWh of electricity in year 2018 and imported 19 TWh from other countries (Energiateollisuus, 2019; Hakala 2019). The three energy resources responsible for the largest shares of production were nuclear (25%), hydropower (15%) and biomass (14%). Figure 3 illustrates electricity production by sources. The largest energy source, nuclear power, will increase in future years when two new nuclear power plants start to operate. Olkiluoto 3 is estimated to start operating in year 2020 (TVO, 2019) and Hanhikivi 1 in 2028. Olkiluoto 3 will have a capacity of 1600 MW and Hanhikivi 1 1200MW (TVO, 2019; Fennovoima, 2019) . When finished, Olkiluoto 3 will increase share of nuclear power significantly and it will be around 40% of total power production.

52 % of electricity was produced using (RES).

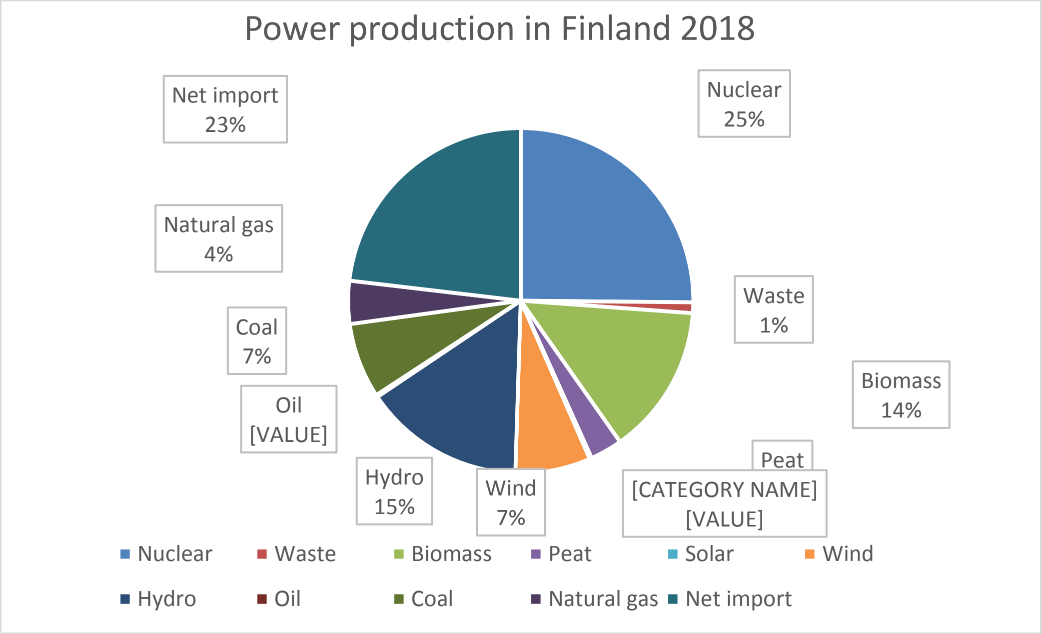

Figure 3. Power production by source in Finland 2018 (retell from Hakala, 2019).

Notable part of Finland's generated power comes from RES and they were 47 % of total share of power generation. Emission-free power was 79% of generated power in year 2018. (Hakala, 2019) RES consists from multiple different energy sources which are: solar, wind, biomass, thermal, tidal, wave, hydrokinetic (marine and river current), hydro potential and geothermal (Beaudin, et al., 2010). From these RES, hydro, wind and biomass have a larger share in Finland (Hakala, 2019). Since RES term itself contains multiple different technologies, methods and characteristics, term variable renewable energy (VRE) is used in this thesis. VRE contains renewable energy sources, which are not adjustable on demand. These mainly are wind and solar power. (Lund et al., 2015)

The amount of power generated annually has been constant in recent years. The amount of produced hydropower, however, has varied year to year. Changes occur due to the amount of available water in the dams, which is result of rainfall. Lack of hydropower is compensated with more fossil fuel-based power plants. (Kostama, Takala & Tuomo, 2019)

Wind power has risen to be a notable source of energy in recent years in Finland. According to Tuulivoimayhdistys (2019) and VTT (2015), production of wind power has increased from 261 GWh in year 2008 to 5857GWh in year 2018. The increasing amount of production is due to big investments driven by the rapid decline of building costs of power plants. Technology has been constantly improving at the same time. This trend is predicted to continue and plans have been made to increase wind power (Tuulivoimayhdistys, 2019).

Finland has different weather conditions compared to many other countries due to geographic location. Northern countries such as Finland have less irradiation compared to the southern ones. This results in photovoltaics (PV) located in the north generate less power (Fraunhofer Institute, 2019). Table 1 illustrates different yearly irradiation levels, which are measured by kWh/ m^2, in Finland, Germany and Italy. Irradiation is measured on the horizontal level. In Finland, irradiation varies between 980 kWh/ m^2 in Helsinki (south) and 790 kWh/ m^2 in Sodankylä (north) (Motiva, 2018). Southern parts of Finland are notably close to irradiation in northern Germany (around 1000 kWh/ m^2) (Motiva, 2018).

Energy pay-back time illustrates how much time it takes to produce energy that was invested to produce complete PV including tracker, inverter, cables etc. In table 1 PV technology is multicrystalline silicon PV, since it is the most used technology for PVs. The table also presents annual production of Finland, Germany and Italy and their share of the country's total power generation. As seen, Germany and Italy have high shares of PV production with a total of 7% of whole power generation. (Fraunhofer Institute, 2019)

Country	Finland	Germany	Italy
Irradiation (kWh/ m^2/a)	790–980 kWh/ m^2/a	1000–1500 kWh/ m^2/a	(Sicily) 1794–1925 kWh/ m^2/a
Energy pay-back	>2.1 years	<2.1 years	1.2 years

time of multicrystalline silicon PV rooftop systems			
Country's annual solar power production	0.134 TWh (2018)	38.4 TWh (2017)	22.9 TWh (2018)
Share of annual power consumption	0.2 %	7 %	7 %

Table 1. Solar irradiation and pay-back time comparison (modified from Fraunhofer Institute, 2019; Motiva, 2018 and IEA, 2018).

From a worldwide perspective, PVs have become one of the most installed renewable energy sources. Similar to wind production, PV's prices have decreased in recent years, to around 73% since year 2010. Globally, new installed PVs in year 2018 was 109 gigawatts (GW) compared to wind power with an installed capacity of 51 GW (IRENA, 2019a).

The downside of both wind and solar power is unpredictability and volatile production. Both of these are weather dependent. In Finland, most PV panels' production comes during summer, spring and autumn; production is normally lower during winter. Wind power plants can produce electricity all year. The VRE are not predictable as thermal power stations, (nuclear, coal, gas, biomass) where power can be produced constantly.

Notable share (23%) of the power supply is from net imports. Finland has transmission connections to Sweden with two links and single transmission lines between Norway, Russia and Estonia. These connections enable trading between countries and limit need to use more expensive energy sources to produce electricity. On the other hand, the transmission lines supply load following power to the regions, which require it.

The current transmission lines are in heavy use, especially lines between Finland and Sweden where majority of the power flows to Finland. In 2018, Finland imported

13,4TWh from Sweden, which was 61.4% of the transmission lines' capacity (Nord Pool 2019e). To be noted, this calculation is based on net imports and some amount of power has flown from Finland to Sweden. Therefore the actual transmission lines' capacity are even higher. This results that notable amount of time during the year, transmission lines physical capacities are at the limit and all required power can't flow to Finland. This increases total electricity prices in Finland, since power must be generated in Finland or export elsewhere.

Addition to Sweden, Finland buys large amounts of power from Russia. More precisely 7,8TWh in year 2018 (Nord Pool 2019e). Transmission connection to Norway don't play as major role as the connections to Russia and Sweden. Net import from Norway to Finland was 0,12TWh in year 2018 (Nord Pool 2019e). Transmission line to Estonia is only connection where annually Finland exports more power than imports. Total exports to Estonia were 1,5TWh in year 2018 (Nord Pool 2019e).

2.1.2 Consumption

Electricity consumption of Finland was 86 TWh in year 2018. Consumption between different sectors are presented in Figure 4. Almost half (47.5%) of electricity is consumed by industry and construction sectors (Fig. 4). The next largest electricity consumers are households and agriculture. The largest individual electricity-consuming business sector in Finland is the forest industry with an electricity consumption of 20 TWh, while total industry and construction electricity consumption were 41 TWh (Hakala, 2019).

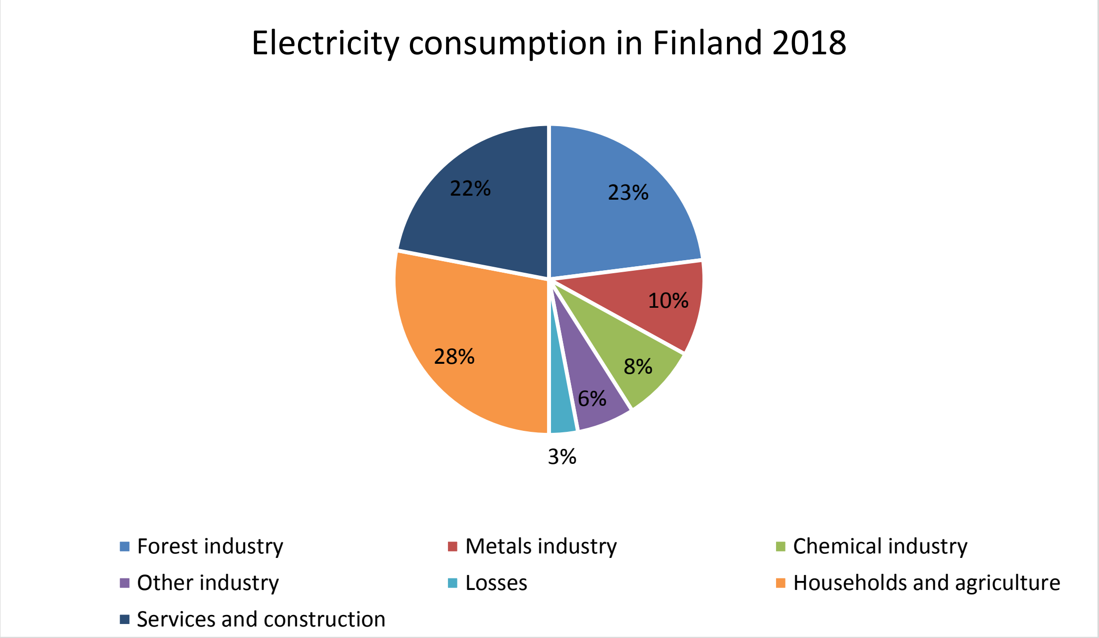

Figure 4. Total consumption of electricity 2018 in Finland (retell from Hakala, 2019).

Households use most of their electricity on space heating. This was 68% of all electricity consumption. The second largest was water heating with a 15% share of electricity consumption. The remaining 17 % included other electrical equipment, saunas, lighting and cooking. (Statistics Finland, 2019)

2.1.3 Fluctuation of consumption and volatile production – a challenge for power systems

An increasing amount of VRE challenges power generation and delivery when power is needed. VRE, such as wind and solar production are difficult to forecast and production is volatile. During less windy and cloudy weather, producing the needed amount of electricity with PVs or wind turbines is a challenge. Demand for power fluctuates within days and between seasons. Figure 5 illustrates wind power forecast and power demand in July 2019. Even though demand fluctuates, there are regular cycles. Demand increases in the morning until around midday and decreases towards night. Lower peaks usually occur during weekends; 6–7.7, 13–14.7, 20–21.7 and 27–28.7 were the Saturdays and Sundays of July 2019.

Like stated wind power production is not constant. In Figure 5, July's wind power production's forecast is illustrated with blue colour. When comparing the generated wind power to demand we can see that, the wind power isn't large share of power on normal days. July's average wind power generation was 5 % of total demand. However some notable peaks are viewable, especially on 1.7 and 31.7. Both of these wind power peaks occurred during nighttime, when the overall demand was lower. These resulted that wind power was 16-18 % of total power demand. Low points occurred during July. On the lowest point of the month, wind power generated less than one percent of total power demand.

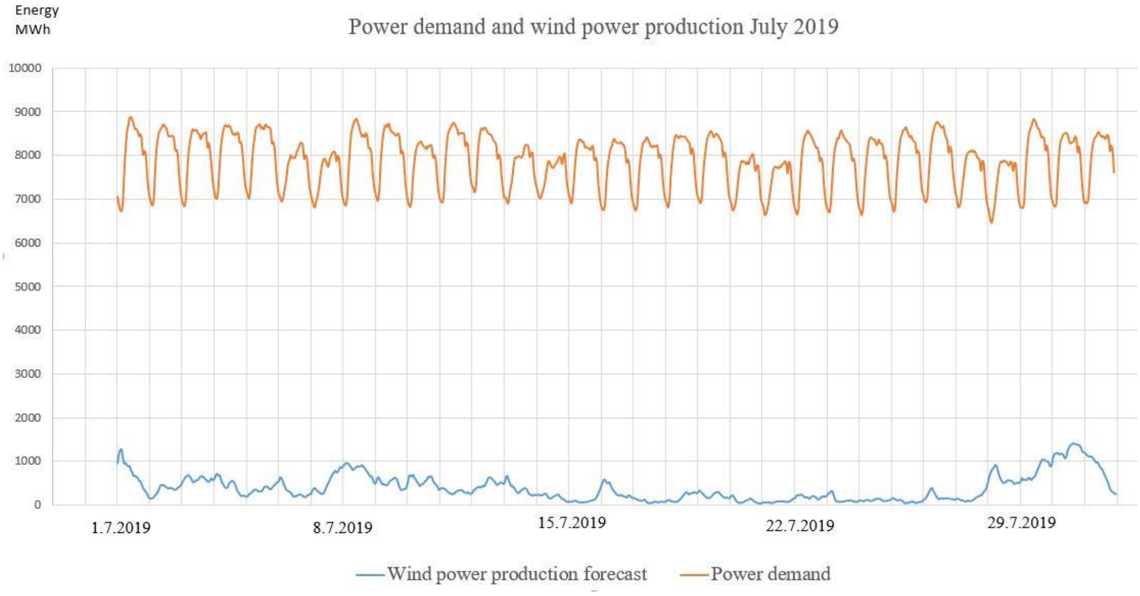

Figure 5. Wind power forecast and power demand July 2019 (modified from Fingrid, 2019d).

Due to the rapid and large-scale changes in wind power generation, measures to ensure system balance are essential. These can be producing more load following power, purchase power from other countries or adjust demand. When supply of VRE increases, it is clear that lack of power needs to be compensated with producing power in other ways or by adjusting the demand side.

In the long term, consumption fluctuation happens between seasons. In Finland, consumption increases during colder periods, since electricity is used more for heating. Flexibility is needed to respond to these fluctuations in both production and consumption of electricity . Since production's flexibility decreases when more VRE are implemented, more flexibility is needed on the demand side.

2.1.4 Assessing cost of power generation

Power generation costs vary depending on the used source of energy and different cost structures. In recent years, prices of renewable power generation have decreased and at the moment they are competing with fossil fuels, even without subsidies (Fig. 6). Cost structure of renewables such as wind and solar power differs from thermal-based power. Wind and solar require high capital investments to set up production, whereas thermal power production requires fuel for power generation. Due to the difference of cost structure, estimating the price of power is difficult without a model. (IRENA, 2019c)

Levelized cost of energy (LCOE) is a way to estimate the cost of power production over a predicted lifetime. LCOE includes the largest costs such as capital costs, fuel costs, fixed and variable maintenance and operation costs. Estimation includes also utilization rate for each power plant. LCOE eases decision-making concerning which power generations are most economically feasible for investment. Like all investment decisions, multiple different country and region-specific factors affect which is the most suitable source of power. Thus, there is no single, best solution for every country. (IRENA, 2019c)

One part crucial for cost structure of LCOE is discounted cash flow analysis (DCF). With this analysis, discount rate/weighted value of capital (WACC) can be calculated. DCF is calculated because money has more value now than it will have in the future and investors expect profit from investment. RES are highly capital-intensive which results in discount rate being a major factor in LCOE. (IRENA 2019c) In addition to RES, nuclear energy is extremely capital-intensive. Large power plants require investments that pay back during a 60-year lifetime. With long payback times and large capital investments, projects have risk of failure, due to changes in fuel costs and improvements in technology, to name a few.

The level of discount rate normally varies between 3–10 %. In Figure 6, the discount rate of RES are 7.5% in OECD countries and China and 10 % for the rest of the world. Nuclear is presented with a 7 % discount rate and its statistics are from year 2015. The importance of choosing the right discount rate highlights its effect on nuclear. With a discount rate of 3 %, nuclear is cheaper than a combined cycle gas turbine or coal. With 7 % they are about even and at a 10 % discount rate, nuclear is the most expensive option with almost double the LCOE compared to its 3 %. (IRENA, 2019c; IEA & NEA, 2015)

Figure 6 presents costs of different power generation technologies in a utility scale globally in years 2010 and 2018. Yellow dashed lines illustrates the LCOE for fossil fuel-based power generation. Costs are presented without financial support. As seen in the figure, most of the renewable power production is compatible with fossil fuel sources. The largest LCOE drop can be seen in PV and concentrated solar power (CSP). Even though CSP is not completely in the price range of fossil fuels, the LCOE trend is falling. Wind power, both offshore and onshore, have declined rapidly 20% and 35% respectively from year 2010. (IRENA, 2019c)

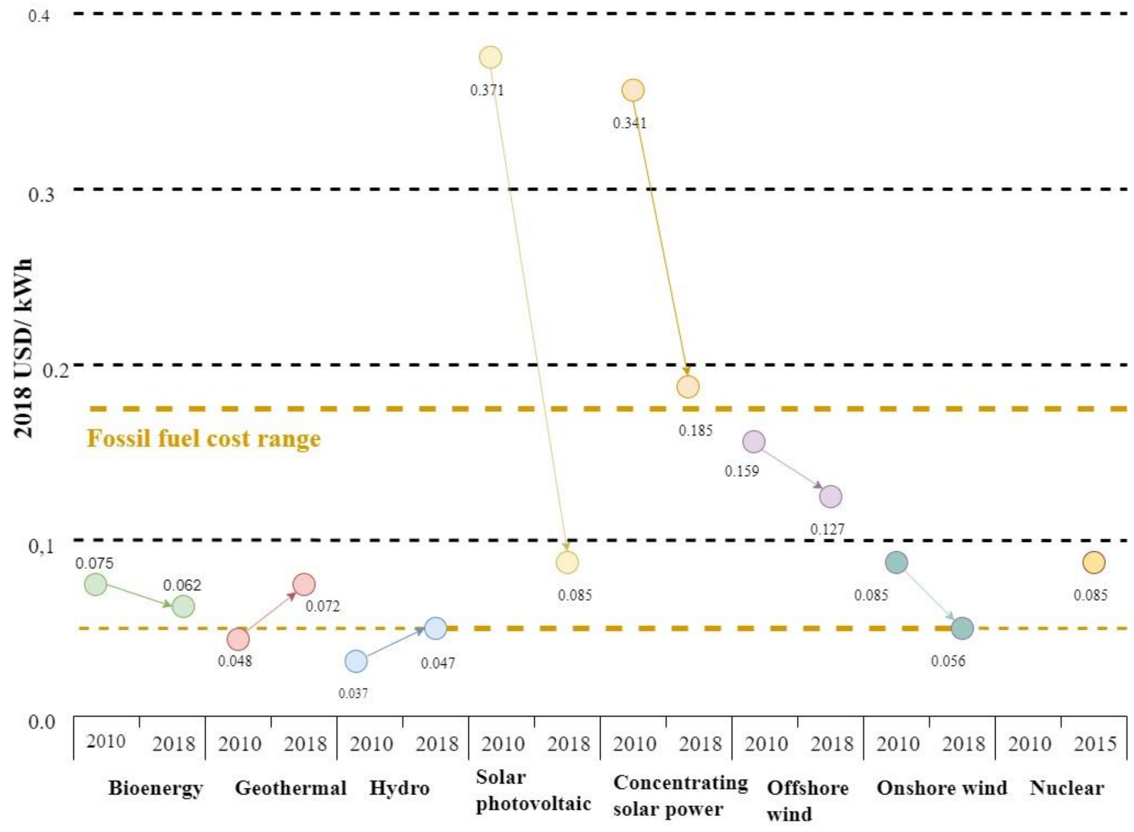

Figure 6. Global LCOE of utility-scale renewables and nuclear power generation technologies, 2010–2018 (modified from IRENA, 2019c).

The price of hydropower has increased since year 2010. This has resulted from different factors. The best locations have already been taken earlier to produce hydropower, thus more difficult, rural and far away locations remain. This requires more infrastructure and therefore higher LCOE. Another reason for higher LCOE prices result from a higher number of hydropower projects in Asia excluding China, Japan and India. Building hydropower plants there has been more expensive than previous projects in general. Geothermal power plants have increased LCOE since 2010. The amount of new geothermal power plants is low compared to other RES. This leads to a situation where LCOE relies heavily on specific projects and their individual characteristics. Installed geothermal capacity was 500 MW compared installed PV's capacity of 109 000MW in 2018. (IRENA, 2019c)

2.1.5 Other methods to estimate investment's feasibility

LCOE is not the only way to estimate financial success of investment. The energy information administration of the United States (EIA) has introduced a method to estimate the value of investment in the grid. This method is levelized avoided cost of energy (LACE). Unlike LCOE, LACE estimates value from the perspective of whole grid. LCOE can be misleading if comparing just costs of power generation technologies and not accounting for other important factors such as when power is produced. LACE is more complex compared to LCOE but offers more factors to estimate investment. Similar to LCOE, cost estimations are throughout the lifetime of a power plant. (EIA, 2019)

LACE compares potential revenues of a candidate project. Due to the fluctuation of the power sources of solar and wind may or may not require load following power plants to produce power when needed. LACE can be used for estimation if these load following power plants are needed at all and therefore these costs can be avoided. For example, when a region or country plan to invest in renewable energy, LACE can help deciding between wind and solar. The LCOE of these power generations might be the same in a specific area, but the value added to the grid differs. PVs generate more power during daytime, when consumption is typically higher. Wind power generation is not related to time of day and turbines can generate power during the night as well. Despite that power is needed at all times of day, normally the highest price and power demand is during daytime. Choosing PVs to generate power might result in avoiding investments in load following power plants that are required when choosing wind power. (EIA, 2019)

In Finland, wind power is by far a larger source of power than solar. Therefore, effects of adding more wind power generation are more relevant. Wind power impacts systems operational security as well as reliability and efficiency. Smaller regions such as countries located on islands and countries that have insufficient interconnections with other countries have a larger negative impact from large wind production. Larger connected areas can buy balancing power from other countries rather inexpensively but countries such as Ireland have higher balancing and reserve costs than countries in continental Europe. Denmark, which has high wind penetration (percentage of total production) had balancing costs around 1.4–2.6 €/MWh in 2011 with a wind penetration of 24% (currently 41%). This supports the estimation that the price of balancing power is somewhere between 1–4 €/MWh with a wind penetration of 20 %. In Finland, balancing costs are estimated to be 0.2–1 €/MWh when wind power penetration is between 1–10% (currently 7%). (Holttinen et al., 2011)

In addition to balancing costs and increasing need for reserve capacity, transmission lines and the grid needs reinforcement, which causes additional investment costs. Grid reinforcement depends on wind penetration level and increasing this amount increases investments needed on the grid. These costs vary but most costs are around 100–270 €/kW. (Holttinen et al., 2011)

2.2 Power system balance

Managing the grid is a complex task. This is a result of electricity's characteristics. Demand and supply must be constantly even in the electricity system. If this balance for some reason deviates from a set target, problems occur for customers. Machines will not work properly and in the worst case, they can even break. If the balance is far from established targets, large-scale blackouts might occur (Fingrid, 2019a).

Derivatives from the nominal frequency of the power system indicate imbalance of supply and demand. Frequency indicates balance between production and consumption of the grid. When they are in balance, the grid has a steady 50 Hz frequency. When demand is higher than supply, frequency drops below 50 Hz and when supply exceeds demand, frequency rises over 50 Hz (Fingrid, 2019c).

When frequency starts to change, the transmission system operator (TSO) must take actions to correct frequency. These methods are presented in Figure 7. In Finland, the

TSO is responsible for keeping the frequency between 49.9Hz and 50.1Hz (Fingrid, 2019c).

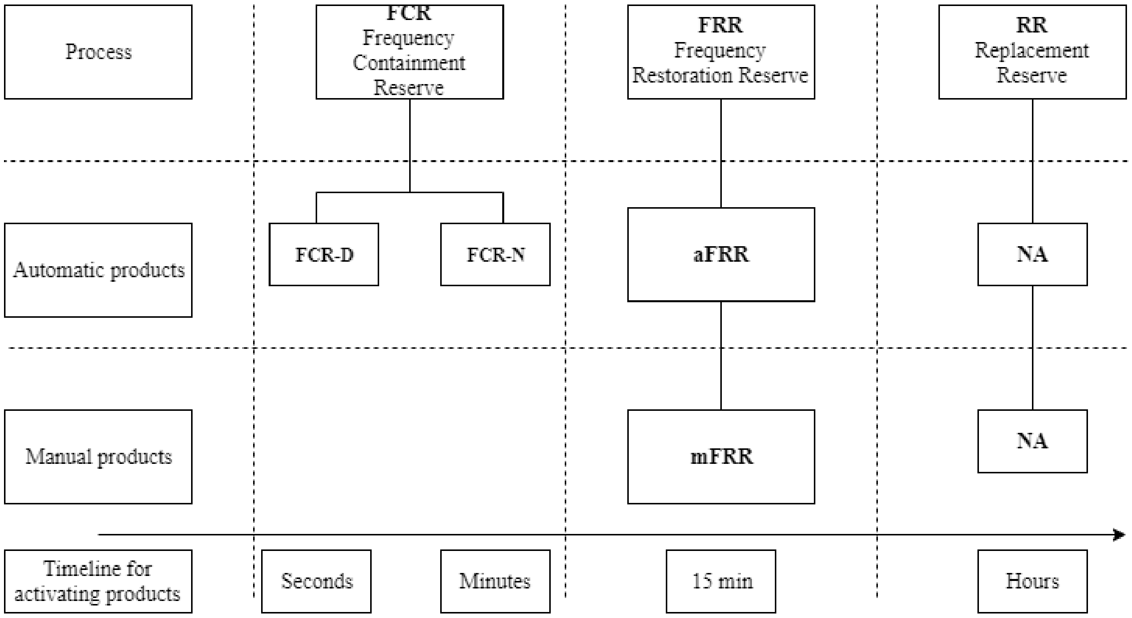

Figure 7. Frequency balancing methods (modified from Fingrid, 2019c).

The most common balancing method is Frequency Containment Reserve for Normal operation (FCR-N), which is operated automatically. FCR-N operates automatically and handles small frequency fluctuations. To ensure electricity supply in case of disturbances, such as when a large power plant stops working, frequency containment reserve for disturbances (FCR-D) is used. FCR-D can withstand a rare power outage of a power plant, without dropping the frequency more than 0.5 Hz. Frequency restoration reserve (FRR) restores balance in such a way, that FCRs are available for coming disruptions. Replacement reserve (RR) is used after disturbances to free FRRs for other disturbances and in cases when FRR is not enough. RRs are power plants, that are switched on when needed. (Fingrid, 2019c)

TSO itself does not control these loads, but buys balancing services from companies. When balancing is needed, TSO sends a signal to these companies to increase or lower production. Companies taking part in balancing services receive payments from TSO. Companies are paid by the amount these reserves are used. Not all companies can participate and there are technical requirements for participating in balancing services. (Fingrid, 2019b)

Like stated before, the electric power system in Finland is a combination of power plants, a nation-wide transmission grid, regional networks, distribution networks and electricity consumers. Currently, electricity flows mainly one-way: from electricity producer to consumer via grid and networks. Finland is also part of the inter-Nordic power system. Countries in this system are Finland, Sweden, Norway and Eastern Denmark. The inter-Nordic system is connected to the electricity system of Continental Europe. Finland has connections to the electricity systems of Russia and Estonia. Connection ensures that the required amount of power is available when needed. (Fingrid, 2019c)

Fingrid is a Finnish TSO company, whose responsible for ensuring a functioning power transmission grid in Finland. Fingrid's responsibility is to ensure that security of the system, electricity usage is balanced and possible disturbances are solved rapidly. The transmission grid consists of 400kV, 220kv and 110kV transmission lines and multiple substations. The largest power plants, industrial buildings, are directly connected to the transmission grid. Smaller consumers and producers are connected to regional and distribution networks. (Fingrid, 2019c)

Fingrid has planned to invest 1200 million euros to upgrade the transmission grid between 2015 and 2025. These large investments are done in order to enable large transition due to shifting towards more RES, two new nuclear power plants and new geographical locations of power plants. Decarbonizing the power system increases the amount of fluctuating wind power, causing challenges for the whole system including the grid.

The transmission grid plays the important role of the electricity system and transition to RES requires changes in the transmission grid. Upgrades need to consider consumer consumption. Power demand is expected to increase in the future and the grid needs to support that. This requires reinforcing the current network as well as creating new transmission lines. (Fingrid 2019c)

Fingrid aims to be more customer centric by introducing Datahub in the near future. Datahub is a centralized data storage for retail market customers. Centralizing customers' data increases speed of data flow. Before Datahub, data has been stored by individual retailers in their own locations. Datahub aim is to increase customer satisfaction and simplify the current process of changing retailers and making new electricity contracts. (Fingrid, 2019c)

2.3 Power markets in Nordic countries

Power markets are the most economical way to balance supply and demand in markets. Markets guide both electricity suppliers' production decisions and electricity users' consumption decisions. Similar for the other products such as oil and metals, power (MWh) is viewed as a commodity. Based on supply and demand, prices in power market fluctuate. TSOs such as Fingrid act as enablers for markets, allowing electricity to be traded and delivered from producer to consumer. There are different markets, to trade power. Time scale of these markets vary from years to minutes (see Fig. 9). (Fingrid, 2019b)

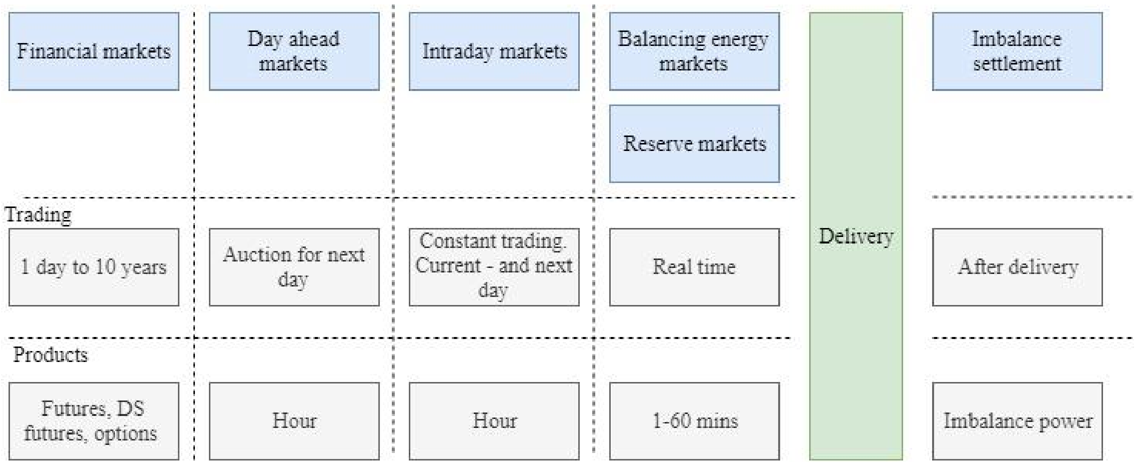

Figure 8. Different power markets (modified from Fingrid, 2019b).

2.3.1 NASDAQ Commodities

NASDAQ Commodities is a market place where power derivatives are traded. These derivatives are Futures, Options, Deferred settlement futures (DS futures) and Electricity price area differential (EPAD) contracts. Derivate markets are for market participants who try to mitigate risks of increasing price of power. Participants can buy power up to 10 years in advance. Reasons for purchasing power early might be expectation of a price increase in the future. (Fingrid, 2019b and Nasdaq, 2019)

2.3.2 Nord Pool day-ahead

The Nord Pool is a power market in Europe including 14 countries (Austria, Belgium, Denmark, Estonia, Finland, France, Germany, Great Britain, Latvia, Lithuania, Luxembourg, the Netherlands, Poland and Sweden). Over 95% of power consumed in Nordic and Baltic countries is traded in the Nord Pool (Nord Pool, 2019a). Nord Pool is owned by the Nordic and Baltic transmission system operators. These operators are Fingrid Oy (Finland), Statnett SF (Norway), Svenska kraftnät (Sweden), Energinet.dk (Denmark), Elering (Estonia), Litgrid (Lithuania) and Augstsprieguma tikls (AST) (Latvia). Nord Pool's customers are both electricity producers and consumers. Nord Pool allows consumers to trade electricity between each other. Nord Pool is divided into two parts: day-ahead and intraday markets. (Nord Pool, 2019a)

In day-ahead markets, customers trade power for the following day for each given hour based on their needs. Power is sold in an auction that closes at 12:00 CET every day (Nord Pool, 2019b). An algorithm calculates price based on supply and demand of energy and available transmission capacity. Based on calculations, the price for the next day is set. (Nord Pool, 2019b) Calculations disregard congestion of power flow (Nord Pool, 2019b).

Day-ahead markets are divided into several bidding areas. A local TSO decides how many bidding areas a country has. The TSO can change the amount of bidding areas if it is more beneficial. Finland and Baltic countries have only one bidding area each. Norway has 5, Sweden 4 and Denmark 2 bidding areas (Nord Pool, 2019c). In theory, price will be the same for every bidding area, but in reality, congestion occurs due to the lack of transmission capacity. These bottlenecks results in a situation where power cannot be transmitted smoothly. Bottlenecks will result in price differences between areas. (Fingrid, 2019; Nord Pool, 2019c) These prices are called area prices. Based on market principles, power flows from low price areas to high price areas. The benefit of bidding areas is to make visible the transmission system's constraints. Congestion results in more expensive power generation and increased total spot prices in Finland. Figure 10 illustrates the equilibrium between supply and demand in surplus area. (Nord Pool, 2019b)

Transmission lines between the areas level area prices. Figures 9 and 10 illustrate how transmission between areas affect point where demand meets supply. In fig. 9 price of power is low, due surplus power generation. When there is no congestion, surplus power flows towards area where price of power is higher. This results change of point of equilibrium point towards higher price. This price point is same for the both of the areas, if there is no congestion. (Nord pool, 2019b)

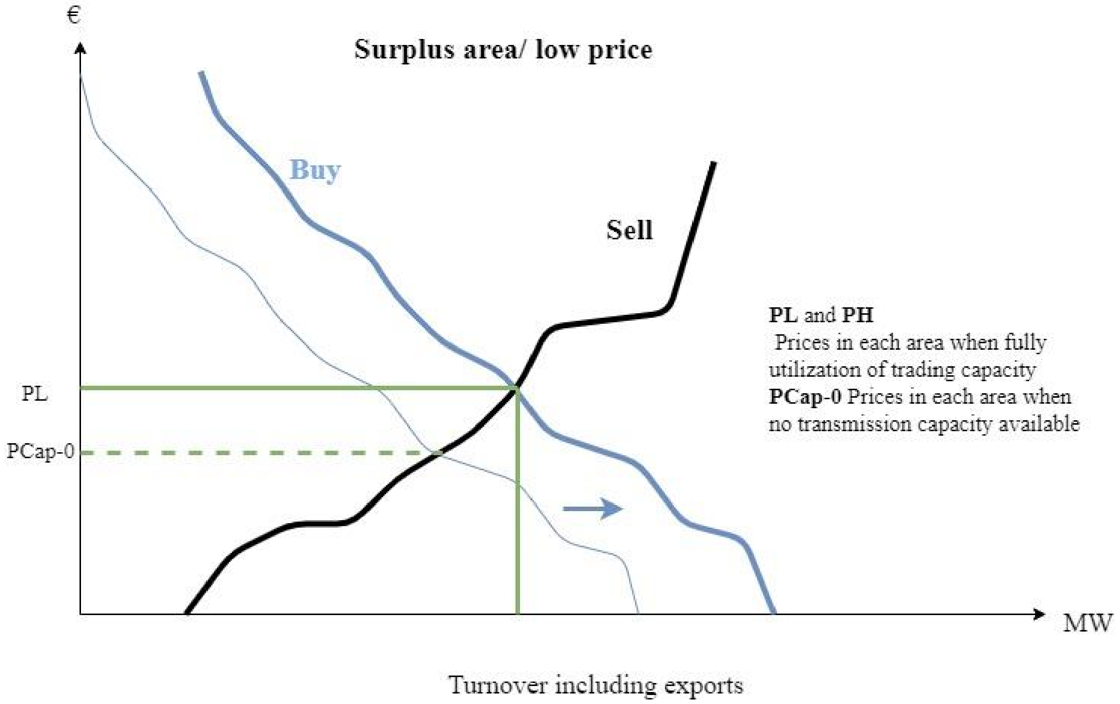

Figure 9. Equilibrium of supply and demand in surplus area/ low price (modified from Nord pool 2019)

Equilibrium point shifts in deficit area as well. Figure 10. illustrates situation, from deficit area’s point of view. Point of equilibrium shifts towards cheaper point, due available cheaper power from other price areas. Addition to cheaper prices, total power traded in the area increases. PCap-o is the point where trading occurs if there is no power transmission. PL is new price point (Nord pool, 2019b).

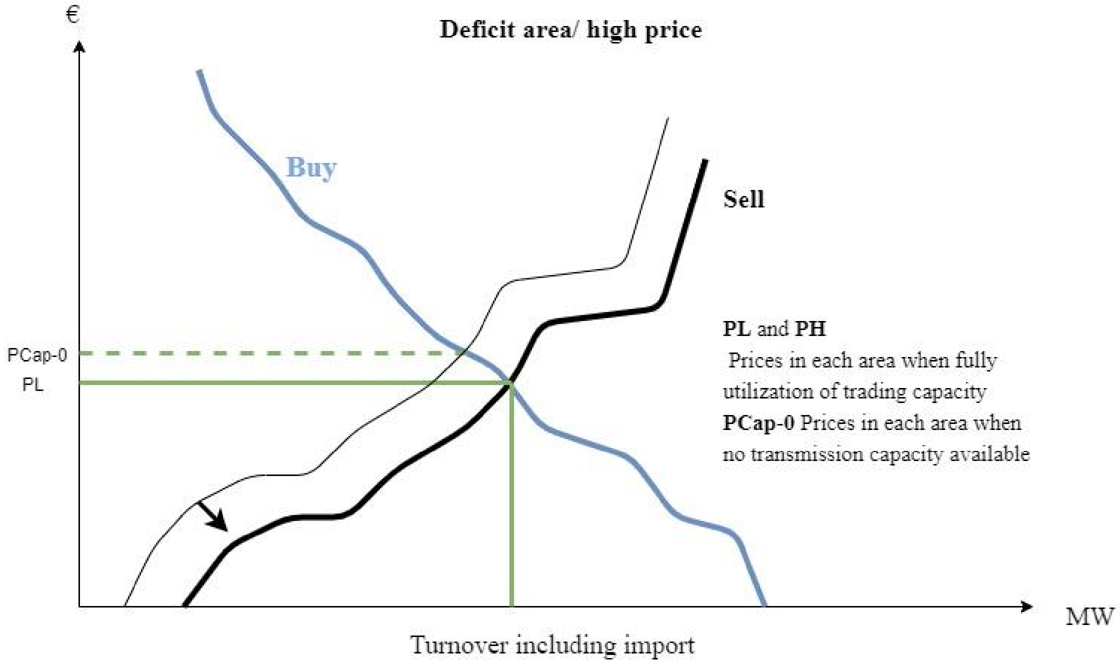

Figure 10. Equilibrium of supply and demand in deficit area/ high price (modified from Nord Pool, 2019)

The day-ahead market has multiple options participating traders. The following lists four types of orders:

- Single hourly orders
- Block orders
- Exclusive groups
- Flexi orders

From these options, single hour orders form the largest share volume of trades. In a single hour order, a participant chooses what price it is willing to pay for each hour of the day. Price can be set between -500 and 3000€ per MWh. Participants can also sell power if they want to. For example, a participant can decide to sell when its consumption is lower or if the prices rise high and the participant gains profit by selling the power. (Nord Pool, 2019d)

Block orders, exclusive groups and flexi orders are conditional order types. These orders form hourly blocks of consecutive hours. Block orders take into account other trades of day. For example, a power supplier’s production ramp up might be expensive, but maintaining production costs are low. In this case, a participant can set a higher price for the first power generation hour and lower the price for the following hours. This way, a power producer can ensure continuity of production and desired revenue. (Nord Pool, 2019d)

2.3.3 Intraday market

Power supply and demand are not always what was predicted in day-ahead markets. Power suppliers might face unseen problems and their power supply cannot reach the amount which was promised in the day-ahead market. Problems might occur on the demand side as well. A large industrial plant might face problems and their demand for electricity may differ from what they bought.

The purpose of the intraday market is to solve these setbacks by allowing participants to trade close to delivery hours (Fingrid, 2019). Nord Pool operates the intraday market, which is similar to the day-ahead market area. The intraday market opens at 14:00 CET for participants to trade next day products and closes one hour before delivery. The intraday market allows participants to trade 15-, 30- and 60-minute products. Participants have the possibility to make similar block orders as in the day-ahead market. (Nord Pool, 2019c)

The intraday market is an important tool to balance the electricity market close to real time. An increasing share of wind and solar power will increase the need for intraday markets even more. Production of wind and solar are stochastic and their production relies on weather forecasts. Forecasts always have an error margin, which increases the importance of intraday market. (Nord Pool, 2019d)

2.3.4 Balancing energy and balancing capacity markets

Nordic TSOs maintain a balancing energy market. Balancing energy markets offer balancing methods for the grid. In balancing energy markets companies can make an offer to increase or decrease their power capacity if needed. Companies can make bids to the local TSO. In Finland, the local TSO, Fingrid, takes offers from these companies 45 minutes before usage. This bidding can be either to increase or decrease power usage. Companies are required to activate adjustments to power capacity within 15 minutes. Minimum capacity is 5MW for electronic activation and 10MW otherwise. Fingrid chooses a balancing-service provider based on prices, which companies have submitted. However, the Nord Pool price area works as a minimum. The price of increasing production cannot be higher than the local Nord Pool price and the price of decreasing production cannot be lower than the Nord Pool price. (Fingrid, 2019c)

2.4 Demand-side management

Currently, the VRE power production fluctuates, and it will do so as well in the future. Current balancing methods, such as peak load following power are not optimal way to increase flexibility of the electric power system. Peak load power plants have low utilization rate and their power generation costs are high. Due to the special nature of electricity, research to find flexibility has been conducted on the demand side as well, hence the term demand-side management (DSM). Point of DSM is influence power consumption in such a way that they are more efficient and beneficial for the whole power system. Electricity price is volatile and large price differences are common. To adjust demand, large cost savings are possible. This limits the need of expensive production methods, such as peak-load power plants. (Behrangrad, 2015)

Previously, changes on demand, peaks or valleys, have been levelled by adjusting electricity production. This has been mainly done by increasing hydro or thermal power production (Järventausta et al., 2015) or by buying electricity from other Nordic countries and lowering consumption of large industrial factories (Energiateollisuus 2019). This model is about to face a large-scale transition in a rather short future. The transition occurs due to the shifting from a fossil fuels-based energy system to RES. The downside of wind and solar is that they cannot produce electricity as predictively as fossil fuels. Windfarms and PV produce electricity when sunlight is available or wind blows, not necessarily when demand is high. The power system requires flexibility and since production is shifting towards a decentralized production, flexibility needs to be found elsewhere. (Järventausta et al., 2015)

Transformation of energy sources leads to an increasing need to balance the demand side more effectively. In short, the purpose of Demand response (DR) is to lower the highest demand peaks and adjust electricity consumption to times when overall consumption is lower.

2.4.1 Different types of DSM methods

Palensky & Dietrich (2011) divides DSM into five subcategories: energy efficiency (EE), time of use (TOU), market DR, physical DR and spinning reserve (SR). In Figure 11, *impact on process quality* is on the vertical axis and *time* is on the horizontal axis. The impact on process quality describes how actions effect overall system balance. The faster the actions can be made, the greater is its impact on overall system balance (Palensky & Dietrich, 2011).

However, DSM can be categorized in other ways as well. Behrangrad (2015) simplifies DSM into two categories: EE and DR. In Behrangrad's (2015) categorization, DR includes TOU and SR. In this thesis DSM is discussed way that Palensky & Dietrich (2011) defined it. Larger categorization helps to understand DSM in more detail. Figure 11 illustrates these different DSM categories and features.

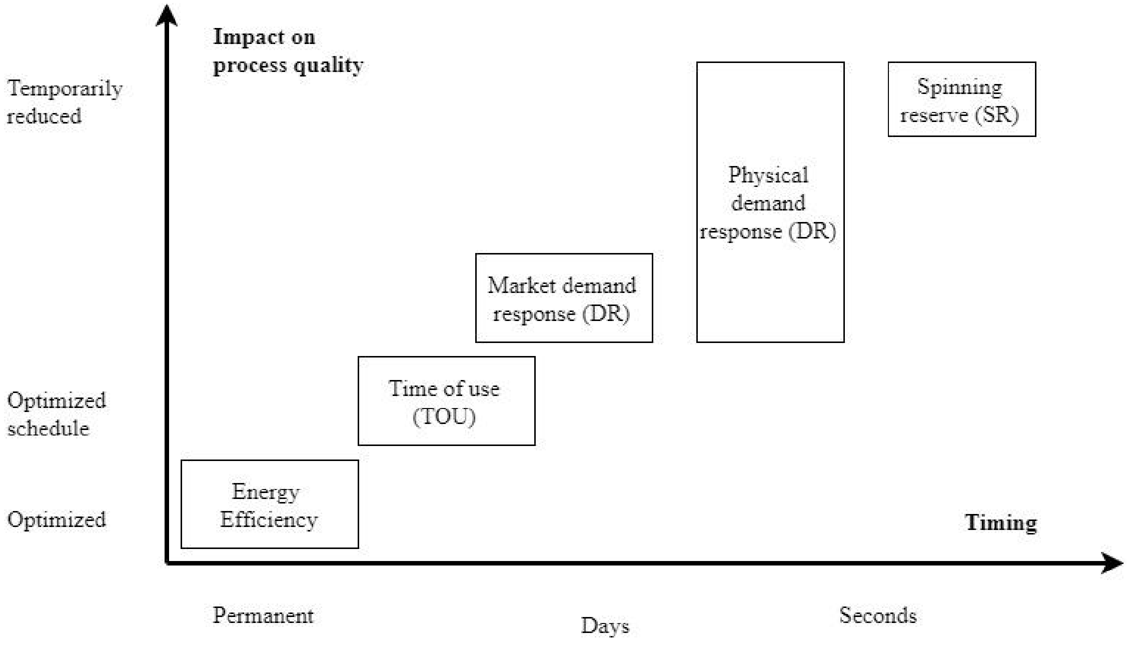

Figure 11. Categories of DSM (modified from Palensky & Dietrich, 2011).

Energy efficiency is located on the bottom left corner in Figure 11. This does not have a fast impact on DSM, but the effects are permanent. Energy efficiency can be applied in households, buildings and the industrial sector to optimize energy usage. Small problems might be overlooked and users might not understand the impact on total energy usage. Collecting data, analysing it and comparing previous usage can lead to lower energy usage. Industrial plants can also benchmark energy usage and processes to other similar types of plants to find better solutions. (Palensky & Dietrich, 2011)

Demand response (DR) is typically divided into two categories: physical and market DR. DR aims to stabilize the grid and reduce system costs. Market DR is activated with price signals from markets. Physical DR is used to balance grid based on emergency signals from the TSO. (Palensky & Dietrich, 2011)

Demand shifting is method to direct demand from a period of time when demand is high to a period of time when overall electricity demand is lower. This reduces operational costs, since peak load power plants are not needed. Customers can shift from peak hours to lower consumption hours such as night time. Integration of smart meters and internet of things (IoT) helps this process and reduces work needed to be done to manually control consumption. Households' HVAC (heat, ventilation, and air condition) systems can be automated to use electricity when demand is lower. Heating, for example, can be automated in such a way that it heats more during night time and the system lowers consumption during peak hours. This way, heat can be viewed as one sort of storing method, where space is heated over the actual need, when the price of power is low. When the price of power increases, power usage is decreased and space cools down. (Palensky & Dietrich, 2011)

Spinning reserve (SR) supports electricity providers to balance the grid. Spinning reserve can increase or decrease load fast. Activation occurs based on signals from the grid (Palensky & Dietrich, 2011).

2.4.2 Aggregator

DSM and DR have previously focused on large electricity consumers in industries. Unused potential lays in commercial and residential sectors since they roughly consume 50 % of electricity in Finland (Hakala, 2019). Normally, residential or commercial buildings are too small to participate in DR themselves or their individual contribution to DR is too low. This creates a need for a service provider who can help them to participate in DR by consolidating customers' flexible resources and providing it to the market. Ikäheimo, Evens, & Kärkkäinen, (2010) discuss *aggregators*, companies who offer services to customers to participate in DR. They define aggregator as the following: *"An aggregator is a company who acts as an intermediator between electricity end-users, who provide distributed energy resources, and those power system participants who wish to exploit these services".* Aggregator therefore shifts consumers from passive to active part of electric power system and creates value for them. This value is typically in form of financial gains. (Ikäheimo et al., 2010)

Aggregators can be categories into two groups: demand aggregators and generation aggregators. Demand aggregation bundles groups of customers and controls their loads. The latter one controls customers' power generation and offers it to the market. Generation demand can be described as a virtual power plant (VPP). An aggregator can be a hybrid of both of these types. (Ikäheimo et al., 2010)

Another way to categorize aggregators is based on their business models. These business models are retail-aggregator, balance responsible party (BRP), retailer's service company or independent aggregator. (Ikäheimo et al., 2010)

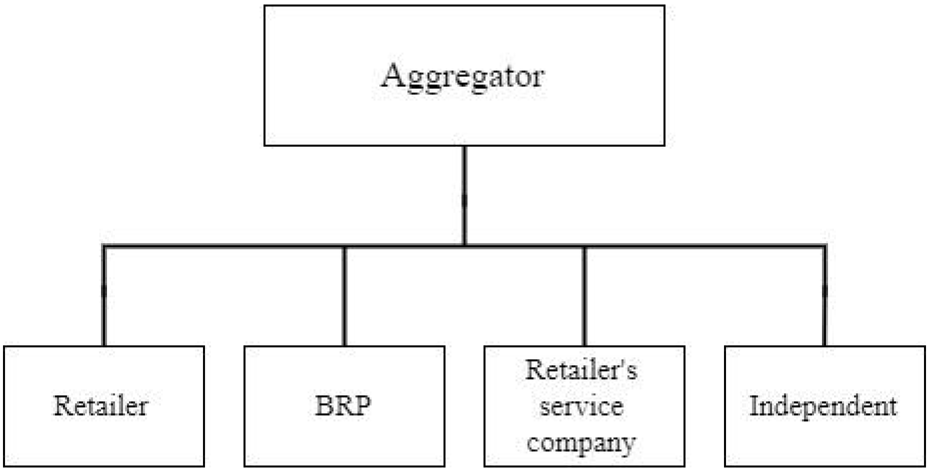

Figure 12. Aggregator business models classified according to the aggregator's identity (modified from Ikäheimo et al., 2010).

Not all residential customers can offer DR, since their consumption is too small to gain flexibility and add value to the system. This, however, does not diminish potential that truly exists in residential and commercial sectors. The commercial sector includes shopping centres, supermarkets, schools, universities, office buildings, etc. An aggregator can focus on small industrial companies, that do not operate in a spot market themselves. Different kinds of aggregators can form specific business models to satisfy a certain customer sector. By focusing on a specific customer sector, a company can increase service quality to the customer. (Ikäheimo et al., 2010) Companies, which have previously operated in different business areas, are interested to aggregate customer loads. One example is Google, which offers Nest smart home solution. Addition smart control of home appliances, air condition and heating can be adjusted remotely to participate DR. Based on participation, customers are compensated with rewards. (Google, 2019)

Nolan & O'Malley (2015) conducted study on barriers of DR. Their focus of the study was consumers' needs, motivation and preferences. According to Nolan & O'Malley (2015), consumers were more interested by financial benefits rather than ecological reasons. Aggregator therefore needs to collect more data to discover customer motivations and offer service to meet these needs. Ruokamo et al. (2018) conducted similar study in Finland. Vardakas, Zorba, & Verikoukis (2015) did study of pricing DSM. They found that in some cases participating DR penalized consumers for participating DR.

Participating in DR programmes requires monitoring of electricity usage in close to real time. This requires implementation of Automated Meter Reading (AMR) which enables monitoring energy usage on an hourly basis. Finland is a forerunner in implementing AMRs and in 2016 99.6% of low-voltage users had AMR. (Pöyry, 2017)

Currently, AMR allows consumers to use cheaper electricity, such as night-rate electricity in water boilers. This naturally requires that an electricity contract has different prices for night and daytime. Even though AMR allows monitoring consumption, it is not sufficient to enable large-scale DR. More developed ICT-systems are needed in order to take DR into use. ICT-infrastructure allows communication between DR participants and controlling devices. With automation systems, loads can be controlled remotely. (Järventausta et al., 2015)

New generation AMR is estimated to be implemented in the next decade around 2022–2028. A new type of AMR will be a smart device and it will enable data collection in real time or at least close to it. New AMR allows new types of products, services and business models to emerge. However, a new generation of AMR requires large capital investments to implement them and their lifecycle is rather short compared to older ones. Therefore, defining requirements and planning the implementation is important to ensure value for the customers. (Pöyry, 2017)

Taking part in DR requires a trade-off for the consumer. This trade-off is loss of sovereignty to control energy use. An aggregator can take control of the energy load directly, based on volume or price. In direct load control, the aggregator takes control of the largest electricity consumption sources, e.g. electric heating, water boilers and electric vehicle charging. In volume-based control the aggregator limits total power supplied to the customer. In price-based control, the aggregator sends electricity price information to the customer. Based on this information, the consumer can adjust consumption. The aggregator can then compensate based on a contract to which participants agree. (Ikäheimo et al., 2010)

2.4.3 Benefits of demand response for producer and consumer

DSM benefits both the consumer and electricity producer. The electricity market follows principals of other markets systems. When demand is higher, the price of the product, in this case, electricity, rises. This incentivizes customers to shift power usage to hours when electricity prices are lower. Currently, in Finland the wholesale market price is hourly based, but in the future it will be adjusted every 15 minutes. When the demand peak is highest, especially during winter peak-load, power plants are turned on to produce electricity. Using peak-load is expensive and produces more CO2 emissions compared to normal electricity production. (Järventausta et al., 2015)

2.5 Energy storage systems

Energy storage systems (ESS) can be divided into two categories: local and centralized large-scale storage. The main use for local storage is to store electricity from household PVs. Household users can then consume self-generated electricity when production is lower. Large-scale storage helps balancing the grid by supplying power on demand. Storing energy is expensive, but recently ESS costs have decreased. This might lead to more wide use of energy storing. (Guney & Tepe, 2017)

Energy storage can be viewed as a process where energy is transformed into a different form and used when needed. ESSs have five different categories based on how energy is stored. These categories are chemical, electrochemical, electrical, thermal and mechanical energy storage. (Guney & Tepe, 2017)

Energy storage increases a system's flexibility. The idea of a storage system is to store energy when it is cheaper and more available on the market. When demand rises, stored energy can be fed to the electricity system. ESS are predicted to be one of the key component of RES integration (Beaudin et al., 2010).

This chapter presents some of the storing methods in more detail. These technologies are pumped hydro storage (PHS), lithium-ion (LI-ion) batteries and power-to X to-power. These ESS have been chosen for different reasons. LI-ion batteries have a large range of applications and PHS is currently the dominant ESS. The power-to X method is chosen, since it decarbonizes the environment. Other methods might be equally applicable and choosing the right ESS requires estimation of ESS's up- and downsides and case-specific requirements of ESS.

2.5.1 Overall picture

RES decreases electric power systems' flexibility, due un-adjustable power generation. This leads to a need to increase flexibility in other parts of the electric power system. Balancing the grid might need to be done in different periods of time: seconds, minutes, hours days or months. This leads to a need for different storing mechanisms since one method most likely will not answer all needs. With an increasing amount of RES, energy storage systems become more crucial for the whole system. (IRENA, 2017)

Suitable storage systems can be estimated in multiple ways. In Figure 13, ESS are compared with rated power, energy and discharge duration. On the right top corner are ESS with large amounts of storing capacity, but slow discharge rate. This means that these methods are able to store larger amounts, but feeding electricity to the grid is slow. Li-ion batteries, for example, are in the middle ground since they are able to feed electricity to the grid faster and can store variable amount of power depending on the size (commercial or utility). Fast speed of discharge is a benefit of super conductors and conductors. (Guney & Tepe, 2017)

2.5.2 Pumped hydro storage

Currently, PHS forms a major part of energy storage with a share of 96% of all storages. PHS is a mature technology and it has little room for improvements. In PHS, water is pumped to a reservoir on higher ground. When electricity is needed, water flows to the lower reservoir through turbine and produces electricity. PHS is widely used, due its low cost compared to other storage methods. PHS also has low self-discharge, i.e., water does not leak from the upper reservoir where it is pumped. PHS is mainly used in larger scales and requires a large land area. The downside of PHS is its small energy density. (IRENA, 2017)

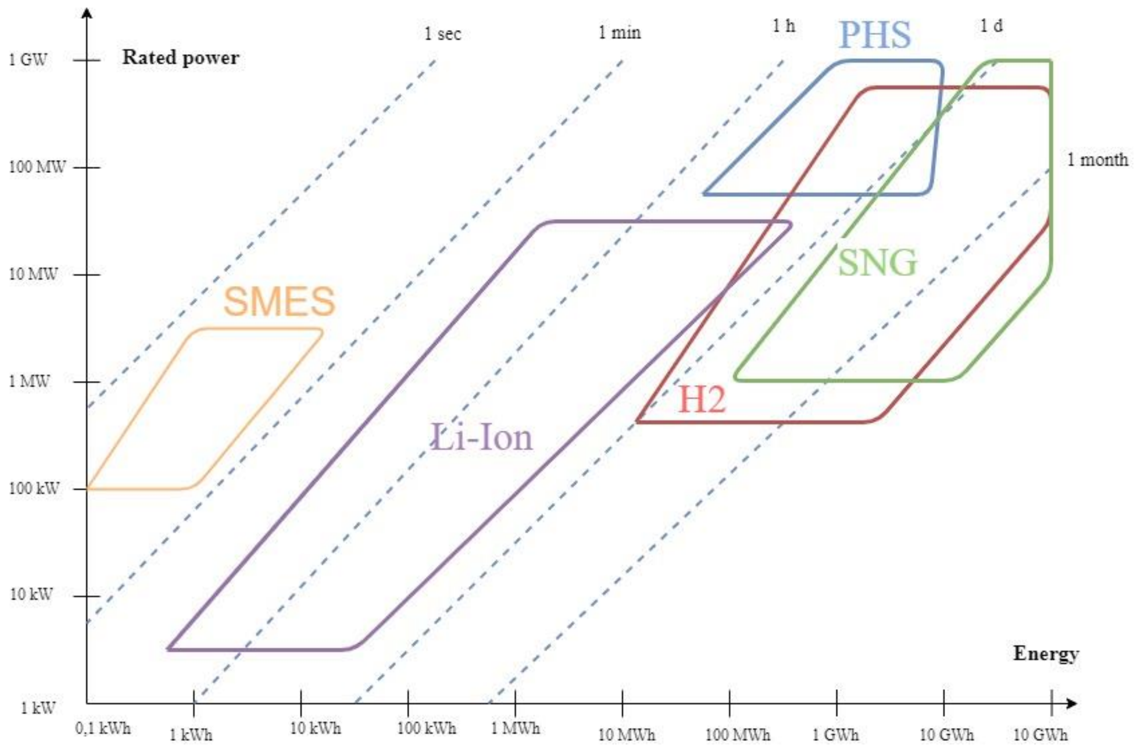

Figure 13. ESS comparison by rated power, energy, and discharge duration (modified from Guney & Tepe, 2017).

2.5.3 Batteries

Handheld devices and other electronics require batteries with high energy density. This has been a key driver for R&D in the battery industry and developing lithium-ion battery (LIB) technologies. In recent years, focus has shifted to other commercial uses. Electronic vehicles (EVs) have reached a mass market to compete with combustion engines. EVs currently use LIB as a source of storing energy. With developments in price and storing capacity, LIB has become a relevant option for a stationary grid storage system.

Research focus on LIB can be seen in technical improvements. Energy density in LIB has increased 7–8 Wh/kg annually since it was taken into commercial use. The current level is 250Wh/kg and the limit of LIB technology is estimated to be around 300 Wh/kg. Due to technical improvements, average price has decreased greatly (Nayak, et al., 2018). The average price of LIBs in year 2010 was 1160$/kWh and it has dropped to under 200$/kWh (176$/kWh) in year 2018 (Goldie-Scot, 2019). True prices might be over or under based on companies' supply chain effectiveness and company size. Prices of LIBs are predicted to continue to decline in the future. Bloomberg predicts LIBs would cost 94$/kWh and 62$/kW in year 2024 and 2030, respectively. (Goldie-Scot, 2019)

Due to LIB's wide applicability, its use will most likely increase. Currently, technology is improving and LIBs are taking larger shares of energy storage markets. The current amount of resources available to produce LIBs seems prominent. Although this might change if LIB production increases greatly. Based on the current known amount of metals, the largest risks constraining LIB's future production are the amount of cobalt and lithium (Nayak et al., 2018). The solution can be seen in the circular economy and more efficient recycling of metals. LIBs are not price sensitive to price fluctuations to its important metals (Li, Co and Ni). For example, if the market price of cobalt increases 100%, battery price would increase only 3% (Goldie-Scot, 2019). Naturally, scarcity of resources might increase prices in such a way that production of LIBs will not be economically reasonable. In such case, other batteries and storage might become more relevant.

Replacement of LIBs could be sodium-ion batteries (SIBs). SIBs use sodium as a main component. Sodium is an abundant element with a low price. SIBs have a similar chemistry to LIBs. Low raw material costs and optimism that SIBs could be a cheaper alternative to LIBs can shift research more towards SIBs. Currently, the downside of SIBs is their weight compared to LIBs. Weight is a more important factor in EVs and electronics than in stationary energy storages. This all might lead to adaptation of SIB to be a possible candidate for grid storage (Nayak et al., 2018). Local batteries can accompany PVs to offer electricity during night time and when more electricity is needed. Tesla, for example, has commercial use of LIBs for this purpose (Tesla, 2019). LIBs can be used at large scale too, to stabilize the whole grid. Tesla delivered the largest LIB in the world in Australia; its capacity is 129MW (Wahlquist, 2018).

2.5.4 Power-to X to-power

Storing energy for the long term has significant benefits to level production of VRE between seasons. The Power-to X to-power concept, which means storing electric power in some other form X and transforming it back to electric power when needed. Here X can be hydrogen, methane, ethanol or some other gas or fuel.

Long-term storing of energy has clear benefits for the electricity system. The power-to-X concept is seen as a possible solution for needing to store energy for longer periods. The power-to-X concept converts power to gas, liquid or to other usable forms of energy.

In P2X process, hydrogen is separated from water using electricity. Hydrogen can then be used as a fuel itself or produce liquid, gas or hydrocarbon. To produce biofuel or gas, carbon is needed. Carbon can be captured from the directly surrounding air. This technology is called DAC (direct air capture). Finally, a synthesis process combines carbon and hydrogen into usable fuels or chemicals. Hydrogen or synthetic fuel such as synthetic natural gas (SNG) can then used in fuel cells to produce electricity. (Vázquez et al., 2018)

Both power-to-gas (P2G) and hydrogen has downside with efficiency. Round-trip efficiency with hydrogen is estimated to be around 35-50% and in some cases low as 16%. P2G technology's efficiency is around 54%, but efficiency rate of 76% has been reached with prototype project. Technical efficiency of P2G is estimated to be around 85%. (Lund et al., 2015; KIT 2018)

P2X doesn't limit to converting power into fuels. VTT and Lappeenranta University of technology have proven that power can be converted into food. With processes of DAC and electrolysis carbon dioxide, hydrogen and oxygen are produced to grow microbes with high protein content. (Ahola & Lienemann 2019)

3 DIGITAL TECHNOLOGIES

This chapter discusses digital technologies that are relevant for future power systems. These technologies are the internet of things (IoT), for collecting and managing data, artificial intelligence (AI), for advanced information analysis and decision-making and distributed ledger technologies (DLT), which allows transactions to occur automatically without third-party involvement.

According to Porter & Heppelmann (2014), IT technology has seen two waves within the last 50 years and the third wave is emerging. The first wave occurred in the 1960s and 1970s when computer-assisting billing systems and manufacturing resource planning were developed. The second wave can be considered as the rise of the internet in the 1980s and 1990s. Both waves had significant economic impacts including changing how businesses operate. Currently, industry is on the third wave, where products are integrated with IT. They call these integrated objects "Smart and connected products", which have physical, smart, and connectivity components. (Porter & Heppelmann, 2014)

3.1 Digital technologies' connection to physical world

A technology stack (Fig. 14) shows the connection between the digital and physical world. These layers are physical, perception, service management, application, operative decision, business, legislation and cultural layers. These layers can be viewed as way that data travels upwards in the technology stack. While traveling, data transforms information, knowledge and insights. The lowest level consists of the physical world's objects. Objects can be people, buildings, machines and animals to name a few. Sensors and meters collect data from these objects to service the management layer and application layer. The communication layer delivers data towards the data-analysis layer (Lin et al., 2017).

In the application layer, data is analysed with data-analytic tools including AI. Analysing data produces information for decision-making in the operational layer. Information continues to the operative and business layers, where more strategic decisions can be made. At this point, information is transformed into knowledge and deeper understanding and reaching the top layers of the stack.

Based on the information, physical objects can be controlled via actuators by signals sent from application, operative decision or business layers. Information travels downwards in the technology stack to give instructions on what to do. Actuators can then affect physical objects, for example, control air conditioning or heating of buildings.

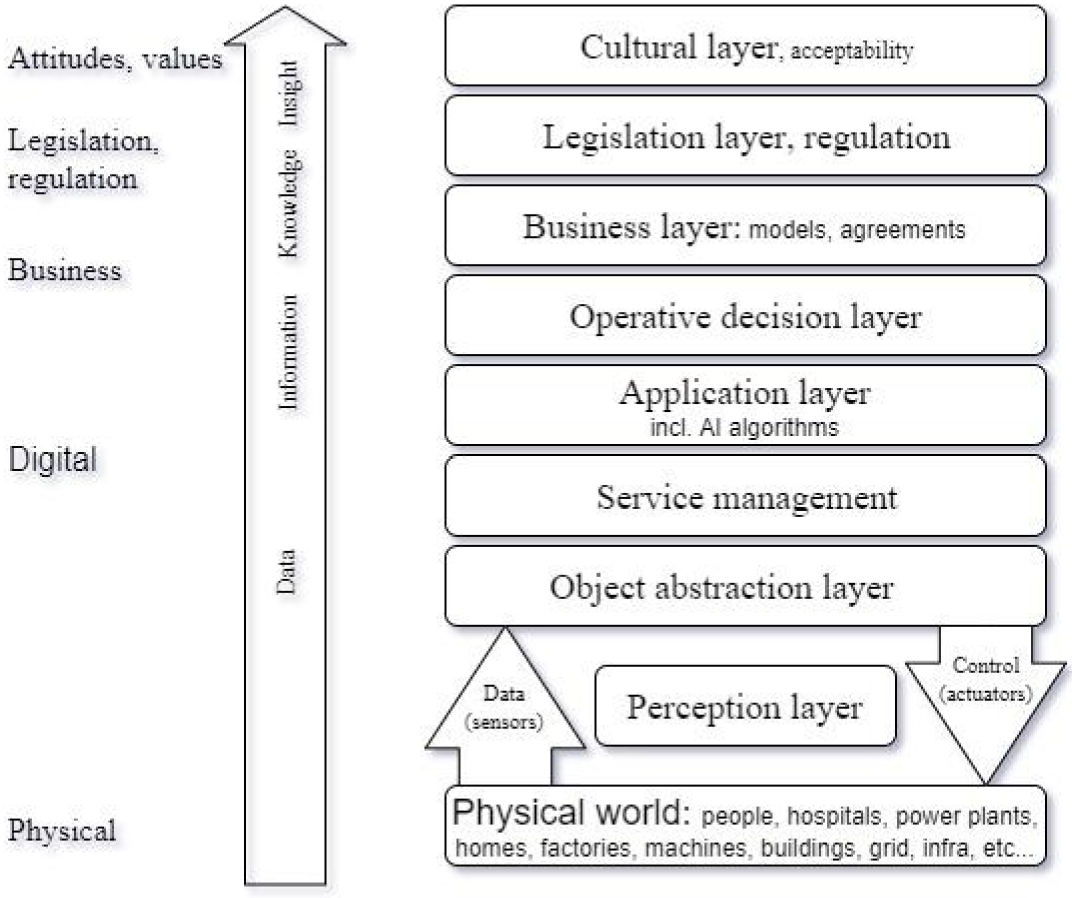

Figure 14. Technology stack (modified from Ailisto, 2019).

3.2 Data

Data collected from the physical world has become one of the most important resources for companies. Collecting more data from different sources has become an essential way to improve a company’s competitiveness in the market. The amount of collected data has been exploding exponentially in recent years. Digitalization has made it possible to collect these massive data sets. These datasets are described as Big Data.

The rise of the IoT is predicted to gain an ever-larger part of data collection. (Chen, Mao, & Liu, 2014)

Big Data has different definitions. Chen et al. (2014) define Big Data with four Vs: "*i.e., Volume (great volume), Variety (various modalities), Velocity (rapid generation), and Value (huge value but very low density)*". In addition to these four Vs, big data is normally labelled as a data set, which cannot be processed with traditional computers within a given time restriction. Value of data comes from processing it into information. This information can be further used to enhance decision-making. With more informed decisions, a company can gain competitiveness in the markets. (Chen et al., 2014)

3.2.1 Techniques and technologies related to big data

According to Chen et al. (2014), cloud computing and big data are closely related. Big data needs the computing capacity of cloud computing in order to process data into valuable information. Cloud computing answers big data's need for large storing and computing capacities. Cloud computing allows parallel computing which enhances efficiency of acquisition and analysing big data (Chen et al., 2014). Companies such as Amazon offer cloud computing services. Cloud computing reduces a company's need to invest in hardware and they pay for the service according their use. Large investments in infrastructure are not needed and companies can focus more on their core competences. (Armbrust et al., 2010)

Chen et al. (2014) describe the big data value chain with the following phases:

1. Data generation
2. Data acquisition
3. Data storage
4. Data analysis

3.2.2 Security/ challenges

The amount of data is increasing annually and it is traded and traveling between companies. A large amount of data is collected from individual people. In some cases this data is sensitive and for these reasons it must be handled accordingly. Data policies have identified important aspects of big data. Data security and securing peoples' privacy has become one of the main aspects of data. In addition to privacy, security, intellectual property and liability are important factors when dealing with data. (Manyika et al., 2011)

3.3 Internet of things

To collect more valuable data, an increasing amount of physical objects are connected to the internet in both industries, infrastructures and households. Additionally, the definition "smart and connected objects" can be defined differently. One of the most-used term to describe these objects is Internet of things (IoT), where connected things form network communicate with each other (Al-Fuqaha, et al., 2015). Other terms are used as well. Lin et al. (2017) discuss cyber-physical systems (CPS), where the physical world is connected by sensors and actuators shown in Fig. 14. These CPS form specific domains such as smart transportation, smart grid or smart health care. These domains are able to communicate between each other and they refer to this connection of different domains as IoT (Lin et al., 2017). Other terms for IoT include Internet of everything and industrial internet (Lee & Lee, 2015). For this dissertation, the term IoT is used instead of these other terms.

3.3.1 IoT architecture

IoT architecture forms the bottom part of the technology stack (Fig. 14). Similar to the definition of the IoT, a stack of IoT can defined differently: either with 3, 4 or 5 layers. In this thesis, IoT is described with five layers to offer more abstraction to the architecture (Al-Fuqaha et al., 2015). These layers are:

1. Perception
2. Object abstraction
3. Service management
4. Application layer
5. Business layer

In addition to these layers, there are five technologies that are used widely to successfully implement IoT. These technologies are:

1. Radio frequency identification (RFID) (in object abstraction layer)
2. Wireless sensor networks (WSN) (in object abstraction layer)
3. Cloud computing (in object abstraction layer)
4. Middleware (in service management layer)
5. IoT application software (in application layer)

RFID is used for automatic identification, for example, for products. RFID uses radio waves to identify a tag and a reader. Applicable domains of use include supply chains and passports, to name few. Passive RFID does not need a battery to communicate with the reader. Active RFID uses a battery and is able measure more different types of data than passive RFID. This data can be important to products such as temperatures or other conditions. Semi-passive RFID uses energy but takes it from a reader.(Lee & Lee, 2015)

A *wireless sensor network (WSN*) can co-operate with RFID systems to track conditions in the environment and surrounding areas. These sensors are spatially deployed. WSN can be used to track preventive maintenance. *Middleware* is the software layer between IoT software and sensing IoT devices. Middleware is important to ease the job for software developers. Middleware helps integrating technologies. (Lee & Lee, 2015)

Cloud computing allows users shared resources to operate and analyse data masses. These resources include: computing, storage, networks, servers, applications, service software. Finally, *software* is needed to operate *IoT*. This software allows connection between objects in the network. Software allows reliable and robust connectivity. These IoT applications can be enabled to do data visualization for reporting. Data visualization is not always needed but sometimes it has the benefit of better representing data. Software makes objects smart and allows them to resolve problems by themselves. (Lee & Lee, 2015)

3.3.2 Controlling smart connected products

IoT or smart connected products' operations can be divided into four levels based on their operations: monitoring, control, optimization and autonomy (Figure 14). All levels are important and advancing to the next level requires the previous level to be working. A monitoring level product inspects itself and the external environment with sensors. With this data, a monitoring level product can send information about the need for actions or corrections. Advancing to the next level is not always desirable. For example, medical devices are often used for monitoring purposes. Automating these devices to do operations might result life-threating situations, if data is misinterpreted. (Porter & Heppelmann, 2014)

Control level allows a product to perform actions at the physical level based on monitored data and feedback sent from upper levels of the technology stack. This can be turning on or off heating in a building depending on the monitored temperature. On the optimization level, the product uses algorithms to maximize or minimize desired outcomes. Optimization is done with historic data and using analytic tools or AI. With algorithms the product can control, for example, wind turbines to maximize power generation and minimize negative impacts to other wind power plants. The fourth level is the autonomy level where an object operates itself independently towards a desired outcome. (Porter & Heppelmann, 2014) Autonomy level can be viewed as the AI level where an object learns and operates. AI is described in more in detail in the next chapter.

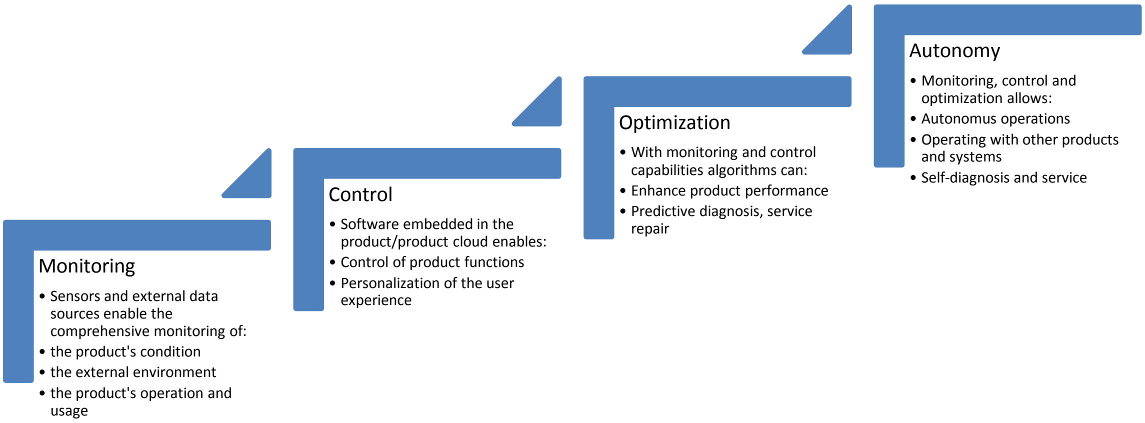

Figure 15. Capabilities of smart, connected products modified from (Porter & Heppelmann, 2014).

3.3.3 Impact on industries

IoT has massive market potential and it has been recognized as one of the most important technologies with the potential to change industries’ structures (Al-Fuqaha et al., 2015; Lee & Lee, 2015).

Manufacturing is predicted to be heavily impacted by IoT. Factories can place IoT sensors to collect data from manufacturing processes. Data can be collected from people, machinery and systems. This data can help in understanding the overall process and help to reduce costs or improve quality. A new term, Industry 4.0, has emerged.

This fourth industrial revolution has high expectations where IoT, big data, predictive analysis and AI shapes manufacturing processes (Mittal et al., 2018) (Al-Fuqaha et al., 2015)

In the energy sector, IoT has and will have a great impact. IoT can help companies improve their profitability. IoT can collect data throughout the value chain and thus increase value in different forms. IoT can measure grid condition and power plant status. This helps to predict grid failures and power production. The use of this preventive maintenance increases reliability of the system and reduces costs resulting from failures. Customers' electricity consumption can be tracked in real time and more precisely than before. (Mittal et al., 2018)

3.4 Artificial intelligence

Artificial Intelligence (AI) is a vast and multidimensional field. AI cannot be described as one technology, but multiple technologies. AI relates to philosophy, mathematics, economics, neuroscience, psychology, computer engineering, control theory, cybernetics and linguistics. There are different approaches to define AI. Russel & Norvig (2016) define AI study with the idea of intelligent and rational agents. Agents perceive the surrounding environment with sensors. After observing, agents take actions towards desired outcomes. From this point of view, AI tries to act rationally to achieve the best outcome, even when uncertainty is involved. Another way to view AI is that machines, computers or programs think and behave like humans. Rational behaviour is distinctive from human behaviour for the reason that humans do not always behave rationally. (Russel & Norvig, 2016)

Launchbury (2019) defines AI as *"programmed ability to process information*". According to them, AI can be divided into three waves based on AI's abilities and time they emerged. These waves are:

1. Hand crafted knowledge
2. Statistical learning
3. Contextual adaptation

In the first wave a machine is given the ability to rationalize specific problems. The machine cannot learn and therefore it has a low capability to handle uncertainty. Hand crafted knowledge-based AI can be described as a classical AI.

At the moment, AI research and applications are on the statistical learning level. AI has the ability to learn from data masses and it has rather good perceptual skills. Machine learning (ML) and deep neural networks are part of this second wave. Performance of AI algorithms has improved considerably in recent years and in some cases, AI has surpassed human capabilities. Good demonstration of AI's ability occurred when the deep neural network, called AlphaGo, defeated a human champion in a board game called GO in year 2015. This Chinese-based board game is immensely complex and human players were expected to be superior in this game for a long time. AlphaGo was trained under supervision, fed data and by playing itself. A new version of AlphaGo performs even better by only playing the game by itself and learning from it. The newest version of AlphaGo Zero achieved the level of championship within two days. (Silver et al., 2017)

Even though AI has shown exceptional success in specific areas, it is still below the human intellectual level. Existing AI implementations have narrow capabilities and therefore it is called weak AI and is unable to perform multiple tasks well. The third wave is considered the future of AI. In future AI systems, the ability to adapt contextually and understand the real world is expected. Currently, research is far away from strong AI. (Russel & Norvig, 2016)

Some concerns have been expressed about the concept of “singularity”, where computers reach a human level of intelligence and a situation where AI starts to see humankind as a threat. However AI is still far behind on human level of cognition (Launchbury, 2019; Russel & Norvig, 2016 pp.10-12)

3.4.1 Machine learning

Machine learning (ML) is one form of AI technology. In recent years, ML has become one of the most implemented AI technologies due to its success in multiple domains. In the training phase, a large amount of data is fed to the algorithm. With this data machine, an algorithm can be rearranged in such a way that it can label samples as well as possible. Once trained, the algorithm can categorize samples or predict values in a numerical series. (Ailisto, et al., 2018)

The ML agent observes, takes actions and improves over time. Learning can be small adjustments or larger improvements. Normally, ML is used in large and difficult environments. Russel & Norvig (2016) define three specific reasons for using ML over traditional programs. (1) Programmers who program algorithms cannot always predict all situations. For example, autonomous driving vehicles, cannot be taught how to drive on every street. In this case, it is easier to teach learning rules and let the vehicle apply traffic rules. Time is an important reason for using ML. (2) Conditions change over time and when this occurs algorithms must match them. Changing algorithms manually requires a considerable amount of work. This is not especially feasible, if this work needs to be done regularly. In this case, learning algorithms are a better option. If an agent, for example, is programmed to predict consumption of electricity of customers, it has to adapt to changes of consumption patterns and other changes over time. (3) The third reason to use learning is that programmers themselves do not know how to program solution or it requires too much time to do it. (Russel & Norvig, 2016, p. 4, 34-59)

ML is divided into three categories based on feedback given to an agent. These categories are supervised learning, reinforcement learning and unsupervised learning. In supervised learning, an algorithm is given a training set of inputs and outputs. Based on this training set, the agent forms a function. After this, the agent is given a test set to test its ability to predict. The test set must be different data from the training set in order truly test an agent’s ability to predict the future. When a model meets set requirements, it can be taken into use. (Russel & Norvig, 2016 p. 693-695; Ailisto et al., 2018)

In unsupervised learning, an agent learns patterns even without explicit feedback and can provide visual presentation of outputs. The most-used unsupervised learning method is clustering. Other methods are k-means-algorithm, anomaly detection, artificial neural networks (ANN) and self-organizing map. (Russel & Norvig, 2016, p. 693-695; Ailisto et al., 2018)

Reinforced learning is between supervised and unsupervised learning. In reinforced learning, the agent receives rewards and punishments based on how well it did. Based on the outcome and reward or punishment, the agent learns which actions led to that situation and improves itself. (Russel & Norvig 2016, p.693-697)

3.4.2 Artificial neural networks (ANN)

Artificial neural networks (ANN) have been inspired by how the human brain works. Neuroscience, in which the brain's nervous system is studied, has contributed to studies of ANN. ANN simulates the way human brain cells, specifically neurons, operate. In the brain, neurons are connected in a network. Within this network, information travels from one neuron to another. ANN can be separated into two different types: feed-forward- and recurrent networks. A feed-forward network is simpler and inputs go from upstream neurons downstream. In a recurrent network, inputs are fed upstream as well. (Russel & Norvig 2016, p. 727-732)

Artificial /deep neural networks have achieved notable breakthroughs in recent years and it is one of the most-used ML technologies. ANN has been implemented successfully in face recognition, speech recognition, language translation and the previously mentioned AlphaGo. Neural networks are widely used in e-commerce and also recommendations on websites are based on a neural network. (Ailisto et al., 2018)

3.5 DLT and blockchain

Contracts, transactions and records are vital components of businesses. Ledgers have been a key way to store information about these events. To operate transactions, a trusted third party is needed (Iansiti & Lakhani, 2017). Typical third parties are banks, exchanges, trading platforms and energy companies. In a traditional transaction, a bank receives payment from a buyer and sends it forward to the party who sold the product or service. This process is not done immediately and it takes some time for the receiver to actually receive the money (PWC, 2016). Therefore, using a third party for enabling transactions slows down the speed of businesses. Naturally, banks and other third parties also charge transaction parties for their services. (Iansiti & Lakhani, 2017) In addition to enabling transactions, third party members collect and store transaction data in a certain storage (PwC, 2016). Storing data in one place poses a security risk, which needs to be taken into account. Cybersecurity failure can result in a situation where millions of peoples' data is stolen.

These three main disadvantages of the current system (slow speed of transactions, centralized data storage and third-party involvement and commissions) have increased interest in changing the current system. Distributed ledger technology (DLT) and especially its subfield, blockchain technology has been predicted to solve these shortcomings of the current system. One of the key applications of blockchain has been Bitcoin and other cryptocurrencies.

Blockchain is still a rather new and emerging technology. The first implementation of blockchain was Bitcoin in year 2008. After this, several different blockchain-based currencies have emerged. Blockchains have high expectations and it can be a disruptive technology in the future to shape industries (PwC, 2016). Iansiti & Lakhani (2017) have set even higher expectations towards DLT. They argue that DLT is not just disruptive technology, but rather a foundational technology. They predict that DLT not only shapes, but creates foundations for economic and social systems (Iansiti & Lakhani, 2017). This is a drastic interpretation of DLT, but highlights well the expectations given to both blockchain and DLT.

Blockchain can be divided into three waves based on the development of technology. The first wave is considered as cryptocurrencies like Bitcoin. The second wave is a smart contract, current wave. The third wave remains uncertain. The prediction is that smart contracts are further developed and blockchain solutions find a larger application area. (PwC, 2016)

3.5.1 How blockchain works

Blockchain has distributed databases, which means that data is not stored in one specific location, but it is distributed to multiple network participants. This brings security for the system, when sensitive information cannot be hacked from one place. In addition to this, each participant of the blockchain has access to the needed information and data. Even though participants have access to the data, they cannot alter or change it. The blockchain transaction process is describe in the following (PwC, 2016) :

1. Parties agree the terms of transactions.
2. Transaction is combined with other transactions within the same time period. Data of these transactions form a data block.

3. Data block is stored in distributed database, i.e. other users' computers. Other users verify the data block automatically.
4. Verified data block is linked with other blocks.
5. Transaction occurs for both parties.

Once information is set on the block, it is permanent. Blocks have unique information, which includes text and numbers. When blocks form a chain, they verify the previous block for information with algorithms and form a unique hash. This hash contains information from previous blocks and is attached to the new block. Therefore changing information of the block requires altering all following blocks as well. If someone wants to alter a blockchain he/she needs to hack all computers that verify these blocks due to the distributed database. The block verification process is called mining and it is done with computing processing power. These miners are rewarded based on their work. (PwC, 2016)

Since blockchain is reliable and secure by its design, third parties are not needed. With blockchain peers can transmit information and transactions between each other. This has been a key success of Bitcoin, which allows participants to transmit money without a bank being involved.

3.5.2 Smart contracts

Smart contracts are an interesting application of blockchain technology. Smart contracts are unchangeable agreements, which cannot be changed later. However there is an option to delete these contracts if needed. Even though smart contracts are called "contracts", they do not have legal obligations. Smart contracts are designed to speed up transactions. These contracts operate automatically and diminishes the need of human interactions in the process. Like blockchain overall, smart contracts do not need third parties to execute transactions and therefore reduce needed resources. Smart contracts are designed to trigger when conditions are met. Parties agree the price of a trade beforehand. Another party then deposits units agreed on the contract. Another person then send currency to execute the trade. When conditions are met, the trade occurs. (Christidis & Devetsikiotis, 2016)

Smart contracts already have real-world applications. One application of smart contracts allows physical world objects to be used when the contract's conditions are met. A company called Slock has smart locks implemented into objects such as cars, houses or other objects. A person who wants to rent his/her property can install a smart lock, which opens for another person via a smart contract. The energy and power sector has also shown interest in smart contracts and some visions predict that energy markets might shift blockchain based peer-to-peer markets, which operate with smart contracts. Prosumers (consumers, which use and produce power on a small scale) generate power and supply it to the market. This power then is traded to someone with a need for electricity via a smart contract automatically. In this market domain, machines operate with each other independently. (Christidis & Devetsikiotis, 2016)

4 DIGITAL TECHNOLOGIES AS ENABLERS OF FUTURE POWER SYSTEM

The energy and electric power system has three dimensions, which are essential for a functional system: 1) economic 2) sustainable and limiting greenhouse gasses and 3) secure in case of supply (Huttunen, J., 2017). Trends, shift the electric power system towards a decentralized, decarbonized and democratized situation (Di Silvestre, et al., 2018)

Digitalization has the potential to aid the transition towards future power systems. Artificial intelligence (AI) offers a group of promising technologies that can improve or even completely change power and energy sectors.

This chapter presents how digital technologies help the power sector transition towards a decentralized, decarbonized and democratized power system. Data can be collected in larger amounts from households' smart meters and IoT objects. Similarly, more data can be gathered from all parts of the grid, power plants and industrial consumers. With better monitoring performance is observed and actions are controlled, optimized and automated (Figure 15). These final levels can be optimized and automated using AI. When processing this data towards information and knowledge, new businesses, business models and ecosystems can emerge.

We present three successful pilot projects in Finland, the United States and Germany, which are used as examples of digital technologies in the energy sector. These pilot projects were chosen to exemplify the state-of-the-art in their own specific area. These pilots are the Capfor Online-capacity forecast tool in Finland, the Brooklyn microgrid (MG) in New York and the virtual power plant (VPP) by Next Kraftwerke in Germany. Capfor Online forecasts production to provide more information about future balances. MG demonstrates how a power system of the future might look like if production is done locally by consumers (prosumers) and neglecting the need for region-wide transmission lines, large traditional power plants and centralized markets. VPP demonstrates how a large group of consumers can be bundled in group in order to take part of demand response programs to cut peak hour demand and limit the need for load following power plants.

Digitalization is expected to penetrate the entire power system, which was described in chapter 2 of this thesis. To summarize, these parts are supply, demand, transmission and markets. In addition to these, demand-side management and energy storage systems are expected to have more influence in the future. Currently, these parts are optimized and automated using AI. (IRENA 2019b)

In Table 2, different parts of the power system are described in addition to how AI can be used to improve those parts. AI and other digital technologies have been recently implemented in power generation, transmission, distribution, consumption, storage and markets.

Power system part	Power generation	Transmission	Distribution	Consumption	Storage	Markets
	Improved power generation forecast	Improved grid stability and reliability	Improved grid stability and reliability	Improved demand forecast Efficient demand-side management	Optimized energy storage	Optimized market design and operations

Table 2. Emerging applications of AI in power system (modified from IRENA 2019b).

4.1 Improving supply and demand with data-based forecasting

Forecasting is one of the key applications of AI in the power system. In the energy and power sector, forecasting is especially important due to the special nature of the electricity, stochastic production of RES and its markets. Electricity needs to be provided at all times, but the needed amount varies. The financial success of companies will depend on how well they are able to forecast in the future. Electricity retailers need to forecast consumption to avoid increased electricity costs when approaching closer to the delivery hour. Similar power generating companies need to forecast their production. Traditional hydro- and thermal power plants' production is adjustable, but for companies with a high amount of VRE, this is a more complex task. Weather conditions affect significantly wind- and solar-based power generation. If production is higher or lower than promised for the market, the energy companies will suffer economically, since they have to produce or buy expensive reserve power.

Forecasts can be divided into three categories based on timeline: short, medium and long (Hong & Fan 2016). These can be also viewed from the management-level perspective. A short-term or operational timeline is a couple of minutes to hours. Medium can be viewed as a tactic level of management and time scale ranges from a few days to months. A long-term forecast can be viewed as a strategic level of management and its time horizon is ranges up to years. Table 3 shows different timelines and characteristics of load forecasting. (Hong & Fan, 2016)

Management level	Strategic	Tactic	Operational	Operational
	Long-term load forecast (LTLF)	Medium-term load forecast (MTLF)	Short-term load forecast (STLF)	Very short-term load forecasts VSTLF
Time period	Months–years	Few days–few months	Minutes, hours days	Seconds, minutes
Actions	Capacity invest planning, site selection, investment analysis, i.e.	Balance sheet calculations, risk management, derivatives	Assessing spot price, intraday prices	Ancillary services, correction for balance

	profitability	pricing		

Table 3. Load forecasting timelines (modified from Hong & Fan, 2016).

Actors in the market need to forecast how much electricity they need in a certain hour on the next day. The electricity producer, on the other hand, needs to forecast their following day's production.

Forecasting is used mainly for:

- Load forecasting
- RES power generation forecasting
- Electricity price forecasting

Many of the power generation forecasting methods are focusing on wind and solar. Price forecasting is immensely important for market operators. In the short term, accurate forecasts can reduce financial risks operating in the markets. In the long term, market operators can hedge against increasing price by operating commodity markets and buying products that support theirs strategy.

Due to the importance of forecasting, multiple methods have been developed and used. There is no one right method and comparison between different models such as ANN and SVM might be a difficult task, since real-life applications operate in different areas and situations which results in comparisons that are difficult. ML has become one of the most-used methods recently.

CapFor Online

Looking at the larger picture, the whole power system forecast is important. With an increasing amount of fluctuating RES, the system becomes more vulnerable due to weather and temperature variations. This leads to the need to forecast capacities of other power plants so situation with a lack of power will not occur. Currently, the largest sources of power in Finland are nuclear power plants and CHP (combined heat and power) power plants. Forecasting the capacity of these power plants interests local TSOs since this information helps maintain the grid better. With capacity forecasting methods, TSOs have a clear picture of how much flexibility and how much base load power is available. (VTT, 2019)

CapFor Online is a capacity forecast model developed by the Technical Research Center of Finland (VTT) and the Finnish TSO, Fingrid. CapFor Online forecasts the capacities of nuclear and CHP power plants in Finland seven days in advance. (VTT, 2019)

CapFor Online uses ANN and statistical models for forecasting. CapFor Online forecasts different power plants using probabilistic forecasting techniques. This has been successful and the model error rate is below 5%. Larger power plants have historic databases, which are essential for ML algorithms and especially ANN. For smaller plants, no such data is available or the sample is too small. Because of the lack of data from smaller plants, they are aggregated with similar plants' data. By aggregating and dividing plants into specific groups, an accurate forecast is possible. The forecasting model was taken into use in 2018. The model is constantly updated to maintain a high level of accuracy. Currently, VTT maintains and re-trains capacity forecasting models twice a year. Figure 16 shows the forecasted maximum capacity (blue) and actual power generation (orange). The graph demonstrates the capacity forecast and real values in year 2018. (VTT, 2019)

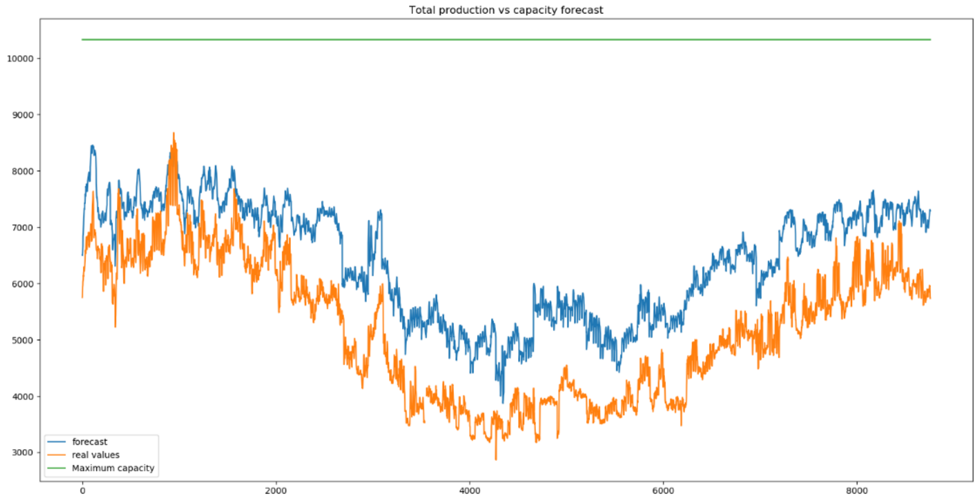

Figure 16. Power demand and forecasted capacity (VTT, 2019).

4.2 Smart Grid and microgrid

With increasing amount of VRE in the power mix and growing demand of electricity pressures grid towards improvements. Traditional grid cannot support these changes and digital solutions are needed. Smart Grid is used term to describe new type of modernized grid, which has premises to enable energy transition. Unlike traditional grid, Smart Grid enables better communication and power flow between participants of the grid. With better data collection and analytics parts of the grid can be automated, faults can be detected more precisely and self-healed. With digital technologies, the new modernized grid enables DSM, smart appliances and smart storages. Electric vehicles (EVs) and vehicle to grid (V2G) are expected to be major part of the new grid. In Smart Grid visions the EVs communicate with grid and offer storage system, which can be charged, when demand of power is low. When demand rises EVs supply stored power back to grid. This reduces need of peak power plants and increases system's flexibility. (Tubella & Abundo, 2016)

The idea of a microgrid (MG) is to form a smaller network with clear boundaries from an actual nationwide grid. A MG can be a grid tied or disconnected to operate in island mode. The US department of energy defines a microgrid as: *''a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode.''* (Ton & Smith, 2012)

MG residences or facilities generate and consume needed power within and between themselves. To operate, MG's consumers and prosumers (consumers who also produce electricity) need to have a way to trade electricity with each other. This trading between consumers is called peer-to-peer (P2P) trading. In P2P, traded power is generated from renewable energy sources (RES) mostly by residential photovoltaics (PVs). With P2P trading intermediate stakeholders such as TSOs, DSOs and large utilities are not needed.

	Current system	Future systems
Production	Carbon based, centralized	Decentralized, DER

Network, transmission	Traditional grid	Smart grid, Microgrid
Power generation size, type	Large scale, hydro, nuclear, coal	Small scale, PV, wind

Table 4. Comparison between traditional grid and microgrid.

Benefits from MG vary depending on what the key issues are with the current system. Overall benefits aim for financial benefit as well as clean and secure energy supply. Resiliency (ability to prepare and recover from disruptions) and reliability are main issues that MG is expected to solve. Especially in North America, extreme weather conditions affect grid and power generation which can lead to power outages. MGs can withstand power outtakes in the national grid or nationwide networks by being in island mode. (Hirsch, Parag, & Guerrero, 2018)

In Europe, the main goal of MG is limiting climate change by improving power systems to be cleaner. MGs in rural areas in developing countries might be able provide power for those who are far away from grid connections. In developing countries, expensive and long transmission lines might be avoided by implementation of MGs. (Hirsch et al., 2018)

Cyber security has also risen as a concern in power systems. Power systems are essential for whole countries' well-being and large outages cause economic impacts and even loss of human lives. MGs are more secure, since hacking multiple MGs is more difficult compared one specific power plant or a certain part of grid infrastructure (Hirsch et al., 2018).

Hossain, Kabalci, Bayindir, & Perez (2014) discuss in their study different MGs and the differences between them. In their study, they divide MGs into three categories:

- Facility MGs,
- Remote MGs and
- Utility MGs.

Facility and utility MGs have grid-tied connections to stabilize balance within a MG. Remote MGs do not have this connection. These remote MGs are normally located in rural areas or even on islands. In these cases, MGs offer power within areas where transmission line connections would not be financially feasible. (Hossain et al., 2014)

With the benefits discussed earlier, companies are more interested in commercial use of MGs. Figure17 shows different components of blockchain-based energy markets and their relations between each other. According to Mengelkamp et al., (2018), these components are:

C1 Microgrid setup
- C2 Grid connections
- C6 Energy trading management system (EMTS)
- Micromarket setup
  - C3 Information systems
  - C4 Pricing mechanism
  - C5 Market mechanism

C7 Regulation and legal environment

C1 is a whole MG setup including technical requirements, market requirements and digital technologies requirements. On the other hand, most of the MGs are connected outside the electric power system and need to follow legal and environmental regulation (C7) both inside the grid and outside the network. Inside the Microgrid C1 setup, C2 demonstrates the need for connections for a superordinate grid. Information systems (C3) play key parts in making MG possible. Information systems connect market participants with each other to be able trade electricity. Smart meters measure power generation and consumption. The energy management trading system's (EMTS) (C6) main objective is to secure power supply for market participants. EMTS has access to real-time demand and supply data, which it uses to forecast supply and demand for future hours. Based on forecasts, EMTS forms a bidding strategy for market participants based on their needs and price limits. C7 showcases regulations and policies related to MGs and energy markets. This section defines how MG can operate, how taxes are paid and how MG is tied to the grid. In addition to this, MG needs to buy electricity generated elsewhere and to do that it needs to have access to wholesale markets or a third-party (retailer) needs to aggregate power for it. (Mengelkamp et al., 2018)

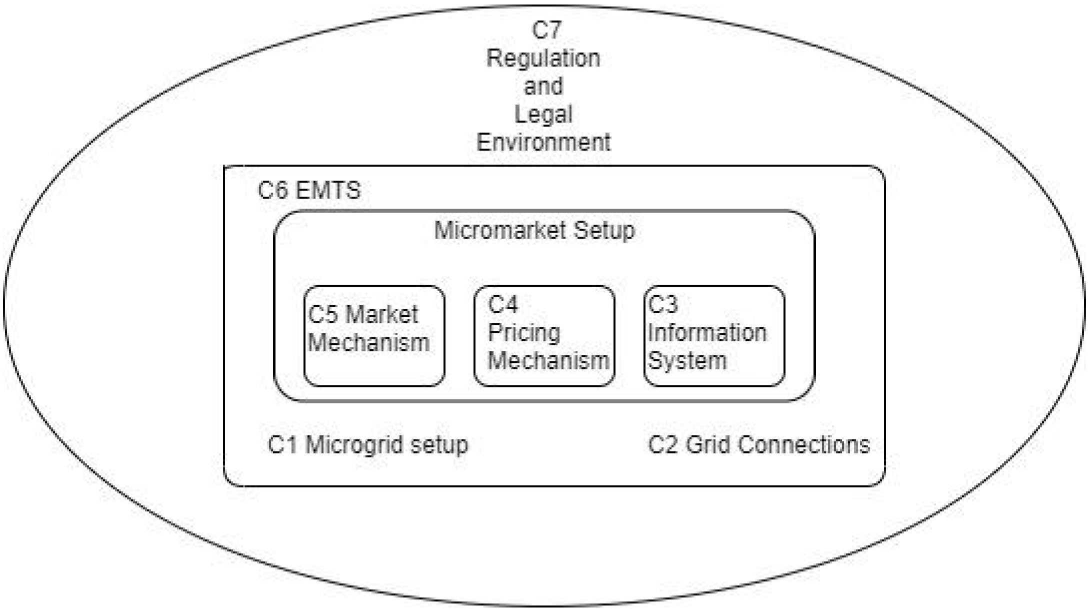

Figure 17. Schematic overview of Microgrid energy markets (Mengelkamp et al., 2018).

Brooklyn microgrid

Potential benefits of MGs have driven companies to invest in MG projects. There are many projects around the globe (Hossain et al., 2014). One of the prominent projects is Brooklyn Microgrid (BMG) in New York City. BMG is the first MG that is in commercial use and it was developed by LO3 Energy. BMG started to operate in 2015 and is the first commercial MG (LO3, 2018).

BMG supports the P2P trading platform, which uses blockchain tokens as currency in trading. LO3 has expanded their operations since 2015 and their system is called Exergy. The system is consumer and prosumer centric. LO3 has developed IoT hardware themselves to collect data, communicate and control with actuators. IoT devices send data to control and communicate with the layer above. At this layer, algorithms control local power generation, storage and smart devices. Algorithms collect data from markets and send data to actuators to operate accordingly. Between IoT devices and algorithms there is a communication layer that plays a vital role in the system. The communication layer includes application for market participants, which eases communication between prosumers and consumers. (LO3, 2018)

The MG ecosystem is designed to create value for stakeholders with adaptive and efficient pricing. In addition to this, MG provides resiliency and reliability for the ecosystem. In this application, participants trade energy between each other using blockchain tokens (LO3, 2018).

In addition to providing a trading platform within MG, BMG offers services for outside stakeholders. Distribution system operators (DSO) are interested in grid balancing services and consumer data to improve their operations. DSOs can acquire consumption and smart meter data from BMG's consumers and prosumers. In exchange, BMG participants receive payments. In addition to data aggregation, BMG offers demand response (DR) services to balance outside the grid. DR is executed by signals from DSO or by automatic self-executing contracts. These signals activate actuators to change consumption. Taking part in demand response programme creates value for DSOs and economic benefits for consumers and prosumers (LO3, 2018). Therefore successful MG can reduce carbon emissions inside the grid with renewable energy production and outside by limiting the need for peak load power plants.

Mengelkamp et al. (2017) have evaluated and researched this project in their case study. They have evaluated MG efficiency from seven different components (Fig. 17.). According to their analysis, C1–C3 were addressed and in use. This means that MG focuses to achieve its function to offer secure and local power between consumers, prosumers and other MG participants. The grid is developed to balance demand and supply and transactions are made by using blockchain-based currency (Mengelkamp et al., 2017).

At the time of their case study (2017), they found out that market mechanisms were underdeveloped resulting in parts C4–C7 that were only partly addressed. Market pricing was predetermined and fixed, which mitigates MG's benefit. With a fixed price, consumers do not have direct market signals to change their consumption patterns. They conclude that currently BMG's EMTS is not sophisticated enough to truly implement intelligent bidding strategies for participants. Participants were unable to execute more advanced bidding strategies and only modest bidding strategies were available. They recommend that bidding strategies should be more advanced and execution of these strategies should be done automatically. However, the largest shortcoming was legislation (C7). Regulations were not fully defined. Legislation and regulation are important aspects of power markets and therefore they need to be addressed and taken into account before MG can be taken into commercial use (Mengelkamp et al., 2017).

4.3 Virtual power plant

Shifting towards distributed energy resources (DER) creates problems that need to be addressed. These issues are overcapacity and under-utilization of assets. When flexible power plants are replaced with DER, these problems occur if they are not taken into account. Problems lead to financial losses since overall efficiency decreases which leads to costs for consumers. (Pudjianto, Ramsay, & Strbac, 2007)

Two different solutions have been suggested to solve these problems, Microgrids and virtual power plants (VPP). Consumers want their power system to be high quality, low cost and highly reliable. In addition to this, concerns about fossil-based power generation create a need to renew and transition towards more sustainable power generation. There is no single clear definition for VPP. VPP can be seen as a combination of various technologies and operating patterns forming an entity. This entity is connected to a distribution network. VPP generates power from DER, control loads and stored energy. VPP is controlled by an energy management system (EMS), which receives data form different units and controls them accordingly. Power can be generated with CHP, biomass/biogas, gas or diesel power plants, hydro, wind and solar. Also, consumption can be controlled. Flexible loads can be implemented as a demand response to lower consumption during peak hours. In addition to power generation and ICT, energy storage systems are important for VPP. Energy can be stored during high production, or when the price of electricity is low. (Saboori, Mohammadi, & Taghe, 2011)

Virtual power plant pilot

There are multiple VPP projects around the globe. One especially interesting case is managed by Next Kraftwerke. Next Kraftwerke provides VPP solutions in Germany, Austria, Italy, Belgium, the Netherlands, Poland, Switzerland and France. With these VPPs, Next Kraftwerke is one of the largest power aggregators in the Europe. They operate over 8000 different units with a capacity of 7000 MW. Traded energy between participants equalled 12.1 TWh in year 2018. In comparison, this amount is around 14

% of the power demand of Finland (86 TWh) (Next Kraftwerke, 2019c). Due to the large aggregated amounts, this company and its project were chosen to be presented in more detail in thesis. Next Kraftwerke has experience implementing digital solutions and the scale of their operations highlights that VPPs are relevant solutions in future power systems.

Next Kraftwerke's VPP solution is based on data collection from internal and external sources. Internal data is collected from production and consumption and external data consists of markets, prices, transmission system operator (TSO), signals, weather forecasts, grid frequency and consumption forecasts. The control system operates based on these datasets (Next Kraftwerke, 2019a).

Being part of VPP, participants can monitor their data and assets. Based on collected data, production forecasts can be made for participants. With better forecasting, grid responsibility parties have better opportunities to change their production amount based on price signals from the market. On the TSO and DSO a large VPP can take part of balancing energy markets. They can sell supply or demand of power for TSOs and DSOs and gain revenue for participants. Loads and productions are controlled with an algorithm which chooses the most suitable assets to control based on the amount of reserve and restrictions of the asset holder. The system allows participants to optimize their power purchase operations by shaping time of use (TOU) of power when it is possible to shift loads to a cheaper time of day. (Next Kraftwerke, 2019a)

The showcased pilot project is VPP in Mainfranken, Germany. The project combines the concept of VPP and the long-term storage solution, Power-to-X. In this project, excess and cheap RES, such as wind or solar power, is directed towards a facility which uses electricity to produce hydrogen from water. The installed capacity of this site is 1.2 MW and it is able to produce 220 m^3 of hydrogen per hour. Efficiency of this plant's process is 70 %. (Next Kraftwerke, 2019b)

Control of the power flow is done on site or remotely from control centre. Controlling is done based on production and price forecasts of wind and PVs and demand of hydrogen. Data is collected automatically and, based on forecasts, the facility starts to operate. (Next Kraftwerke, 2019b)

The focus of this project has been more on the ecological rather than on the financial side. With a combination of the electrolysis process and RES, a project can reduce carbon footprint. On the other hand, with the high-level integration of RES, supply might be higher than consumption. Storage solutions such as the VPP project help to reduce this problem by offering received power when it is abundant. The facility owner benefits from this since the price of electricity drops heavily when there is overcapacity; therefore their operation costs drop to low levels. Optimizing power demand and purchasing hours result in mitigation of the risk of high prices. (Next Kraftwerke, 2019b)

Even though the project is motivated by ecological reasons, it is estimated to be also economically viable. Accurate numbers were not available to estimate this project in detail. Information also is based Next Kraftwerke’s website and their customers’ opinions. Therefore, deep analysis for this solution and project are difficult. However, this solution demonstrates one interesting possibility that VPP offers: to optimize supply and demand with digital solutions and some other customers can achieve notable benefits from VPP.

5 DISCUSSION

The aim of this master's thesis was to study power systems and their future. The Paris Agreement binds countries to reduce their carbon footprint (United Nations, 2015) while other global megatrends such as electrification of transport and heating (WEF, 2017) increase demand of electricity. Therefore, significant changes in the electric power system are to be expected.

5.1 Key findings

To decreases GHG fossil fuel-based power generation needs to be reduced as well as an increase in carbon-free power generation. This new power can be generated by RES or by nuclear power. However, that volatile production of RES cannot be implemented without careful consideration and systematic changes. Increasing volatile RES, such as wind or solar, decreases flexibility of the power system and can affect the balance between supply and demand. Balance between supply and demand is critical for a power system and the need to be in balance at all times.

The challenge to balance supply and demand increases even more when flexible production, such as combined heat and power (CHP), is reduced. This leads to a need to balance power to maintain equilibrium of supply and demand. Volatility increases negative impacts, such as high price variation, however these can be mitigated. Solutions for increasing flexibility are increasing flexible power generation, energy storage systems (ESS) or affecting how power is consumed by implementing demand-side management (DSM). These solutions require financial investments and, for example, ESS and increasing production capacity has high costs. This leads to a need for more advanced optimization of processes and data-based decision making, where digital technologies and artificial intelligence (AI) can improve the current system and support the transition towards a new system.

Previous research emphasizes that digital technologies can improve the current power system and help to transition towards future systems (IRENA, 2019b). AI has been implemented in different parts of the power system and the benefits of using it have been studied. These sectors are forecasting demand of electricity (Ahmad et al., 2014), forecasting consumption (Hong & Fan, 2016) and production (Voyant et al., 2017) to name a few.

AI, data collection and computing lay the foundation to the transition towards new types of power systems. The price of producing electricity by RES has decreased rapidly in recent years. RES price drops help countries implement RES more economically and therefore reach climate goals. (IRENA 2019c) The downside is lack of flexibility.

Energy storage will have a larger impact in the future system when the share of volatile RES increases (Guney & Tepe, 2017). A dominant long-term energy storage solution is pumped hydro (IRENA, 2017). A new solution for seasonal storage might be hydrogen, which is produced from water using an electricity process called electrolysis. Hydrogen can be further processed into carbon-based fuel adding carbon collected from the air (Vazqyez et al. 2018). These solutions are still under development, but they show promise. Short-term energy storage's importance increases and batteries are a prominent solution for this task (Nayak et al., 2018). A real-life solution is the VPP Next Kraftwerke project, which stores electricity during cheap hours and when their own power generation is high. Electric vehicles have large batteries and studies have been made on their usability for power storage for the grid (Tubella & Abundo, 2016).

This study found that AI can be used to optimized in various parts of the electric power system. AI has been successfully used in forecasting production, price, demand, optimizing demand-side management, grid stability and predictive maintenance. AI can increase value for different stakeholders throughout the value chain. A power plant owner can optimize production more effectively and TSOs and DSO can maintain the grid and power system better. (IRENA, 2019b) For traditional consumers, smart solutions for homes offer better energy efficiency and cost savings. This is currently possible due IoT and smart metering that collect more data, which is essential for AI and machine learning (ML).

This research described three successful pilot projects. These were the capacity-forecasting models using ANN algorithms (CapFor Online) made by VTT for Fingrid. Microgrid in New York made by LO3 using IoT and blockchain technologies and virtual power plant (VPP), made by Next Kraftwerke implementing energy aggregation to produce economically feasible hydrogen, which can be used as fuel later. These projects demonstrate different aspects and give insight into what future power systems might look like.

CapFor Online, a capacity forecast model, uses ML algorithms to forecast future production capacity of combined heat and power (CHP) and nuclear power plants. With this model, TSO gains information about flexible production. This information helps them to better maintain the grid. (VTT, 2019)

The second project introduced in this research was the Brooklyn microgrid (BMG) in New York City. BMG is the first commercial microgrid where consumers and prosumers generate electricity and trade it with each other. Within this, microgrid trading is done using blockchain tokens and smart contracts. Currency is the company's developed tokens. This project demonstrates a solution that was not previously available due to the lack of technology. This customer-centric approach allows consumers to trade electricity in an economically feasible manner. (LO3, 2018) The third project introduced is the virtual power plant (VPP) by Next Kraftwerke. One of the most important results is that VPP can be used as DSM and it can operate in balancing energy markets. (Next Kraftwerke, 2019b)

5.2 Implications

This study found that the electric power system is in a transition phase (IRENA, 2019a). This transition affects all electricity users, companies that are part of the value chain and governments. The current system will be replaced, but it remains uncertain how a new system will look. Transition shapes the market and companies operating inside it. Countries plan to phase out fossil fuels to reduce emissions and improve aspects such as safety and resiliency of the electric power system. This transition forces energy companies using fossil fuels to produce electricity, to change their strategy and overall how they operate. On the other hand, the industry is shifting towards more digital and data-driven businesses. Use of AI and data analytics can improve companies operational effectiveness. Companies that embrace change towards these solutions have an advantage. Data-driven businesses most likely succeed and provide new products and services for customers. This leads to the possibility of new businesses and business models.

Demand response (DR) was discussed in the literature review can play a major part in the electricity system to control consumers' loads. Controlled loads can be shifted to a period of time when consumption is lower (Palensky & Dietrich, 2011). The aggregator, who controls loads of multiple consumers, can then sell this service to a TSO or DSO. DR services help the TSO and DSO balance grid. With this service, customers can gain economic benefit (Järventausta et al., 2015). Currently, DR is not widely used in Finland. This is a result of multiple barriers. DR has the potential to rise as one of the major aspects in power markets. DR requires multiple customers to participate in order to have effect. Maintaining and controlling multiple loads at the same time with fast response times is difficult to do manually. In this case as well, automatisation can be used to optimize and control demand. Companies have implemented smart home hardware to monitor and control demand. Google, for example, has the Nest smart home solution where hardware is implemented in households and it is controlled via digital technologies and AI. The residents then can take part in DR programmes automatically without even noticing (Google, 2019).

Nolan & O'Malley (2015) discuss barriers of DR. They highlight the importance of taking consumers into account and providing them needed value. Consumers need to be willing to participate in programmes and companies also need to consider customer motivations and their preferences. This means the voice of the customer should be listened to carefully. DR programmes as well as other changes in the system must provide value for customers either financially or otherwise. Vardakas, Zorba, & Verikoukis (2015) emphasize this view with their study on DR programmes. They found that consumers participating in DR programmes did not always benefit them and in some cases even penalized them for participating. DR programme providers might have price-based incentives which penalize power usage in high-demand hours. In some cases customers cannot change their consumption, which results in a higher electricity bill. Therefore, it is essential to offer different contracts for different needs. In addition to this, companies should ensure customer activation since power-using households lack interest in taking actions themselves in DR programmes.

Technology push is driving markets to change. It is essential to shift focus and towards, where customers recognize their needs and want new products, services and finally a new ecosystem. Customers are without a doubt more willing to change when they realize their benefits, and understand value created to them by new solutions and technologies. This requires focusing the right technologies and commercialization of products that rely on these technologies. Focusing only on technologies and products will result in failure: no product sells itself.

Small solutions should not be neglected. Discussion could be made about e.g. application that can activate energy users to recognize how, when and what kind of energy sources are used? Gamification and applications have shifted how, e.g., learning is done. Could this be a way to activate customers early to gain interest in electricity consumption? Could this application-based system continue towards a more advanced solution?

The trend in recent years has been that product-based companies are shifting towards service-based business models in other industries and customers are billed based on hours of usage. Some discussion could be made about what kind of future electricity and power markets have. Defining what electricity, power and energy means for customers is essential. Similar to transportation, customers do not need petrol or other fuel types, they need the most convenient way for themselves to travel distances. One might argue that transportation can be substituted with ICT, since communication can be done via other means. This opens up new ways of thinking about how new business models serve those customers better. The platform economy has been suggested as one option; this however requires a P2P network. MGs, such as demonstrated in pilot project, have P2P trading and what is learned from these kinds of projects could help to develop P2P power trading in the future.

5.3 Limitations and recommendations

This research was conducted doing conceptual qualitative research with a predetermined saturation point. This research was done reviewing scientific and technical literature about the electric power system and digital technologies. Due to the abundant amount of information available, saturation point was decided to be when “no new data has novel information relevant for this study”. This research excluded legislation, regulation, taxation or other financial subsidies. These aspects were not researched since the research area were already too wide. These aspects, however, play a significant role in the energy / electric power system and they need to be considered when applying changes.

Conceptual research, which this research was based on, was conducted with an attempt to exclude previous information and assumptions about this topic. This might be considered as achieved, since the research topic was new for the researcher and previous knowledge was limited. However, this might lead to question of how thoroughly data was collected and did research process neglect essential data. Research was done on iteration, collecting data from a larger perspective and then focusing on each specific area. After data collection achieved saturation, data collection ended. Notably, data assessment occurred during the writing phase in order to ensure validation of data.

Based on collected data, most relevant theories and methods were found. Based on these theories and methods, the most suitable pilot projects were chosen to highlight different aspects of the electric power system. These pilots were chosen to demonstrate usage of artificial intelligence or other digital technologies to improve some part of the electric power system.

Since this research was done with a predetermined saturation point, some of the data might have been missed. Attempts were made to mitigate this by analysis of the data, but still risks remain. If this research was replicated, new aspects and findings would undoubtedly emerge.

Financial benefit of forecasting is an under-researched area. Some research has been conducted, but has yielded more or less estimations. The focus in this area has been mainly on methods; those that are the most suitable. Therefore, the true economic impacts of implementation of different technologies would offer insight into how beneficial they truly are. For example price forecasting is popular research topic and different types of methods exist. However financial benefits lay hidden. All forecasting methods become more crucial when electric power system transitions toward more complex and stochastic power generation. Therefore value that forecasting methods create should be studied more.

There is a lot of research on technical applications and visions for the future. To apply changes to the power grid and whole power system requires consumer activation. In a new system, customers and prosumers are predicted to actively participate in forms of power generation, DR or markets. They have the power and ability to affect changes and transition to a new system. Market opportunity lay in what kind of products and service consumers require and need.

Therefore suitable research should be done regarding customer needs. Some research in this field has been conducted, also in Finland. Ruokamo et al. (2018) studied preferences of consumers on how willing consumers are to participate in DSM-programme and what type of trade-offs they are willing to make. These trade-offs were loss of control of loads to gain financial gains and reduce carbon footprint. These types of studies are good start, but more and advanced research, must be conducted in order to gain more information of consumer preferences and finally needs. Based on information, new solutions can be created to offer value for consumers.

6 CONCLUSION

The power and energy sector is in a transition phase. Megatrends such as climate change and electrification drive the energy sector towards change. This transition alternates the whole value chain of the energy sector including power generation, transmission and power usage.

With the requirement to reduce carbon emissions while increasing power supply, electric power systems need to reduce carbon-based power generation and increase carbon-free power generation. This requires massive investments globally to replace existing power plants either with nuclear power or with renewable energy sources (RES).

RES includes multiple technologies such as wind, photovoltaics, hydro and biomass. Especially solar power and wind power have seen decreases in price in recent years and the total installed capacity has risen notably.

The first research problem in this dissertation was the following: *How do renewable energy sources affect the electric power system?*

Volatile renewable energy sources such as wind and solar have downsides compared to traditional thermal power plants and hydropower: they are weather dependent and therefore they cannot be adjusted to match power demand. This reduces total electric power system flexibility. Solutions to improve the power systems and increase flexibility can be found in digital technologies, to collect data, monitor, control, optimize and even make parts of the system autonomous. Digital technologies also enable demand-side management (DSM) to change consumption patterns. Addition to digital technologies energy storage has larger part of power system. Long-term storage solution, power-to-X was discussed and managerial implication of its use was illustrated in VPP-case.

The second research problem was formed to improve understanding of the future of the electric power systems and it was: *How can digital technologies and AI help transition to a power system with a high integration of renewable energy sources?*

Digital technologies have already shaped other industries' ecosystems and companies' business models. Transition towards digital solutions is viewable in hospitality, taxi-industry, delivery and e-commerce to name a few. Peer-to-peer (P2P) services and platform economy with new marketplaces offer consumers better value than traditional ones.

In the energy sector, similar solutions are emerging. DSM allows consumers to be active participants in the electric power system. Aggregators (service provider) bundle consumers into larger groups to control their consumption data and their loads. The smart load controlling aggregator can shift demand towards a period of time when demand is lower. This results in economic benefits for consumers, since during that time, electricity is cheaper. Demand shifting helps to balance supply and demand by reducing the need for expensive peak load power plants.

Power flow has been a one-way stream from the power generator towards consumers. Interest in changing this to generate needed power locally in a microgrid (MG) and trading it between consumers has gained interest. Even though commercial MGs are a rather new concept, they have the potential to improve the grid resilience and security while reducing carbon footprint of power generation with distributed energy resources such as wind power and PV. Participants trade power using blockchain technologies with the help of data collection of IoT devices.

Digital technologies including artificial intelligence (AI) and IoT assist companies to shift towards data and information-based decision-making. Digital technologies enable optimization and self-operating algorithms, which process massive amounts of data to operate.

The third research question seeks implemented real-life solutions. It was stated as follows: W*hat are most suitable pilot projects using digital technologies to enable renewable energy systems?*

This thesis illustrated three novel solutions, which improve the system compared to traditional ones. These cases were chosen, since they include advanced implementation of digital technologies, improve the current system and highlight emerging transitions that might even change the electric power system completely.

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