TAMPERE UNIVERSITY OF TECHNOLOGY

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USE OF ELECTRICITY STORAGES IN SMART GRIDS

Master of Science Thesis

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TIIVISTELMÄ

TAMPEREEN TEKNILLINEN YLIOPISTO
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Energian varastointi perustuu erilaisten kemiallisten ja fysikaalisten ilmiöiden hyödyntämiseen. Energiaa on siten mahdollista varastoida useilla eri tavoilla kuten mekaanisessa, kemiallisessa, sähkökemiallisessa ja termisessä muodossa. Tässä työssä energiavarastot on rajattu koskemaan seuraavia ns. sähköenergiavarastoja: akkuja, superkondensaattoria, vauhtipyörää sekä suprajohtavaa sähkömagneettista energiavarastoa (SMES). Akuista tähän työhön on valittu lyijyakku, natrium-rikkiakku, nikkeli-kadmiumakku, nikkeli-metallihydridiakku sekä litiumioniakku.

Sähköenergiavarastoja ei ole perinteisesti käytetty sähkönjakeluverkoissa, sillä ne ovat kalliita ja niissä aiheutuu häviöitä varastoinnin aikana sekä muunnettaessa energiaa muodosta toiseen. Sähköenergiavarastoista akkuja on käytetty sähköasemilla ja kauko-ohjattavilla erotinasemilla niiden omia ohjaus- ja tietoliikenneyhteyksiä varten mutta ei kuitenkaan sähkön laadun parantamiseen tai tasapainottamaan kysynnän ja tuotannon aiheuttamaa tehon vaihtelua verkossa.

Tilanne saattaa kuitenkin muuttua lähitulevaisuudessa monista eri syistä. Akkuteknologia on kehittynyt viime vuosina paljon sähkö- ja hybridiautojen kehityksen myötä ja vaikka sähköenergiavarastot ovat sinänsä vanhoja keksintöjä, niin esimerkiksi nanoteknologia on vienyt superkondensaattoreiden ja suprajohtavan sähkömagneettisen energiavaraston kehitystä eteenpäin. Lisäksi sähkönjakelun laadun odotukset yhteiskunnassa nousevat jatkuvasti, mihin sähköenergiavarastot tarjoavat osaltaan yhden ratkaisun. Sähköenergiavarastoja voidaan tulevaisuudessa käyttää myös tasapainottamaan kuormituksien ja tuotannon vaihteluita. Vaikka sähköenergian kysyntä on vaihdellut aina, verkkoon liitettäessä yhä enemmän uusiutuvaa epäsäännöllistä tuotantoa, kuten tuulivoimaa, tehon vaihtelu sähköverkossa kasvaa entisestään.

Sähköenergiavarastoja vertailtaessa tärkeitä tekijöitä ovat mm. teho, energia, vasteaika, teho- ja energiatiheys, elinikä, kustannukset, koko, itsepurkautuvuus, turvallisuus sekä ympäristönäkökulmat. Lyijyakut edustavat perinteistä ja edullista tekniikkaa, mutta ne ovat teknisiltä ominaisuuksiltaan selvästi muita akkuja huonompia. Natrium-rikkiakuilla on taas sekä korkea teho- että energiakapasiteetti sekä pitkä elinikä. Nikkeli-kadmium- sekä nikkeli-metallihydridiakut kärsivät suuresta itsepurkautuvuudesta, mutta toisaalta pystyvät toimimaan laajalla lämpötila-alueella.

Litiumioniakuilla on puolestaan korkea energiatiheys sekä hyötysuhde verrattuna muihin sähköenergiavarastoihin. Superkondensaattorista saadaan puolestaan suuri teho, ja se pystytään purkamaan kokonaan lähes välittömästi, tosin sen energian varastointikapasiteetti on melko rajallinen. Suprajohtavalla sähkömagneettisella energiavarastolla on taas pitkä elinikä ja sen varastoinnin aikaiset häviöt ovat lähes olemattomat, mutta se on vielä nykyään aivan liian kallista tekniikkaa. Vauhtipyörä puolestaan kärsii suhteellisen suuresta itsepurkautuvuudesta, mutta sillä on kuitenkin korkea hyötysuhde ja elinikä.

Sähköenergiavarastot nähdään oleellisena osana tulevaisuuden älykkäitä sähkönjakeluverkkoja. Ne mahdollistavat osaltaan esimerkiksi mikroverkkojen käytön, mutta toisaalta niiden hyödyntäminen tulevaisuuden jakeluverkoissa asettaa myös omia edellytyksiä ja vaatimuksia, kuten esimerkiksi kaksisuuntaisen mittauksen sekä haasteita verkon suojaukselle ja käytölle. Sähköenergiavarastoja voi tulevaisuudessa olla hyvin erikokoisia ja niitä voi olla sähkönjakeluverkoissa eri paikoissa. Lisäksi niitä voidaan liittää suoraan myös esimerkiksi hajautetun tuotannon yhteyteen ja toisaalta myös asiakkailla voi olla tulevaisuudessa omia energiavarastoja kuten sähköautoja.

Koska sähköenergiavarastojen verkkoon liittämisestä ei ole vielä standardia, niiden liittäminen sähkönjakeluverkkoon voidaan rinnastaa hajautetun tuotannon verkkoon liittämiseen. Pääperiaatteita on, että energiavarastot eivät saa aiheuttaa verkkoon häiriöitä ja niiden pitää toimia turvallisesti ja lisäksi vaaditaan mm. näkyvä erotusväli. Esimerkiksi standardissa SFS-EN 50438 on esitetty mikrotuotannon verkkoon liittymisen vaatimuksia. Sähköenergiavarastojen verkkoon liittäminen AC- ja DC-verkkoihin on käsitelty tässä työssä erikseen. Sähköenergiavarastoja AC-verkkoon liitettäessä vaaditaan tasasuuntaaja ja verkkoon syöttäessä taas vaihtosuuntaaja, sillä monet sähköenergiavarastot toimivat DC-jännitteellä. Jos sähköenergiavarasto taas liitettäisiin tulevaisuudessa suoraan DC-verkkoon, niin se olisi yksinkertaisempaa, koska suuntaajia ei tarvittaisi.

Sähköenergiavarastojen hyödyntäminen voidaan jakaa kahteen pääryhmään: sähkönjakelun laadun hallintaan sekä energianhallintaan, mikä tarkoittaa tuotannon ja kuormitusten aiheuttaman tehovaihtelun tasapainottamista. Sähkönjakelun laatu pieni- ja keskijänniteverkoissa määritellään standardissa SFS-EN 50160. Tässä työssä sähkönjakelun laadun osalta käsitellään jännitekuoppia, jännitteen nopeaa vaihtelua, välkyntää sekä lyhyitä ja pitkiä keskeytyksiä, mutta ei kuitenkaan esimerkiksi taajuuden muutoksia. Sähkönjakelun laadun hallinnan kannalta tärkeimpiä ominaisuuksia ovat suuri teho mutta verraten pieni energiamäärä sekä erittäin nopea vasteaika. Uusiutuvan energiantuotannon aiheuttamaa tuotannon vaihtelua sekä kysynnästä aiheutuvaa vaihtelua varten taas vaaditaan suurempi energiamäärä ja riittävän nopea vasteaika, minkä ei tarvitse olla niin nopea kuin sähkönlaadun hallinnassa.

Superkondensaattori, SMES, vauhtipyörä, lyijyakku, nikkeli-kadmium, nikkeli-metallihydridi sekä litiumioniakku sopivat parhaiten sähkönjakelun laadun hallintaan. Energian hallinnan sovelluksiin sopivat tässä työssä tutkituista energiavarastoista ainoastaan natrium-rikkiakut ja tulevaisuudessa mahdollisesti litiumioniakku sekä

SMES, mikäli sen kustannukset laskevat rajusti. Pumpatut vesivarastot sekä paineilmavarastot sopisivat myös hyvin energian hallintaan, mutta niitä ei tässä työssä käsitelty tarkemmin.

Yhteenvetona voidaan sanoa, että vaikka sähköenergiavarastot ovat vielä kalliita, ne nähdään monella tapaa oleellisissa rooleissa tulevaisuuden älykkäissä sähkönjakeluverkoissa. Ne mahdollistavat esimerkiksi hajautetun tuotannon paremman hyödyntämisen, ja ovat myös osittain kilpaileva vaihtoehto esimerkiksi kysynnän joustolle. Sähköenergiavarastoilla voidaan tulevaisuudessa parantaa sähkönjakelun laatua ja saada tasapainotettua kysynnän ja epäsäännöllisen tuotannon aiheuttamaa vaihtelua, jolloin voidaan vähentää huipputuotantokapasiteettia ja sähkönjakelun laadun, kuten keskeytysten aiheuttamia kustannuksia. Mikäli sähköenergiavarastoja liitetään sähkönjakeluverkkoihin, tulee niillä olemaan vaikutusta mm. verkkotopologiaan sekä verkon suunnitteluun. Joissain tapauksissa saattaa olla esimerkiksi mahdollista mitoittaa verkko kevyemmin ja säästyä kalliilta investoinneilta.

ABSTRACT

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Electrical energy in an AC grid cannot be stored electrically without a storage device. Distribution networks have traditionally contained almost none electricity storages. Main reason for this has been that storing electricity is incredible expensive but the situation will be different soon for many reasons. This study will focus more closely to following promising electricity storage technologies: batteries, capacitors, superconducting magnetic energy storages and flywheels which are the most interesting applications from distribution network point of view.

Electricity storages can be seen as an integral part of the Smart Grid concept and they will have a significant role in three classes: generation, distribution and end-user. Automated meter infrastructure and penetration of PHEVs and EVs will partly enable the use of electricity storages. On the other hand, electricity storages will allow the use of microgrids and increase the value of distributed generation.

The connection of electricity storages into electricity distribution networks allows and by contrast, requires the operating principle of network to be changed from passive to active network. Since there are no official requirements for distribution connections of electricity storages it can be assumed that same requirements are valid than those concerning distributed generation. Also, a power conversion system is needed between the grid and the electricity storage because most of the electricity storages release power as DC current and current of distribution network is AC. On the other hand, if DC supply becomes common integration of electricity storages into DC systems would be much easier compared to AC systems.

Electricity storage technologies can be simply categorized into two main categories: quality of supply and energy management technologies. First category contains such as supercapacitor, SMES, flywheel, lead-acid, nickel-cadmium, nickel-metal hydride and lithium-ion batteries that are intended mainly for high power ratings with a relatively small energy content making them suitable for quality of supply applications. The other category includes today only NaS batteries where relatively large amount of energy is needed.

In summary, electricity storages can be used to balance fluctuations in the supply and demand of electricity and also improve quality of supply. In addition, electricity storages can smooth out variability of renewable power production by allowing unused

electricity to be stored for later use. Utilization of electricity storages decreases the need for reserve power plants and cuts the costs of power failures. In addition, distribution network can be designed differently. Thus, construction costs will decrease and moreover, losses will reduce. In some cases, it is possible to avoid large investments in distribution network improvement. Furthermore, storage technologies provide significant environmental, economical and energy diversity benefits since overproduced unused energy can be stored and it can be reused during times when it is actually needed.

FOREWORD

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CONTENTS

TIIVISTELMÄ....II
ABSTRACT....V
FOREWORD....VII
ABBREVIATIONS AND NOTATION....X
1. INTRODUCTION....1
 1.1. Objectives and scope of the study....1
 1.2. Structure of the study....3
 1.3. Fortum Oyj....3
  1.3.1. Fortum Distribution Oy....4
2. ELECTRICITY STORAGES....6
 2.1. General....6
 2.2. Batteries....8
  2.2.1. Lead-acid battery....8
  2.2.2. Sodium-sulfur battery....9
  2.2.3. Nickel-cadmium battery....10
  2.2.4. Nickel-metal hydride battery....10
  2.2.5. Lithium-ion battery....11
 2.3. Capacitors....12
  2.3.1. Supercapacitor....13
 2.4. Superconducting magnetic energy storage....14
 2.5. Flywheel....16
 2.6. Discussion and summary....17
3. SMART GRID....22
 3.1. Concept of Smart Grid....22
  3.1.1. Distributed generation....24
  3.1.2. Microgrids....25
  3.1.3. Automated meter infrastructure....27
  3.1.4. Plug-in hybrid electric vehicles and electric vehicles....28
  3.1.5. Distribution automation....31
  3.1.6. Smart homes....31
  3.1.7. Demand response....32
 3.2. Smart Grid versus traditional distribution network....33
 3.3. Discussion and summary....34
4. NETWORK CONNECTIONS OF ELECTRICITY STORAGES IN SMART GRID....37
 4.1. General....37
 4.2. Requirements for distribution network connection....37
 4.3. Connection to AC loads and feeder....38
  4.3.1. Integration of electricity storage system into FACTS devices....38
 4.4. Connection to DC loads and feeder....39

5. USE OF ELECTRICITY STORAGES IN SMART GRIDS 42
5.1. General 42
5.2. Quality of supply management..................................43
5.2.1. Voltage sags 44
5.2.2. Rapid voltage changes and flicker 44
5.2.3. Short interruptions..................................44
5.2.4. Long interruptions..................................45
5.3. Energy management..................................45
5.3.1. Production management..................................46
5.3.2. Load management..................................46
5.4. Conclusions and discussion..................................47
6. SWOT ANALYSES OF ELECTRICITY STORAGES 51
6.1. Batteries..................................51
6.1.1. Lead-acid battery..................................51
6.1.2. Sodium-sulfur battery..................................52
6.1.3. Nickel-cadmium battery..................................52
6.1.4. Nickel-metal hydride battery..................................53
6.1.5. Lithium-ion battery 53
6.2. Supercapacitor 54
6.3. Superconducting magnetic energy storage..................................55
6.4. Flywheel 55
6.5. Summary 56
7. SUMMARY 57
REFERENCES..................................59

ABBREVIATIONS AND NOTATION

A	Area of the plates
C	Capacitance
E	Stored energy
I	DC current
J	Moment of inertia
L	Inductance of superconducting coil
q	Stored charge
Uc	Declared voltage
V	Voltage
ε	Permittivity
ω	Angular velocity

AMI	Automated meter infrastructure
AMR	Automated meter reading
CAES	Compressed air energy storage
CENELEC	European Committee for Electrotechnical Standardization
DE	Decentralized energy
DG	Distributed generation
DR	Demand response
EV	Electric vehicle
FACTS	Flexible AC transmission system
G2V	Grid- to-vehicle
HTS	High-temperature superconductor
ICE	Internal combustion engine
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
Li-ion	Lithium-ion battery
LTS	Low-temperature superconductor
NaS	Sodium-sulfur battery
Ni-Cd	Nickel-cadmium battery
Ni-MH	Nickel-metal hydride
PCS	Power conversion system
PHEV	Plug-in hybrid and electric vehicle
SGEM	Smart Grids and Energy Markets
SMES	Superconducting magnetic energy storage
STATCOM	Static synchronous compensator
SVC	Static var compensator
UPS	Uninterruptible power supply
V2B	Vehicle-to-building

V2G	Vehicle-to-grid
V2H	Vehicle-to-home

1. INTRODUCTION

Secure and high-quality supply of electricity is more and more important in today's society. Besides the world tries to struggle against climate change and to increase energy efficiency in many ways. All these facts mean also both new challenges and opportunities for electricity distribution networks. Distribution network is changing thus a lot in the near future.

It seems that electricity market will be more customer and small-scale power producer-driven in the future. The power grid will be a common marketplace for consumers and producers. Distributed generation, like wind and solar power plants, are increasing year by year. On the other hand development of telecommunication, information systems and especially automated meter infrastructure (AMI) enable a cost-efficient and real-time connection to each consumer and producer.

This means that distribution network in not passive anymore. Power does not flow on future grid in one direction from the power stations to the consumer but consumers can sell surplus of the own produced electricity to the grid. In addition to the above a high penetration of plug-in hybrid electric vehicles (PHEV) and electric vehicles (EV) having a grid connection will have enormous impacts on both the distribution network and energy market. Distribution network will become intelligent grid, called Smart Grid.

On the other hand, driving forces for development of electricity storage technology has also been the development of electrical and plug-in hybrid vehicles, in particular battery technologies, development of distributed generation as well as improvement of renewable and uncontrollable power production like wind and solar power plants. In addition preservation of nature, problems regarding reliability of network and quality of supply increase more and more needs of energy storages in the future.

1.1. Objectives and scope of the study

Electricity has traditionally been used at the same time at which it is generated. Although electricity storages have not been used in distribution networks for such purpose as improving power quality, batteries have been used e.g. as back-up power for automation devices of primary substation and remote-controlled disconnecting substation. Moreover, capacitors are in general used for as very short-term storage in inverters [1]. It can provide significant benefits regarding possible utilization of DC supply. Distribution networks have traditionally contained almost none electricity or energy storages if not taking account of as back-up power like diesel generators and pumped water that can store potential energy and used during periods of high peak demand. Main reason for this has been that storing electricity is incredible expensive but the situation will be different soon for many reasons.

Energy which can be converted into electricity can also be stored in many ways. This study will focus more closely to following promising electricity storage technologies: batteries, capacitors, superconducting magnetic energy storages (SMES) and flywheels that are most interesting applications from the distribution network point of view.

Electricity storages can be seen as an integral part of the Smart Grid concept and they can have a significant role in three classes: generation, transmission and distribution and end-user. Electricity storages can be used to balance fluctuations in the supply and demand of electricity and also to improve quality of supply. [2] Utilization of electricity storages decreases need for reserve power plants and cuts the costs of power failures. In addition, distribution network can be designed differently. Construction costs will decrease and moreover, losses will reduce. In some cases, it is possible to avoid large investments in distribution network improvement. [3] Furthermore, storage technologies provide significant environmental, economical and energy diversity benefits because overproduced energy can be stored and it can be reused during times when it is actually needed. [4]

This Master of Science Thesis is self-contained but also a part of a larger project called Smart Grid and Energy Markets which is operated by CLEEN Oy. Smart Grids and Energy Markets (SGEM) are divided further to five substances: Intelligent management and operation of Smart Grids, Active resources, Future infrastructure of power distribution, Smart Grids architecture and Energy market. Energy storages are one part of Active resources as shown in Figure 1. [5]

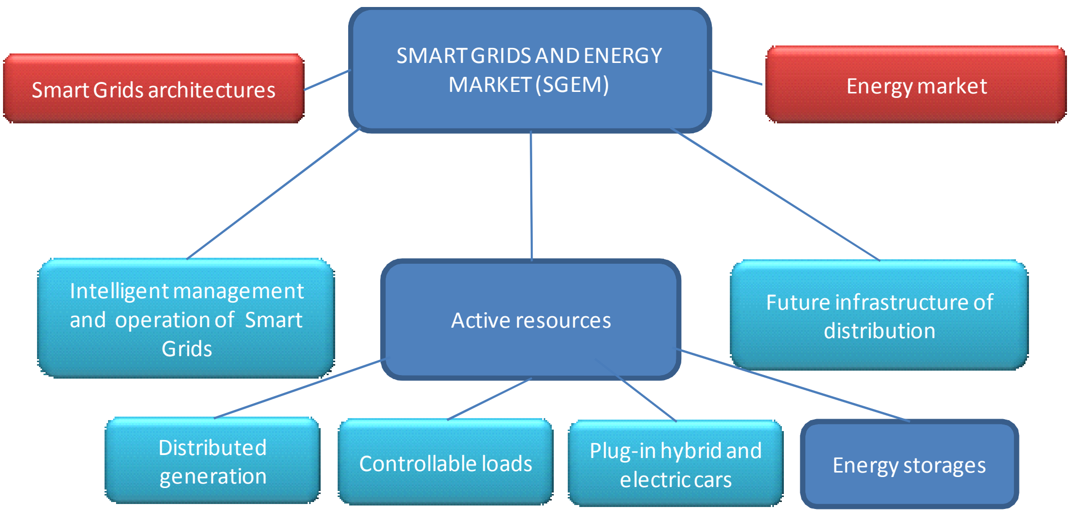

Figure 1. *The role of energy storages in SGEM. [5]*

1.2. Structure of the study

This study consists of seven chapters. The first chapter, Introduction, gives general information about the study and Fortum Oyj where this Master of Science Thesis is done. In addition, it includes background and trend as well as objectives, scope and structure of the study. After that, notable electricity storages like batteries, capacitors, superconducting magnetic energy storages and flywheels are studied in chapter 2.

There are basic facts about concept of Smart Grid in chapter 3. The goal is to provide clarification of what the Smart Grid is and give information of distributed generation, microgrids, automated meter infrastructure, plug-in hybrid and electric vehicles, distribution automation, smart homes and demand response. It is an important part of this study because the Smart Grid will enable utilisation of electricity storages in distribution networks in the future. At the end of the chapter comparison of today's distribution network and Smart Grid is shown.

Chapter 4 introduces network connections of electricity storages in Smart Grid. Next chapter 5 is the most important chapter of this study. Use of electricity storages in Smart Grid are examined in it. The point of last chapter 6 is to summarize features of different electricity storage technologies in the form of SWOT analysis.

1.3. Fortum Oyj

Fortum Oyj is a leading energy company in the Nordic countries, Russia and the Baltic Rim area. The main business sectors are generation, distribution, sale of electricity, and operation and maintenance of power plants (Figure 2). Fortum's shares have been quoted on NASDAQ OMX Helsinki since 1998. Sales of the company were 5435 million euros in 2009 and operating profit was 1782 million euros. There are approximately 13 300 employees in the company. [6, 7]

Fortum is number one in the Nordic market area in electricity distribution and district heat. In addition, the company is the second-biggest in electricity sales and third in power producer in the Nordic market area. Fortum's core purpose is that their energy improves life for present and future generations. Fortum operates responsibly and is also mindful of the global and local challenges in energy production as well as consumption. Sustainability is also an integral part in all of Fortum's operations. [6, 7]

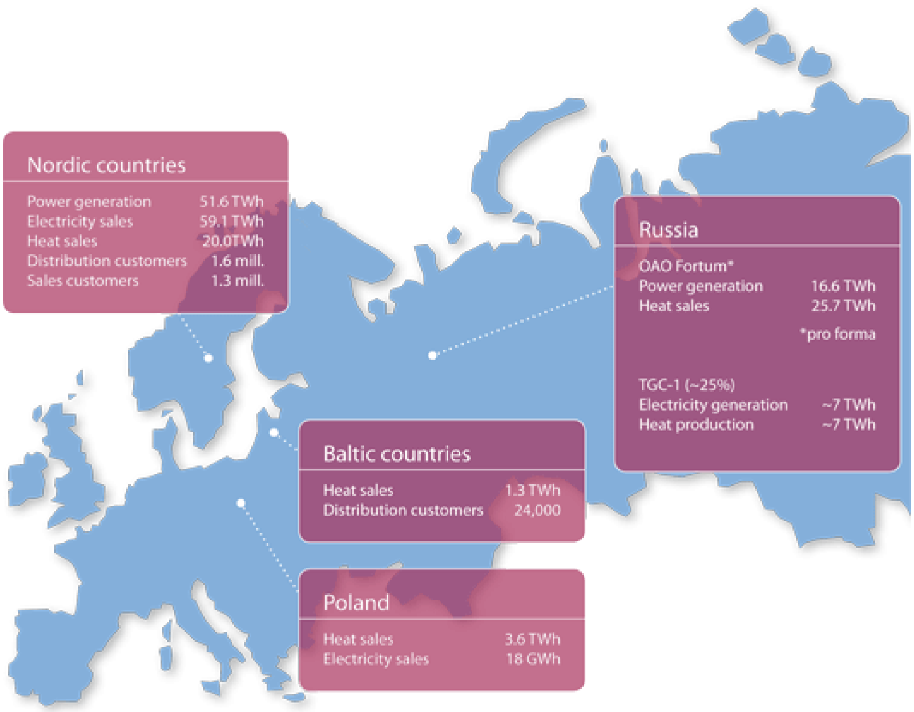

Figure 2. *Fortum in brief [6].*

Fortum consist of four business divisions: Power, Heat, Russia and Electricity Solutions and Distribution as shown in Figure 3. Power Division consist of following areas: power generation, physical operation and trading, operation, maintenance and development of power plants and expert services for power producers. Heat Division consists of combined heat and power generation, district heating activities and business to business heating solutions. Electricity Solutions and Distribution Division is in charge of Fortum's electricity sales, solutions and electricity distribution in regional and distribution networks. Russia Division is responsible for power and heat generation as well as sales in Russia. [6]

Figure 3. *Fortum organizational structure [6].*

1.3.1. Fortum Distribution Oy

Fortum Distribution Oy has total of 1.6 million electricity distribution customers in Finland, Sweden, Norway and Estonia. Combined length of distribution and transmission networks is 156,100 km. Network reliability is the most important goal of

Fortum Distribution Oy. By means of systematic maintenance, renewal and development of networks it is possible to provide quality, safety and reliability to electricity supply. [6, 7]

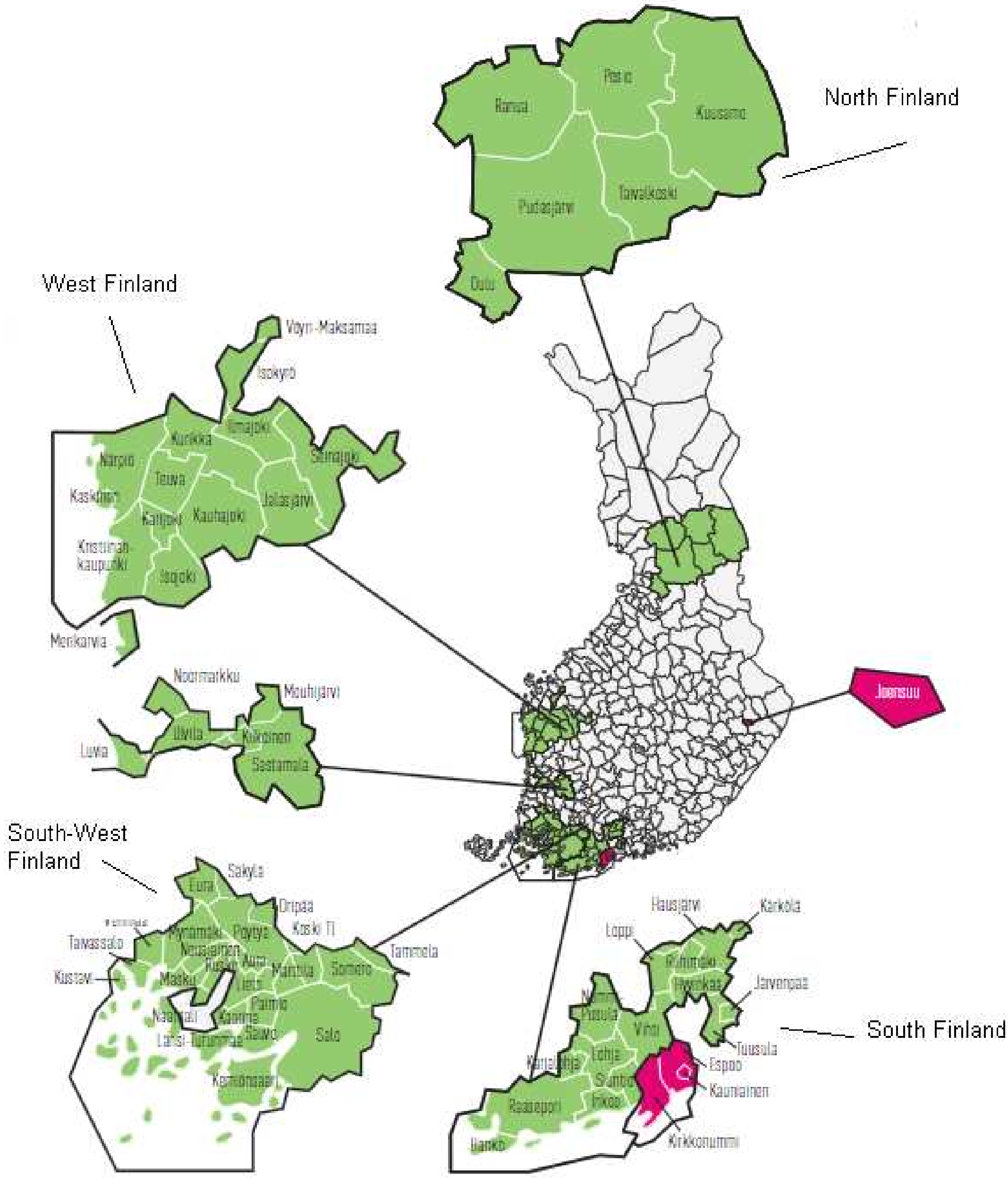

Figure 4. *Distribution areas of Fortum Distribution Oy in Finland [6].*

2. ELECTRICITY STORAGES

Electrical energy in an AC grid cannot be stored electrically without a storage device. Different energy storage technologies are based on the exploitation of physical and chemical phenomena. Energy which can be converted into electricity can also be stored in many ways. It can be stored not only in electric form but also in mechanical, chemical and thermal form, for instance pumped storages, compressed air, heat, secondary batteries, superconducting coils and hydrogen gas as shown in Table 1. [8, 9] However, this chapter will focus more closely to following promising electricity storage technologies: batteries, capacitors, superconducting magnetic energy storages and flywheels that are most interesting applications from distribution network point of view. Flywheel is also handled in this study but other mechanical such as pumped hydro and compressed air energy storage (CAES) or thermal are excluded because they have some essential restrictions and requirements on their use. For instance, geographically conditions will limit utilization of CAES. [8]

Table 1. *Energy storage technologies categorized by technology type [8, 10].*

Electrical:	Superconducting magnetic energy storage (SMES)
	Capacitors, for instance supercapacitor
Electro-chemical:	Batteries
Mechanical:	Pumped hydro
	Compressed air energy storage (CAES)
	Flywheel
Chemical:	Electrolyser / H2 / FC or ICE
Thermal:	Hot water, steam, ice, ceramics etc.

2.1. General

The problem of storing energy for electrical purpose has been the high price of storages, inadequate benefits and losses caused by storing. Short life cycle and complex control of electricity storages have moderated utilisation of storages in distribution networks. For these reasons there has not yet been sense to use electricity storages in the distribution network. [8] However, distribution networks are experiencing dramatic changes in operational requirements due to many reasons. The situation will probably change in the near future and electricity storages can be exploited widely in many ways. Recent advances and developments in electricity storages are making the application of electricity storage technologies a viable solution for power applications. [1] Thus, electricity storages will play a key role in Smart Grid.

Most of electricity storage technologies are based on the old innovations but the innovations for example in material technology has lately speeded up the development of energy storage applications. Development of new materials impacts on nearly all electricity storage technologies. For instance, increased knowledge of microtechnology has improved the development of the battery and capacitor systems. [8] On the other hand, nanomaterials are clearly promising for high surface area applications, such as supercapacitors and SMES. In particular, most of electricity storages would benefit from the development and identification of new materials that can increase energy densities [11].

Two factors mainly determine the application of an electricity storage technology. First is the amount of energy that can be stored in a device. Another factor is the rate at which energy can be transferred into or out of the storage. This is also impacted by the response rate of the storage device itself but it depends mainly on the peak power rating of the power conversion system. Each electricity storage technology usually includes such a power conversion system which converts the energy from one form to another. [1] Comparing different technologies all of the following factors should be considered as shown below [8, 11, 12]:

- Quantity of energy stored (kWh or MWh)
- Power level (kW or MW)
- Duration of discharge required (seconds, minutes, hours)
- Response time
- Transportability
- Energy density i.e. the capacity (Wh/kg)
- Power density (W/kg)
- Lifecycle
- Self discharge
- Capital cost and per-cycle cost
- Operating conditions
- Size and weight
- Environmental aspects
- Safety factors

2.2. Batteries

An early solution to the problem of storing electricity was the development of the battery. Battery technologies have evolved significantly in recent years in order to meet the challenges of practical electric car and utility applications. Batteries are electrochemical storage devices which are charged when they undergo an internal chemical reaction under a potential applied to the terminals. On the other hand, batteries are discharged when they reverse the chemical reaction. [1]

Batteries are divided into two categories: primary and secondary batteries. Primary batteries can be charged and discharged only once. Secondary batteries are possible to charge and discharge even thousands of times. The point of view is secondary batteries in this study. [1, 8]

There are a lot of battery technologies under consideration for large-scale energy storages. Traditional lead-acid batteries represent an established technology offering a low-cost option for most applications requiring large storage capabilities although it has low energy density and limited life cycle. In turn several other battery technologies also show promise for stationary electricity storage applications. All these batteries have higher energy density than lead-acid batteries but they are not cost effective for higher power applications. Nickel-cadmium (Ni-Cd) and lithium-ion (Li-ion) batteries are both being pushed for electric car applications where high energy density is possible to offset higher cost to some degree. [1]

In general, due to the chemical kinetics involved, batteries cannot operate at high power levels for long periods of time. The storage capacity of batteries will have a direct impact on the physical size of the storage system. [13] Advances in battery technologies offer increased energy storage densities, greater cycling capabilities, higher reliability and lower cost. The biggest challenges in using batteries as electricity storage are probably to make them both inexpensive and long-lived [11]. However, it is reasonable to expect that batteries will have important role as electricity storages in future distribution networks. The question is not if batteries can become a valuable component of the distribution networks in the future but rather when and which battery technology will dominate. [1]

2.2.1. Lead-acid battery

Lead-acid batteries are one of the oldest and most developed battery technologies. Lead-acid battery consists of a lead anode and lead-oxide cathode and a sulphuric acid solution electrolyte. During discharging the lead and lead dioxide react with electrolyte of sulphuric acid to create lead sulphate, energy and water. During charging the lead sulphate and water are electro-chemically converted to lead-oxide, lead and sulphuric acid by an external electrical charging source. [8, 14]

Lead-acid batteries are available in wide range of sizes and capabilities. They can also deliver high currents and are also reliable due to over 140 years of development. Lead-acid battery offers even today a very low-cost option for most applications requiring large storage capabilities even if it has limited life cycle, danger of overheating during charging, high weight, low energy density and it is not suitable for fast charging. On the other hand, their poor technical performance makes them gradually obsolete for the applications onboard vehicles. [15] Improvements in energy density and charging characteristics are still an active research field. Although it is an old invention, improvements are still being made to the lead-acid battery and despite of its shortcomings and the competition from newer battery technologies the lead battery still has a significant market share of the high power battery market. [1, 14]

2.2.2. Sodium-sulfur battery

Sodium-sulfur battery i.e. NaS belongs to high-temperature batteries which operate above 250 ºC. High operating temperature is not a problem for stationary applications since the inherent efficiency is extremely good. [16, 17] NaS batteries are composed of liquid, molten, sulfur at the positive electrode (anode) and liquid, molten, sodium at the negative electrode (cathode). Between these electrodes is a solid beta alumina ceramic electrolyte, which allows only the positive sodium ions to go through it as shown in Figure 5. [8, 12]

NaS batteries represent relatively secure technology offering both high energy and high power. NaS battery cells are efficient, 75-89%, and have no raw material limitations [12]. NAS batteries are more durable technology as average batteries because of their lifetime is almost 15 years. Therefore, it can be a good choice for utility scale applications. [10, 17] Widespread use of NAS batteries for distribution network applications would require significant reduction in current cost [11].

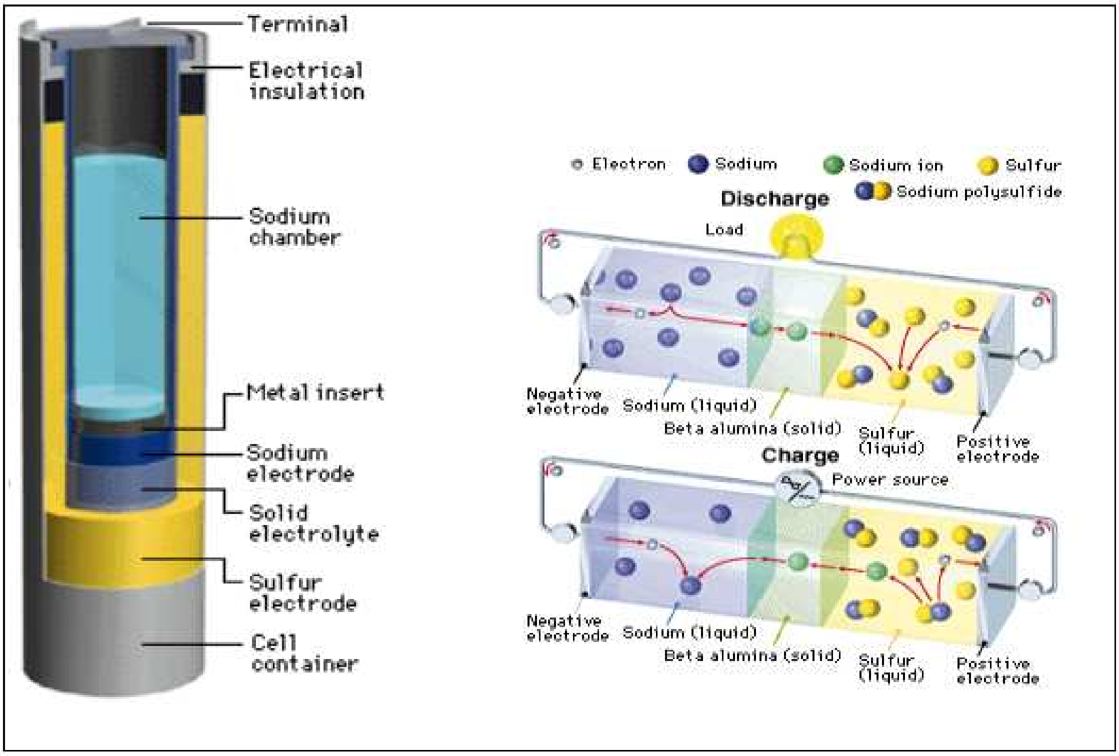

Figure 5. *NAS battery construction [12].*

2.2.3. Nickel-cadmium battery

Ni-Cd battery consists of nickel hydroxide as the positive electrode and cadmium as the negative electrode. Electrolyte is an alkaline potassium hydroxide. Ni-Cd battery is quite simple to charge and it allows also high number of charge/discharge cycles. It also allows recharging at low temperatures. One significant benefit is that it is a lowest in terms of cost per cycle. In addition to above, Ni-Cd batteries are available in a wide range of sizes. [8, 18]

Ni-Cd battery has also some limitations. It suffers from relatively high self-discharge and also memory effect which means that it must periodically be exercised (charge/discharge). It also has relatively low energy density and is environmentally unfriendly due to toxic metals. [18]

As a result, technology is mature but cadmium is undesirable because of raw material availability and it is also bad from an environmental perspective. However, it offer better life cycle than for example lead-acid with very good performance at both low and high temperature operation. [17]

2.2.4. Nickel-metal hydride battery

Ni-MH batteries are similar to Ni-Cd batteries except that the positive conductor (anode) is made from a far less toxic hydride alloy as opposed to cadmium. Advantages of Ni-MH are high energy density, wide operating temperature range (-30 - +45ºC), rapid charge possibility and flat discharge characteristics. The modern Ni-MH batteries present up to 40% higher energy density compared Ni-Cd batteries. [14]

Ni-MH batteries suffer also from memory effect and very high self discharge rate. Features of nickel-metal hydride battery deteriorate during long time of storage. This problem can be solved by discharging and charging the battery several times before use and in addition, it also serves to overcome the problems of memory effect. [11, 15]

Nickel-metal hydride batteries have better performance than lead-acid batteries but significantly higher cost. Compared to lithium-ion batteries, they are considered to be losing in the medium term, although today they are still more mature. They are also much more environmentally friendly than most other batteries. [15] Nickel metal battery look very promising for storage applications although it has some disadvantages such as low energy density and its vulnerability to overcharging in addition to above. [11]

2.2.5. Lithium-ion battery

Lithium-ion batteries are well known due to the fact that they are very common in consumer electronics. Li-ion batteries are found in laptops, mobile phones and other portable equipments. During charging, the lithium atoms in the cathode become ions and migrate through the electrolyte toward the carbon anode. (See Figure 6.) This process is reversed when the battery is being discharged. [8, 12]

Lithium-based batteries are divided into several different subtypes. Different types of lithium batteries use little bit different chemistry and have different performance, safety characteristics and cost. [3, 12] Their high energy density (300-400 kWh/m^3), high efficiency (near 100%) and long life cycle make them suitable for several applications. Some manufactures consider them very suitable for electric cars. Therefore, the car industry is currently main driver behind development of Li-ion batteries. [10, 12, 15]

Although Li-ion batteries are generally very common there are still some challenges for making large-scale Li-ion batteries. The main one is the high cost because of special packaging and internal overcharge protection circuits. Their power and energy ratings are still relatively small scale. They are not yet considered mature concerning power applications and are still at an early stage of development. However Li-ion batteries will continue to be used as smaller scale electricity storages and they will play an important role in mobile applications. [10, 17]

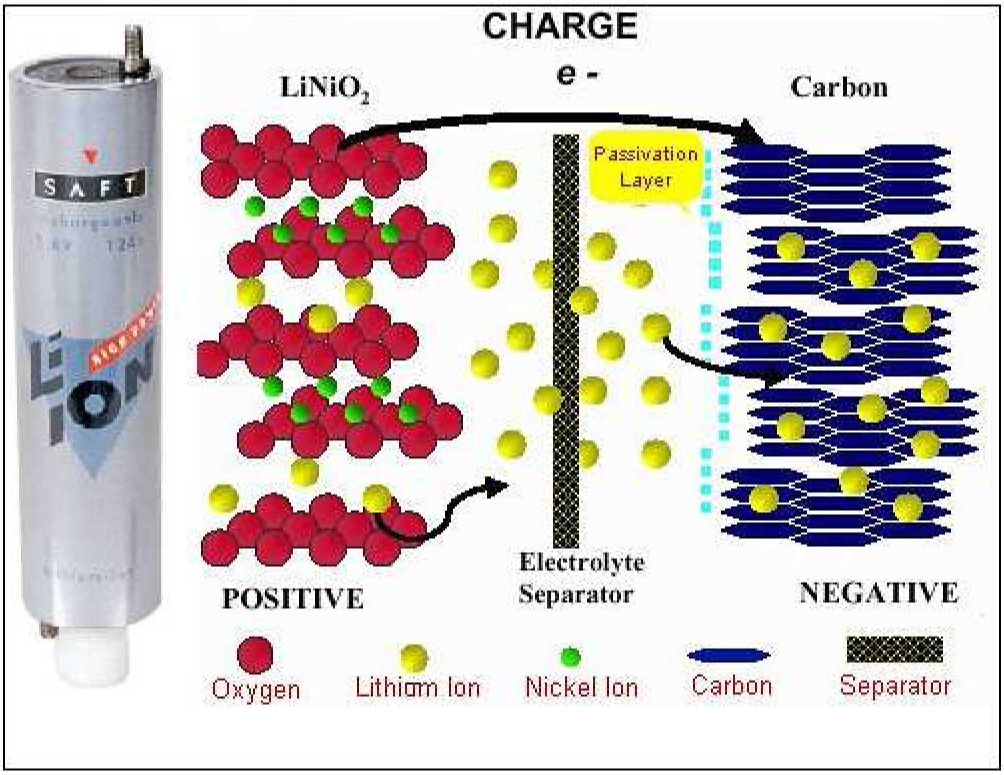

Figure 6. *Li-ion battery [12].*

2.3. Capacitors

Capacitors store electrical energy by accumulating negative and positive charges separated by an insulating dielectric. As shown in formula 1, the capacitance C represents the relationship between the voltage and the stored charge q. As formula 2 shows, the capacitance can be increased by decreasing the distance between the plates or, on the other hand, adding permittivity, ε, or increasing the area of the plates. Capacitors store their energy in an electrostatic field. The stored energy is related to capacitance and to the square of voltage as shown in formula 3. Thus, the amount of energy a capacitor is capable of storing is possible to add by increasing either the voltage or the capacitance or both of them. [1, 8]

$$q = CV \qquad (1)$$

where

q = stored charge
C = capacitance
V = voltage

$$C = \frac{1}{2}\frac{\varepsilon A}{d} \qquad (2)$$

where

C = capacitance

ε = permittivity
A = area of the plates
d = distance between the plates

$$E = \frac{1}{2} C V^2 \qquad (3)$$

where

E = stored energy
C = capacitance
V = voltage

2.3.1. Supercapacitor

Supercapacitors are relatively new electrochemical storage devices. Supercapacitor, also known as double-layer capacitor or ultracapacitor, can be used as electricity storage as well. Supercapacitors store energy in the two series capacitors of the electric double layer, which is formed between each of the electrodes and the porous electrolyte ions as in Figure 7. The distance over which the charge separation occurs is just a few hundred picometres. Several different combinations of electrolyte and electrode materials have been used in supercapacitors, with different combinations resulting in varying energy density, capacitance, cost characteristics and cycle-life.

Electrodes are mostly made of active carbon and they have wide specific surface area, round about 1000-2000 m^2/g. The electrolytes can be either water or organic based. Water based electrolyte limits the voltage to a little above 1 V, while with organic electrolytes the voltage can be increased to above 2.5 V. [9] Water based capacitors work in a wider temperature range but have a lower energy density due to a lower cell voltage. However, they are cheaper than others. [12] Generally, capacitors are capable of very fast charges and discharges. [1]

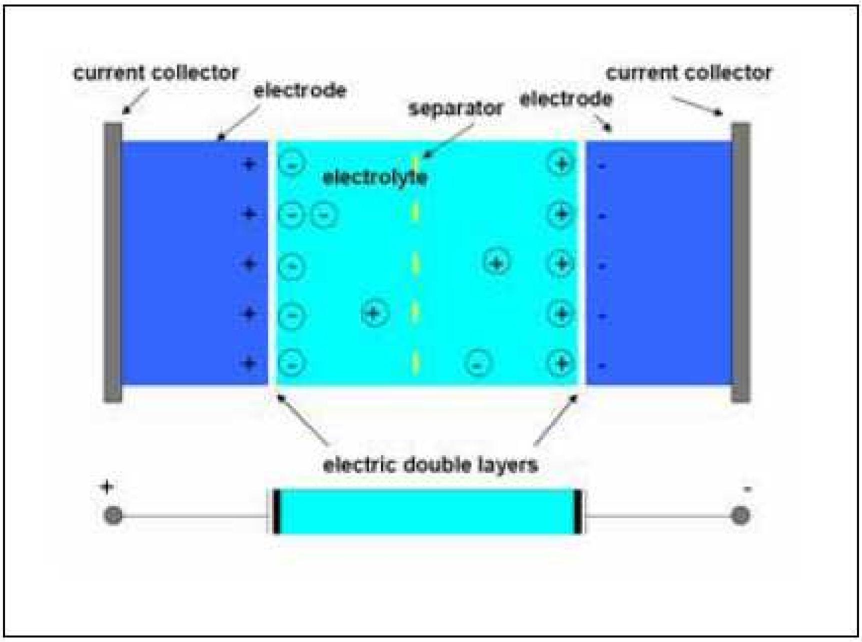

Figure 7. *Supercapacitor structure [18].*

Supercapacitors have long cycle of life, more than 500 000 charging/discharging cycles, and high power density (100-10000 W/kg). The capacitance and energy density of these supercapacitor applications is thousands of times larger than electrolytic capacitors although the density is still about tenth of the energy density of lead-acid batteries. Development of materials, for example nanomaterials, gives possibilities to increase energy density. As any new technology, challenges to widespread commercial use still exist. [8, 9, 12]

2.4. Superconducting magnetic energy storage

Superconductivity was discovered back in 1911 but it was not until 1970s that SMES was first proposed [1]. Superconductivity is based on the fact that in low enough temperature certain materials have no resistance to the flow of electricity. Well-known superconducting materials have this feature at very low temperatures, close to absolute zero (0 K=-273.15 ºC). Such materials were discovered later that become superconducting at higher temperatures. These materials are classified into two categories: low-temperature superconducting LTS and high temperature superconducting HTS. Today, most superconducting applications continue to make use of LTS wires. However, high temperature superconductive prototypes are more and more under development with encouraging results. [8, 19]

Superconductivity is based on electromagnetic phenomena. The current will not decay and energy can be stored indefinitely when coil is charged. The SMES store energy in the magnetic field generated by the DC current flowing through a superconducting coil. The maximum magnetic energy stored by a coil carrying a current:

$$E = \frac{1}{2}LI^2 \qquad (4)$$

where

E = stored energy
L = inductance of superconducting coil
I = DC current

Increasing the size of the coil can add the amount of stored energy although larger windings present a challenge because of the associated increase in magnetic field becomes more difficult to contain due to large magnetic forces. [11] Since energy is stored as circulating current, electricity can be drawn from an SMES unit with almost immediate response with energy stored or delivered over periods ranging from a fraction of a second to several hours. [1]

Structure of SMES systems are presented in Figure 8. It consists mostly of three main parts: a huge superconducting coil, power condition system PCS and cryogenically cooled refrigerator. Low temperature is maintained by a cryostat or dewar that contains nitrogen liquid vessels or helium. [1, 8]

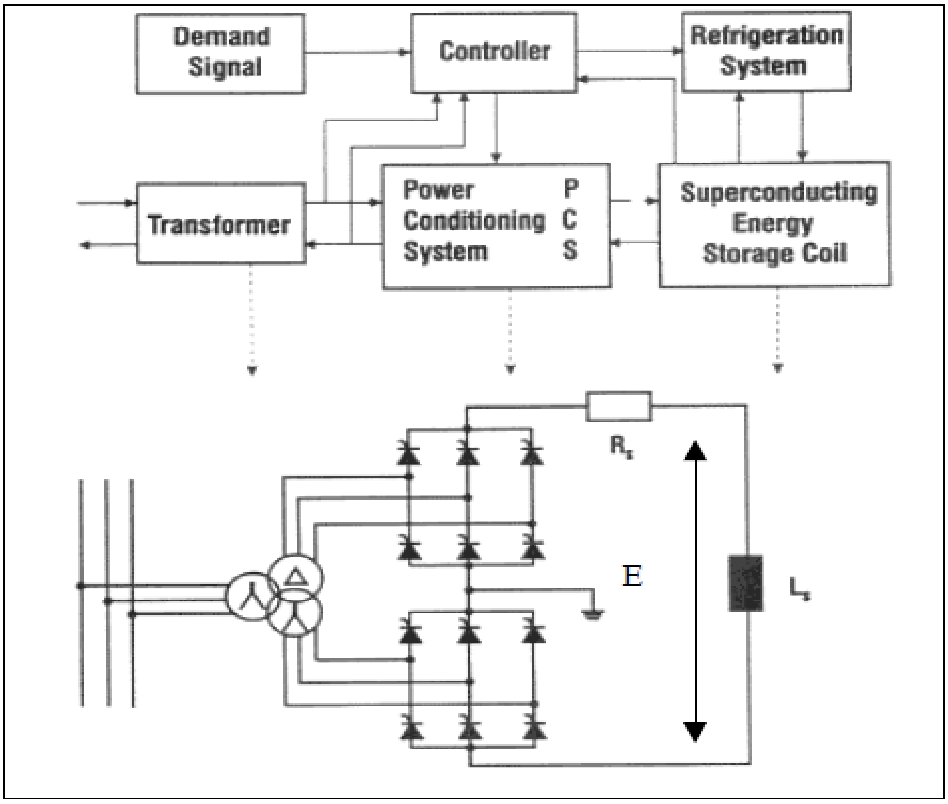

Figure 8. *Structure of SMES [8].*

SMES systems offer several potential advantages. The time delay during charge and discharges is quite short, power is available almost instantaneously and efficiency is very high, greater than 90%. In addition, it has very high power output in a brief period of time and power losses are low because of the coil resistance is negligible which means that energy can be stored almost indefinitely. Due to their fast response and high efficiency they suit theoretically well in applications at all levels of electric power systems. Addition to these, SMES system is reliable and requires little maintenance due to the fact that main parts of SMES are motionless. The magnetic field is the only environmental disadvantage. [8, 11, 19]

The main challenge of SMES is decreasing the overall cost of the system. Current technology is still based on low temperature superconductors, which require expensive cryogenics. Improvement in high-temperature superconductivity will play a big role in moving towards less expensive cryogenics and lower conductor costs. Although cryogenic costs are falling, the costs of high-temperature superconducting components are bigger than the possible savings in cryogenics. [11]

2.5. Flywheel

Flywheels are one of the oldest and most used energy storage technologies. Flywheel is mechanical storage where energy of flywheel is stored in the kinetic energy of rotating mass. Flywheels store the energy in a mechanical way and the storage capacity is proportional to the moment inertia of the flywheel unit and the square of its angular speed as shown in formula below. As in formula 5, the amount of energy stored depends upon the linear speed rotation and the mass of the disk, the energy storage capability of flywheels can be improved either by turning it at higher rotational velocities or by increasing the moment of inertia of the flywheel. [1, 8, 20]

$$E = \frac{1}{2} J \omega^2 \qquad (5)$$

where

E = stored energy
J = moment of inertia
ω = angular velocity

In general, flywheel unit consist of rotor, driving system, bearing and housing. The rotor consists of a generator/ motor that convert energy between mechanical and electrical form. An electric current flows during charging through the motor increasing the speed of the flywheel. During discharging, the generator produces current flow out of the system slowing the wheel down. [20, 21]

First-generation flywheels, typically consists of steel, increased the mass while maintaining rim speeds on the order 50 m/s. On the other hand, second-generation flywheels are manufactured from fiber-composite materials. These higher-speed systems are limited by the expansion of the rim and they also experience bending resonances and other dynamical instabilities. Third-generation flywheels are currently under development in which are combined high mass with high rotational speed to maximize overall electricity storage. However, the limited capacity and high cost of first- and second-generation flywheels has limited the implementation of this technology. [11, 21]

Bearing losses result in significant self-discharge and rotational losses due to drag from air, which poses problems for long-term electricity storage but flywheels have several advantages too. [1] Flywheels have long lifetimes (20 years), large maximum outputs and the efficiency can be as high as 90-96%. They require also very little maintenance and they are little affected by temperature fluctuations. In addition to above, flywheels contain no hazardous chemicals. [11] Flywheels can discharge their power either slowly or quickly. They can be divided in two categories for low-power applications or as short-term power quality support for high-power applications but most of flywheels belong to the second category. [20]

Figure 9. *Construction of flywheel [12].*

2.6. Discussion and summary

The goal of this chapter is to summarize features of different electricity storage technologies. Table 2 presents features of different electricity storages such as storage capacity, power level, lifetime, energy density etc. Also, power density versus energy density (Figure 10), discharge time at rated power (Figure 11) and cost comparison of different technologies (Figure 12) are presented.

Energy density (Wh/kg) is a measure of how much energy a storage can hold. The higher the energy density, the longer the runtime will be. Power density (W/kg) indicates how much power a storage can deliver on demand. (See Figure 10). It shows that batteries have very low power density but high energy density. According to Figure 10 capacitors can have in general very high power density but according to Table 2 supercapacitor has not the highest power density because for example SMES can have even ten times bigger power density than supercapacitor.

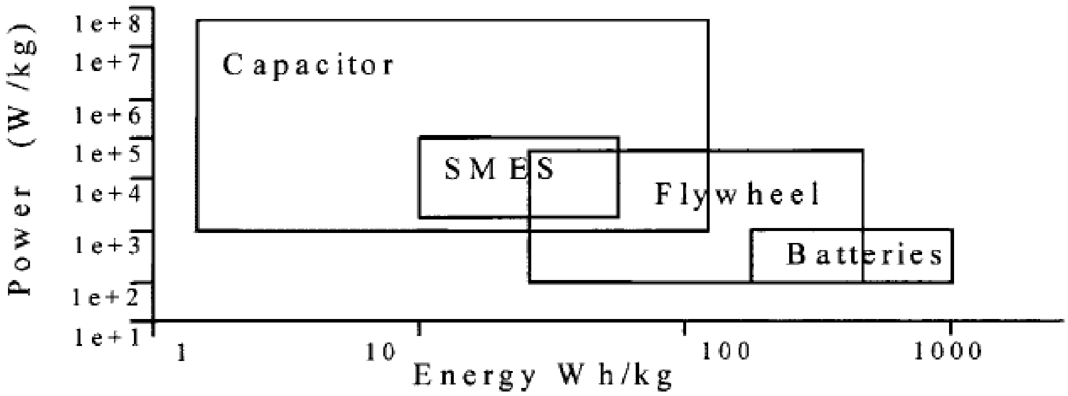

Figure 10. *Power density versus energy density ranges [1].*

According to Table 2 Li-ion and NaS have the biggest energy density while supercapacitor has the lowest. Supercapacitors energy density is only about one tenth of the batteries. On the other hand, SMES, flywheel, Li-ion and supercapacitor have high efficiency compared to other storages. Flywheels and SMES have the longest lifetime in years but if lifetimes in cycles are examined seems that supercapacitor has the longest lifetime in years. Supercapacitor, SMES and flywheels have very short response time (5 ms) but all batteries can respond in 30 ms. Supercapacitor and flywheels suffer from very high self discharging while SMES systems standby losses are almost zero.

Table 2. *Features of different electricity storages [3, 11, 17, 22].*

	Lead-acid	Li- ion	NaS	Ni-Cd/ Ni-MH	Supercap.	SMES	Flywheel
Energy storage capacity (up to)	500 MWh	500 MWh	500 MWh	500 MWh	0,2 kWh	500 MWh	500 MWh
Power level	1-10 MW	1-10 MW	1-6 MW	1-8 MW	1 MW	1-100 MW	1-100 MW
Response time	30 ms	30 ms	30 ms	30 ms	5 ms	5 ms	5 ms
Cycle efficiency	81-94 %	93-100 %	75-89 %	50-85 %	85-100 %	90-99 %	90-96 %
Lifetime (yrs)	3-15 yrs	6-20 yrs	15 yrs	10-20 yrs	10-15 yrs	20-40 yrs	20 yrs
Lifetime (cycle)	500-1200	1000-4000	2500-4500	1000-2500	500 000	100 000	100 000
Self discharge (% per month)	1-4 %	0-6 %	1-4 %	5-40 %	50 %	-	72 %
Energy density (Wh/kg)	35-40	30-200	53-116	10-60	5	4-75	5-100
Power density (W/kg)	400	6-2000	9-15	40-1300	100-10000	1000-100 000	1000-10000

Compared to supercapacitors and flywheels, batteries can store in general higher energy but due to higher internal impedance, can deliver the energy at much lower power level, as describe in Figure 11. In addition, most batteries cannot be completely discharged in few seconds unlike SMES and supercapacitors as shown in Figure 11. [13]

Figure 12 projects only estimated costs of technologies because different technologies are quite difficult to compare due to the number of cost components for such as storage device itself, installation, construction, maintenance, converters, control and protection systems etc. According to it, lead-acid battery is the cheapest (euro/kW) and it provides quite long backup time as in Figure 11. Slow flywheels are cheapest (euro/kW) for short backup time applications while supercapacitors are considerably expensive although their cost varies quite a lot. Also, batteries such as Li-ion, Ni-Cd and Ni-MH seem more expensive compared for example to lead-acid battery. [3]

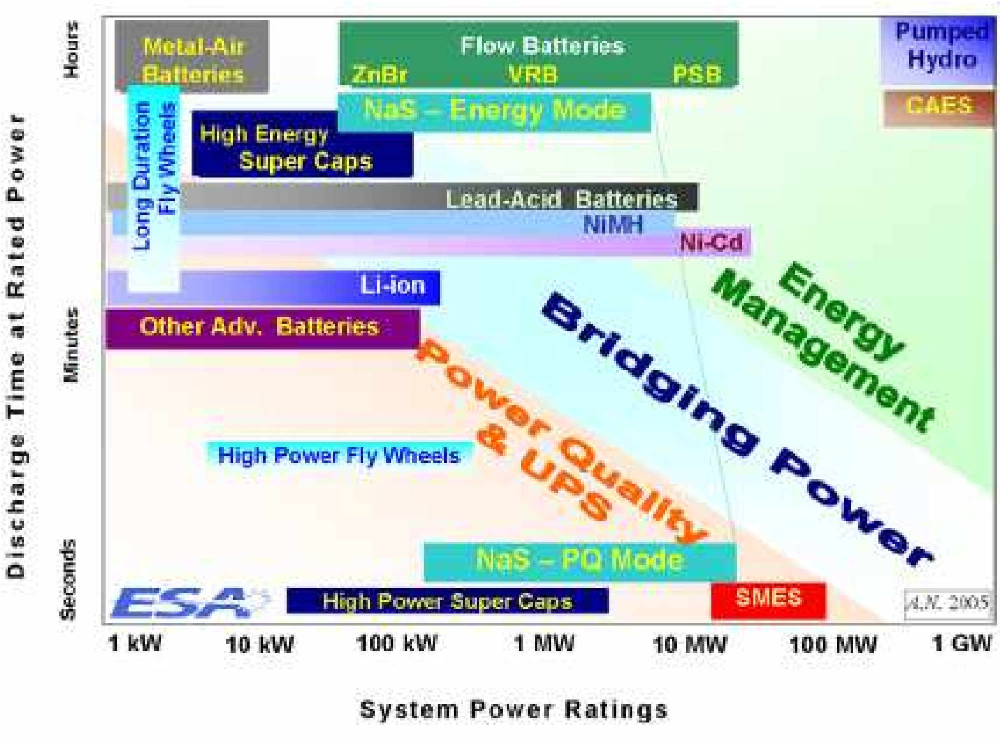

Figure 11. *Discharge time at rated power of different types of electricity storages [12].*

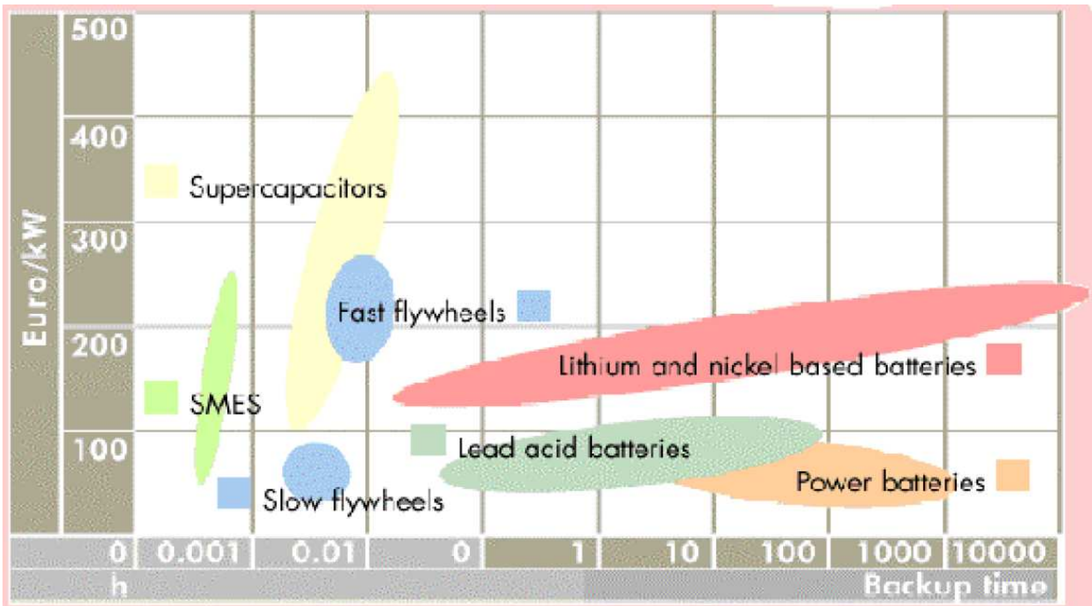

Figure 12. *Cost comparison of different technologies [8].*

All in all, batteries have in general relatively poor cycle efficiency (excluding Li-ion), short life time except Ni-MH and Ni-Cd batteries and response time is quite long compared other technologies. The advantages of supercapacitor, flywheel and SMES over batteries include long life cycles, high charge/discharge efficiency and fast response. SMES is also environmentally friendly and can respond rapidly to changes in power demand. But compared with other technologies SMES systems are still costly. Flywheel and most of batteries are cost-effective compared to other technologies. On the other hand, supercapacitors have several advantages such as a temperature-independent response, high power density and low maintenance but main disadvantage of supercapacitors is relatively high cost and low energy density. In turn, main disadvantage of flywheels is very high self-discharging. Although SMES systems and supercapacitors are still in their prototype stages they are receiving more and more attention and therefore they might be also very promising technologies in the future too. [1, 11]

3. SMART GRID

In this chapter the concept of Smart Grid is discussed introducing driving factors towards it and gives also definition to Smart Grid. After this, main parts of Smart Grid like distributed generation (DG), microgrids, automated meter infrastructure (AMI), plug-in hybrid and electric vehicle, distribution automation, smart homes and demand response (DR) are introduced. Each subsection describes basic facts about it and also provides information from the electricity storages point of view. In addition, traditional distribution network and Smart Grid comparison is presented. This chapter concludes with discussion and summary.

3.1. Concept of Smart Grid

There are three factors which are pushing for changes regarding electricity grids as shown in Figure 13. These factors are European internal market, security and quality of supply and the environmental issues like the need to reduce harmful pollutants. Furthermore, appreciable factors towards the intelligent grid are such as aims to decrease climate change, aging infrastructure, increasing demand for energy and in addition, improving energy efficiency. In practise, such facts like rapid development of telecommunications and information systems which enables a cost efficient and real-time connection to each consumer and producers and on the other hand, a high penetration of plug-in hybrid and electric vehicles plays also significant role concerning Smart Grid. [12, 23]

Directive 2009/72/EC requires among other things incentives to develop distribution network both in the long and short term, development of network in the most cost-effective way and in addition, increased integration of large and small-scale production of electricity from renewable energy sources and distributed generation in distribution networks. [24] Although the present distribution network has served well enough there are lot of improvements still to do.

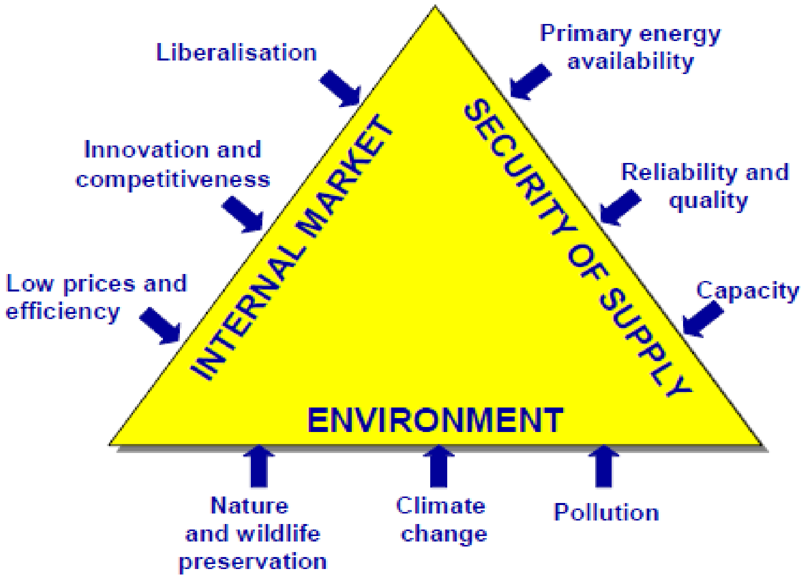

Figure 13. *Three factors pushing for changes regarding electricity grids [2].*

Smart Grid has many definitions but it can be characterized for instance as follows and as shown in Figure 14 [25]:

- interactive with consumers and markets
- self-healing grids with high level of automation
- secure and reliable
- proactive rather than reactive, to prevent emergencies
- adaptive and scalable to changing situations
- having plug-and-play –features for network equipment and ICT solutions
- integrated, merging monitoring, protection, control, maintenance, EMS, distribution management system and AMI
- optimized to make the best use of resources and equipment

Smart Grid is also defined simply as follows: Electric power system that closely integrates the supply and demand sides of the electricity business with advanced information, communication, and control technologies. [26]

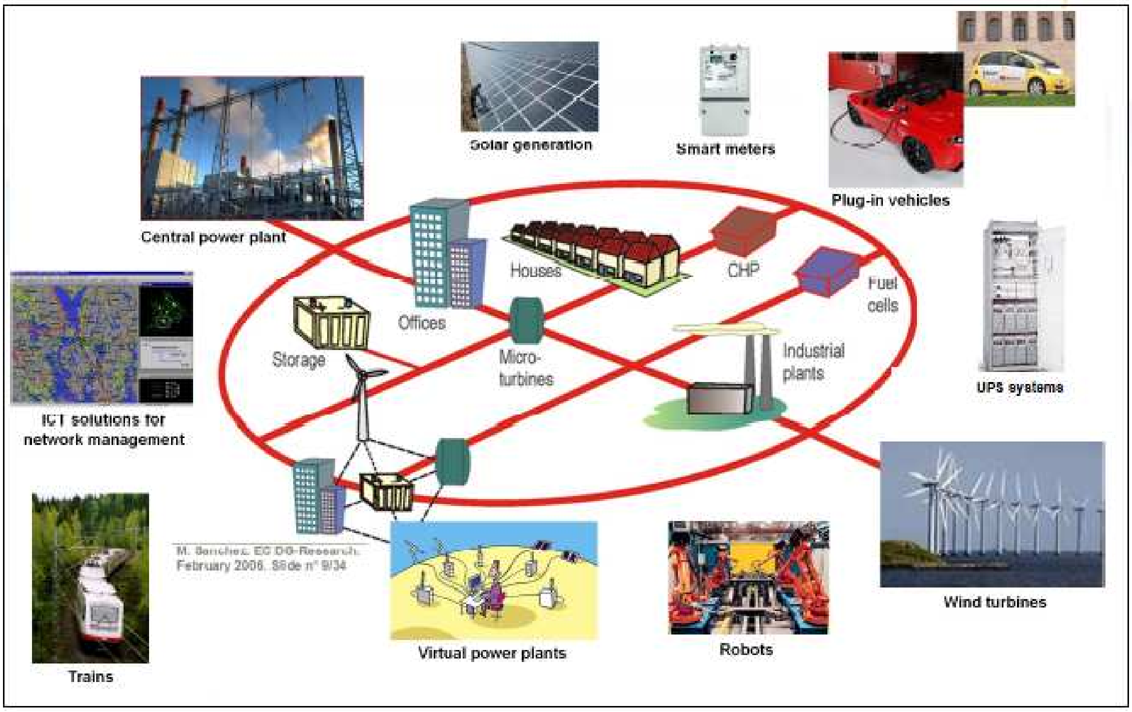

Figure 14. *Concept of Smart Grid [27].*

3.1.1. Distributed generation

Electricity has traditionally been produced centralized in large plants and far from the end users. Power must be transported over long distances at high voltage before it can be put to use. However, the situation has gradually changed due to penetration of distributed generation (DG). Distributed generation or decentralized energy (DE) is defined as energy production near the consumer and the energy is produced at many locations as opposed to the centralized generation. [28] Main drivers for DG development has been for instance environmental issues, development of small power generation systems, cost of power and open electricity markets [9].

Distributed generation means all production, which is produced near the end-user despite the size and type of the power plant. Internationally, DG includes different technologies not only non-fossil, renewable, like solar and wind power plants but also high efficiency cogeneration which means often fossil fuelled technology. In practice, DG includes many different energy technologies such as wind turbines, solar energy, hydro power, geothermal energy, micro-turbines, gas turbines, fuel cells and stirling engine. Further, technologies can be divided also into two main categories: renewable and high efficiency cogeneration which means production of electricity and useful heat. [28, 29]

Electricity storages can be seen as a key component for the further implementation of DG because they will allow a larger share of uncontrollable energy sources. [9] According to [23] for the integration of wind energy suitable electricity storage that offers capacities from hours up to several days is desirable. One vision is that wind turbines have their own electricity storages for example batteries, but today it is still too expensive. [15, 17]

DG when properly applied may have many benefits such as more reliable supply, better management of energy use and production, increased use of renewable energy, energy savings and decreased need for building new transmission lines. [9] Distributed generation gives also the consumer an opportunity to participate in the energy production for instance with small wind power plants. However, the connection of DG into electricity distribution network enables and also requires the operating principle of network to be changed from passive to active. Therefore, there are a lot of challenges for distribution network among other things to improve the capability to serve the increasing amount of DG and safe operation of distribution networks in all circumstances. [25] All in all, implementation and use of DG systems and their integration to electricity networks can be challenging task and can require new products and systems. [18, 30]

Distributed generation and centralized generation will not compete with each other but complement one another in the future. [28] Centralized power generation is supposed to form the majority but DG will play a notable role in the future. All in all, significance of DG is hard to predict accurately for instance due to the uncertainly of the development of the regulation. Distributed generation will also partly enable utilization of microgrids which is discussed next. [26]

3.1.2. Microgrids

Microgrids are a collection of DG technologies grouped together in a specific area and connected at a single point to the larger grid. [28] Microgrid system includes some local generation, consumption, controllable loads and one or more energy storages. Microgrid is a part of low-voltage network and it can be considered as a controlled unity perspective of the main grid. A microgrid system is capable of independent island operation if required. If a fault occurs on the main distribution network the microgrid can continue to operate in an island. Islanding is enabled by DG and energy storages as described above. [26, 29]

The low-voltage section that forms the microgrid or part of it can be switched either in the occurrence of fault or pre-planned to island operation. When the fault has been cleared it can again be reconnected and synchronised with the rest of the grid. For this purpose, microgrids need some kind of data system for the local network that manages and controls the network in island operation. [21] Figure 15 shows an example of a simple microgrid.

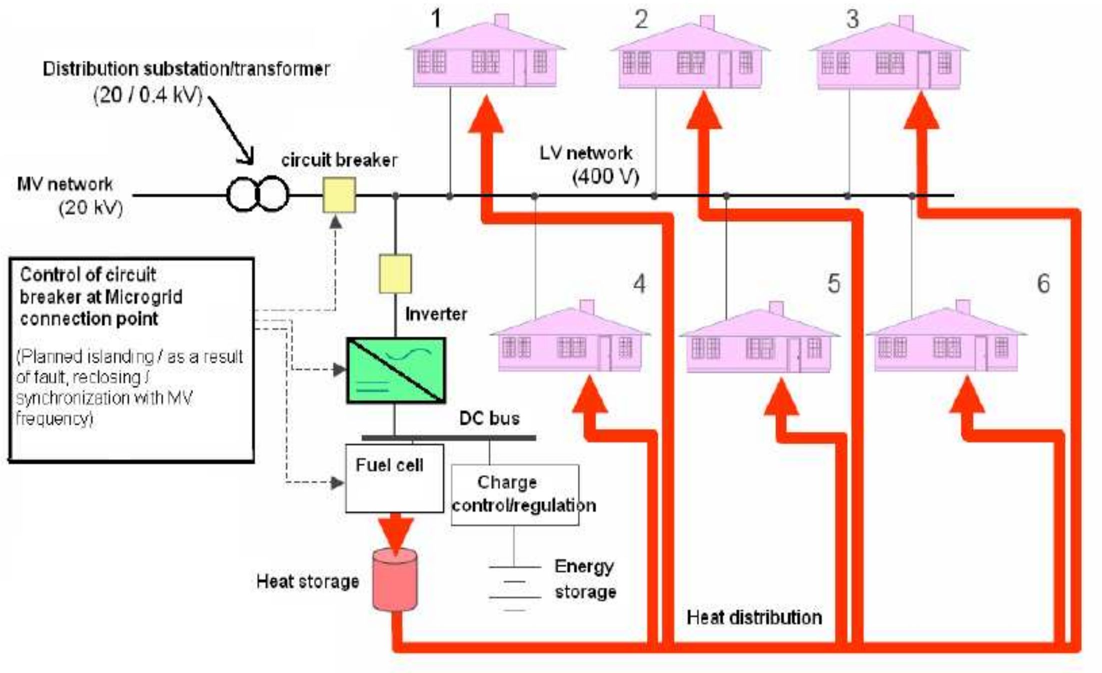

Figure 15. *An example of a simple microgrid [26].*

The primary operational requirement of power system is that it must always operate safely from the user point of view, even during contingencies. Before island is started the technical issues like power balance, voltage and frequency control and safe operation of network needs to be checked. [31] According to [30] probably the most important challenge of island operation is the control of voltage and frequency in the island system i.e. management of reactive and active power balance.

If microgrids are built from an existing distribution network structure that has some useful lifetime left, an AC microgrid is likely the most reasonable and advisable solution. On the other hand, when constructing a new low-voltage network, a DC network can be useful solution because it will be flexible to connect DG and energy storages to the network. However, these two network solutions (AC and DC) require completely different protection and systems for power balance. For instance in DC microgrids it may be a challenging task to implement protection system and connecting AC consumers to a DC network always requires a frequency control. On the other hand, in DC microgrids, it is possible to get rid of systems required for the frequency control and synchronised reclosing of the island system. [26]

It is necessary to utilise microgrid systems if distribution companies want to take advantage of the improved reliability and power quality resulting from the growing DG and energy storages [26]. In general, microgrid systems are assumed to improve both reliability and the cost structure of the distribution network and also improve local quality of supply. In addition, microgrids can improve energy efficiency and reduce the environmental effects of energy generation and total electricity consumption. Microgrids enable a non-discriminating distributed energy system by utilising small-scale generation units and also flexible connection of small units to the grid. In the best case microgrid increases the value of both the distribution company and the customer. [26, 28, 29 31]

3.1.3. Automated meter infrastructure

Automated meter infrastructure (AMI) is one of the first waves of Smart Grid. AMI consist of three main parts: reading, processing and utilizing data. AMI means not only metering of electricity but also processing a huge number of data. Automated meter reading (AMR) is the main and biggest part of AMI. In fact, there is no any exact definition for AMI but it is generally regarded as the reading of the electricity consumption by means that does neither require physical access nor visual inspection of the meter. These AMI meter devices are also called intelligent or smart meters. [32, 33]

Distribution companies have introduced AMI due to several different reasons. Among these are need to manage peak demand, the need for faster and more accurate billing and long term cost savings. Regulations on automatic meter reading were also accepted by Finnish government on the 5th of February 2009. The Act requires that 80% of every distribution company's customer sites must have a remotely readable electricity meter by the end of 2013. Some of the companies have also mentioned that they wanted to change meters before it was required by legislature. [24, 33]

In general, metering energy consumption and power quality is a vital part of distribution network business because it is used for billing and planning distribution networks. The most obvious development step enabled by the smart meters is that invoices and planning are based on actual consumption instead of estimations. Remote-reading enables many other improvements for example in customer service. In the case of power outages AMI system considerably improves the customer service, as more detailed data is available about starting time and length of the outage. [32, 33] In Table 3 main characteristics of smart meter are introduced.

Table 3. *Characteristics of smart meter [23].*

Four chacteristics of smart meter:	
1. Interval measurements: Measuring both consumption and time	2. Interface with data monitoring and discrete loads
3. Automatic transmission of resulting data To energy provider - no manual meter reading To consumer - load and usage control To grid operator - Grid optimazation	4. Two-way communications Data collection Monitoring Ancillary services and load control

The first AMI systems used telephone lines for communication. Later several other communication methods have been developed and today there are already various different communication possibilities for smart meters available [33]:

- Power line communication PLC
- Radio network communication
- A wireless modem system GSM and GPRS
- Combination of above systems

Meters can use one-way communication or two-way communication. Distribution network companies can read the meters remotely and also remotely disconnect and reconnect a customer and set also a limit to the energy that can be used with software fuses. In addition, tariffs can be remotely modified by the supplier and information concerning energy use and real-time data can be sent to the customer. [33]

AMI will enable hour measuring, electricity quality controlling, power cut registration and electricity remote break off. From electricity storage point of view necessary requirement for smart meters is for example two-way power measuring. However, all the services are not necessary to provide instantly but they can be chosen optionally. [33]

AMI has been seen as a very important part of Smart Grid concept because it allows the consumer to become an active participant in energy savings and energy markets. AMI make it possible to implement demand response with the small consumers either by price flexibility or by load control benefiting all the participants of the electricity market. Accurate electricity metering will improve functionality of the electricity market and increase electricity saving when the customers have opportunity to adjust their consumption according to the price. [34] For instance smart meters enable a way to offer customers a reward for restricting their electricity use during peak hours. In addition, smart meter helps also consumer to provide energy supply through their own distributed energy and generation assets. [23, 33]

All in all, AMI brings many benefits like cost savings for the distribution network company’s billing, planning, metering and customer service functions and processes. It will improve also the quality of customer service. Most advantages are acquired with smart meters using two-way communication and having a notable ability to store data/information. [33] AMI can be widely utilized by besides distribution network companies but also by customer and other companies, like companies selling energy and main grid company. [34] Addition to above, from the perspective of this thesis main benefit of AMI is that it will enable utilisation of electricity storages.

3.1.4. Plug-in hybrid electric vehicles and electric vehicles

Plug-in hybrid electric vehicle (PHEV) and electric vehicle (EV) both utilize somehow electrical energy. PHEV combines a conventional internal combustion engine (ICE) propulsion system with an electric propulsion system. The main purpose of electric propulsion system is to increase efficiency of ICE. In addition, modern PHEVs enable regenerative braking which converts the vehicle's kinetic energy into battery-replenishing electric energy. PHEVs are vehicles with rechargeable batteries that can be restored to full charge by connecting a plug to the electricity network or an external electric power source. EVs have only batteries but no internal combustion engine. Therefore, all used energy comes from electricity network or an external electric power source. [35]

Penetration of PHEVs and EVs are divided in three phases: grid-to-vehicle (G2V), vehicle-to-home (V2H) or vehicle-to-building (V2B) and vehicle-to-grid (V2G). Nevertheless, the first-generation PHEV vehicles will not include V2G capability primarily due to warranty concerns about battery technologies and a desire to avoid additional cost and complexity [16]. From the viewpoint of this study the most interesting phase V2G will be in the future which requires successful first phase. Thus, first phase G2V and PHEVs in general are discussed first.

The energy consumption of an electric vehicle is 0.20-0.25 kWh/km at winter time in Finland. [35] The energy consumption (kW/km) of an individual electric car depends on many things such as [36, 37]:

- Efficiency of the charging-discharging cycle (including efficiencies of the charger and the battery)
- Energy needed for heating and air-conditioning
- Efficiency of regenerative braking system
- Rolling resistance
- Total mass of the vehicle
- Driving cycle
- Driving velocity

It is obvious that charging has impact on the distribution networks. Extent of the impacts depends on the penetration level of plug-in vehicles and their charging methods. However, small penetration level of vehicles does not necessarily have a great impact on distribution network except on the low voltage networks. On the other hand, great penetration level of cars can have a notable impact on the distribution network concerning both medium and low voltage networks. First results show that full-scale utilization of vehicles will increase the use of electricity by 10%. [36]

It is generally expected that the adoption of PHEVs will begin in the short term with vehicle charging managed by pricing that encourages charging in off-peak times. Accordingly, it requires changes in pricing and metering policy. [16] Harmful overlapping with the present network peak loads should be avoided. Therefore, it is possible to have saves when vast reinforcement investments will not be required if the network peak loads do not increase because of the charging. The ideal charging will happen mostly at night time when inexpensive base-load generators must keep turning and there is a lot cheap capacity available. [23, 36] The impact on the electricity network should be positive assuming that most charging of PHEVs occurs at night instead of uncontrolled daytime or early evening charging by PHEVs [16].

To minimize charging infrastructure costs, to reduce adverse impacts on the network and to make electricity market operation more effective, different kinds of smart charging methods should be developed. Smart charging concepts can be divided into two groups: methods which need and methods which do not need a communication system to realize control actions. [4] First one includes methods based on local control such as control based on time. On the other hand, in control methods based on communications chargers interact actively with an information system managed by a network company. The information system can be for instance an extension of a distribution management system. In principle, the possibilities of these kinds of systems are enormous. [38, 39]

In Finland, electric outlets/sockets and vehicle preheating are commonly available because of winter use which is unusual worldwide. [36] There are still some barriers which restrict high penetration of plug-in and electric vehicle. The most important barrier is the battery technology but the technology is continuously evolving and prices are expected to go down. Secondly, a lack of adequate charging infrastructure is a significant barrier too. [39]

If fast charge station becomes common in the future it means that electricity storages can play pivotal role there. In the places where there are now gas stations it would require quite large electricity storages so that voltage sags and other negative impacts on distribution network can be avoided. Electricity storages can be charged when the demand and price of electricity is low.

The next logical step of infrastructure development is the vehicle-to-home or vehicle-to-building concept. Hence, a PHEV or EV would have the ability to communicate with the building. The PHEV battery might be operated in a way that makes it available for emergency backup power for building. [16]

From the view point of this study the most interesting phase V2G may be possible in the long term. V2G will allow for full bidirectional electric flow between the grid and the vehicle [16]. An average vehicle is on the road approximately only 4-5 percent of the time. As PHEVs are parked most of the time they can be regarded as electricity storages. Although each can handle power only several 10 kW, in sum they enable several hundred to thousand MW. [40] The idea of V2G is simply that cars can be charged during hours with a surplus of energy and in turn, when electricity price is high or there is lack of production, electric cars can feed energy back to the network. This can be possible using a continuous transfer of electricity price information with automatic control of the power flow to and from the EV. Electric cars require a high power and energy density by unit of weight and volume and a high number of charge-discharge cycles. The best storage technologies in the future might be certain types of battery or supercapacitor. [23, 41]

All in all, despite the present promising and upward trend of plug-in vehicles, the schedule of their total breakthrough is still unknown. The most influential factors affecting the development of PHEV vehicles are uncertain regulatory requirements, including consumption regulations and carbon taxes. Moreover, if the battery technology improves dramatically due to the penetration of plug-in hybrid and electric cars, there will be still need for research in basic electrochemistry to identify the combinations of chemical compounds that have the highest potential for use in electricity storage devices. [16]

In addition, the issue of the actual effects of electric cars on electricity distribution network is challenging in many ways and there are many technical and economical questions still open. The power demand can stay almost at the present level or increase dramatically depending on the electric car charging methods. [36] However, according to [16] PHEVs will become an integral part of the distribution system itself within 20 years, providing emergency supply, storage and grid stability.

3.1.5. Distribution automation

The main goal of distribution automation is to obtain better system performance and also to improve the reliability of supplies to customers, by faster clearance of faults and restoration of supplies [42]. The most important aspects of distribution automation are issues on protection and switching. [43]

As known, traditional distribution network has been designed with one-way power flow concept in mind. Smart Grid will enable two-way power flows due to utilization of distributed generation and electricity storages. The typical feeder protection problems due to distributed generation and electricity storage relate e.g. to sensitivity and selectivity problems. For instance, traditional distribution networks use time-current coordination for protection devices. These devices assume that faster devices are topologically further from the substation. In Smart Grid; topology will be flexible and this assumption will be problematic. [42, 43]

Moreover, other potential problems relate to operation of both distributed generation and electricity storage protection during reclosings and maintenance operations. The DG units and electricity storages must become disconnected during these events because of safety and operation issues. Therefore in the future, protection system and system topology must be planned together to ensure proper protection system coordination for a variety configurations. [30, 43]

3.1.6. Smart homes

Smart home has not only one definition but it depends on the point of view. Smart home means for example a building which has smart meters, plug-in hybrid car, electricity storages, smart thermostats and smart appliances which contain on-board intelligence that communicate to the network, senses grid conditions and also automatically turns devices off or on as needed. In general, it means for instance increasing automation and energy efficiency. For example, plug-in hybrid and electric vehicles can store energy, act as back-up generators for houses and supplement the grid during peak hours or outages. Smart thermostat can communicate with the grid and adjust device settings to help load management. Smart meters allow real-time pricing and thus increased options for consumers. [44]

In addition to above, the building regulations are becoming tighter and new houses are constructed in a better way. It means that passive and low energy houses are constructed more and more. Because of this electricity use will decrease during winter time. On the other hand, in the warm summer time the need of cooling capacity will be increased which will increase electricity consumption during summer time. [45]

It is seen also that in the future there will be zero energy houses and even plus houses as well. The aim for zero and plus houses is to reduce the energy (electric heating) demand of the buildings. These houses will produce their own energy and they can even sell the surplus of their own produced electricity to the grid. This will happen through micro generation and electricity storages. In addition, in the future customers who have a so called normal house where the consumption of electricity is high might be of interest to invest in a wind power plant or solar panels. All of these facts mean that the development of smart home systems and devices will increase rapidly in the future. [45]

Although the feeding of electricity to the grid will be possible in technical mind, it will have a lot of challenges. The amount of sold electricity is quite small and it will require some operator/aggregator in the middle who will bring production together.

The potential benefits of smart houses are cleaner power and increased energy efficiency. It will also decrease power costs, improves systems reliability and enables flexible and more efficient network. In summary, smart home or smart building has smart appliances like smart devices and at least smart meter. Electricity storages, probably batteries, will be common sooner or later in the future's houses due to the penetration of plug-in hybrid cars. Despite the fact that smart home is still many years in the future, it is closer than it has ever been. [9, 23, 44]

3.1.7. Demand response

Demand response (DR) means simply that customers are encouraged to shift consumption later or reduce consumption when market price is high or demand of electricity is high and system reliability is at risk. [48] It is possible to maintain grid stability and have other positive impacts which are discussed next.

Since there is still limited capacity to store energy, demand response in one alternative that can be used to balance fluctuations in the supply and demand of electricity. Demand response is a cost efficient and energy saving alternative to controllable power generation. Demand response is an important option for managing energy prices, ensuring reliable and secure power supply, reducing carbon emissions and in addition, lowering the investment needs for additional power generation and distribution infrastructure. Demand response can also be used to increase demand during periods of high supply and/or low demand. Demand response and electricity storages can be together notable alternative for expensive peak-power generation. [46]

Demand response allows retail customers to participate in electricity markets by giving them the ability to respond to prices as they change over time. Methods of engaging customers demand response efforts include offering a retail electricity rate that reflects the time-varying nature of electricity costs or provides incentives for reducing loads at peak times. Thus, smart meters and real-time pricing etc. are required that also small-customers react on different price signals. With this information they can then choose when and how to consume electricity. [23, 47] In case where small-consumers do not face actual market prices, they have no incentive to reduce consumption or defer consumption to later periods during times when production costs are significantly higher. [49]

In Finland, the main potential to increase the price flexibility of demand is especially in electrical heating and in smaller electricity users because most of the big industrial controllable loads are already either responding to electricity market prices or reserved for emergency control purposes. [48]

However, all consumption cannot shift for later time. Loads can be divided in two categories: shiftable and curtailable loads. The first one means loads that can be consumed at any point in time and total consumption of energy is independent from the period at which they do it but they have to be consumed completely for achieving their facility. Thus, it is possible to avoid peak consumption periods. Water heating, space heating, cooling etc. are examples of flexible loads. Curtailable loads are those that cannot be consumed at any point of time. An example of this kind of load is a light. This flexibility can be used also to reduce consumption in peak periods but it probably has a direct relationship with comfort of the user. It is good to keep in mind that theoretically almost all electricity consumption is flexible if the electricity price is high enough. From this perspective potential for demand response is huge. [15, 49]

All in all, demand response can result in a reduction in energy consumption at times of peak use and at times of high wholesale market prices. Demand response can be a win-win solution for utilities and consumers because it offers benefits to both in the form of increased electric system reliability and reduced price volatility. [23]

3.2. Smart Grid versus traditional distribution network

In the future, electricity distribution networks have to respond to changes in the values in society, in technology, in environment and in commerce. [2] The characteristics of Smart Grid are different than in today’s distribution networks. Although there are some intelligent systems for example distribution automation devices widely used in Finland distribution networks have generally been dumb and radial. Distribution system of the future can be described as intelligent, integrated, flexible and co-operational. Intelligence means investments on controllability, protection, and both information and communication technologies instead of passive transformers, lines, cables and switchgears. On the other hand, flexible represents future grid because it will utilize controllable resources throughout the network. [25] The key differences between traditional versus Smart Grid are shown in Table 4 .

Table 4. *Smart Grid versus traditional distribution network [2, 29].*

Traditional distribution network	Smart Grid
Non or one-way communication	Two-way communination
Centralized generation	DG(renewable) + centralized generation
Blackouts and failures	Adaptive and islanding
Electromechanical	Digital
Few sensors	Monitors and sensors througout
Blind	Self-monitoring
Manual restoration	Semi-automated restoration and self-healing
Check equipment manually	Monitor equipment remotely
One-way power flow	Two-way power flow

Traditional grids include centralized power generation and at distribution level one-directional power-flow. On the other hand, distributed generations including energy storages and existing controllable resources like reactive power compensation, direct load control and demand side integration enable a good potential as controllable resources for Smart Grid. Together, these will benefit the network when managed appropriately. [25] Therefore, Smart Grid will be able to provide new abilities such as high reliability, self-healing, energy management and real-time pricing [43]. They also integrate distributed and active resources such as generation, plug-in vehicles, loads and energy storages into power systems and energy markets. Those active resources enable change in the traditional passive distribution network to become an active one. [43]

All in all, distribution networks will be more or less a customer- and small-scale driven market place in the future. Telecommunication and information systems enable a cost-efficient and real-time connection to each customers and producer. Therefore, Smart Grid enables active market participation of customers and distribution generation. In addition to above, a high penetration of plug-in hybrid and electric vehicles having a grid connection will have remarkable impacts on both the infrastructure and the market. [25, 39]

3.3. Discussion and summary

In the future, there will be major changes in how distribution electricity networks are constructed. Smart Grid combines energy, telecommunication and IT markets. [23] It is also important to bear in mind that there are a lot of challenges and uncertainty factors associated with distribution network development towards Smart Grid such as following [26, 50]:

- Development of communications and information technology
- Information security

- Economic and technical development of DG
- Environmental issues and climate change
- Development of power electronics considered as intelligent components
- Development of materials technology and its effects for example on battery technology
- Synergy with advanced metering infrastructure
- Regulation changes

Electricity storages will be keen part of Smart Grids as described many times above. Electricity storages can be seen for example as a key component for the further implementation of distributed energy because they will allow a larger share of uncontrollable energy sources. On the other hand, electricity storages will also partly enable the use of microgrids in the future. [49] However it is important to keep in mind that Smart Grid will not treat electricity storages as separate issues. Instead, Smart Grid will integrate the functions for example DG, electricity storages, AMI and distribution automation so that the total advantages are greater than the sum of the parts. [43]

However, the renovation of the old infrastructure of electricity systems will be a big challenge but the renovation is also a great change. It is possible to apply the modern technology with intelligent information systems in the renovation process. [51] Modifying the existing system into a Smart Grid will probably take decades because the existing distribution infrastructure was not designed with Smart Grid in mind and the lifetime of distribution network is very long. Figure 16 shows the visionary network for rural area in the future. [26, 43]

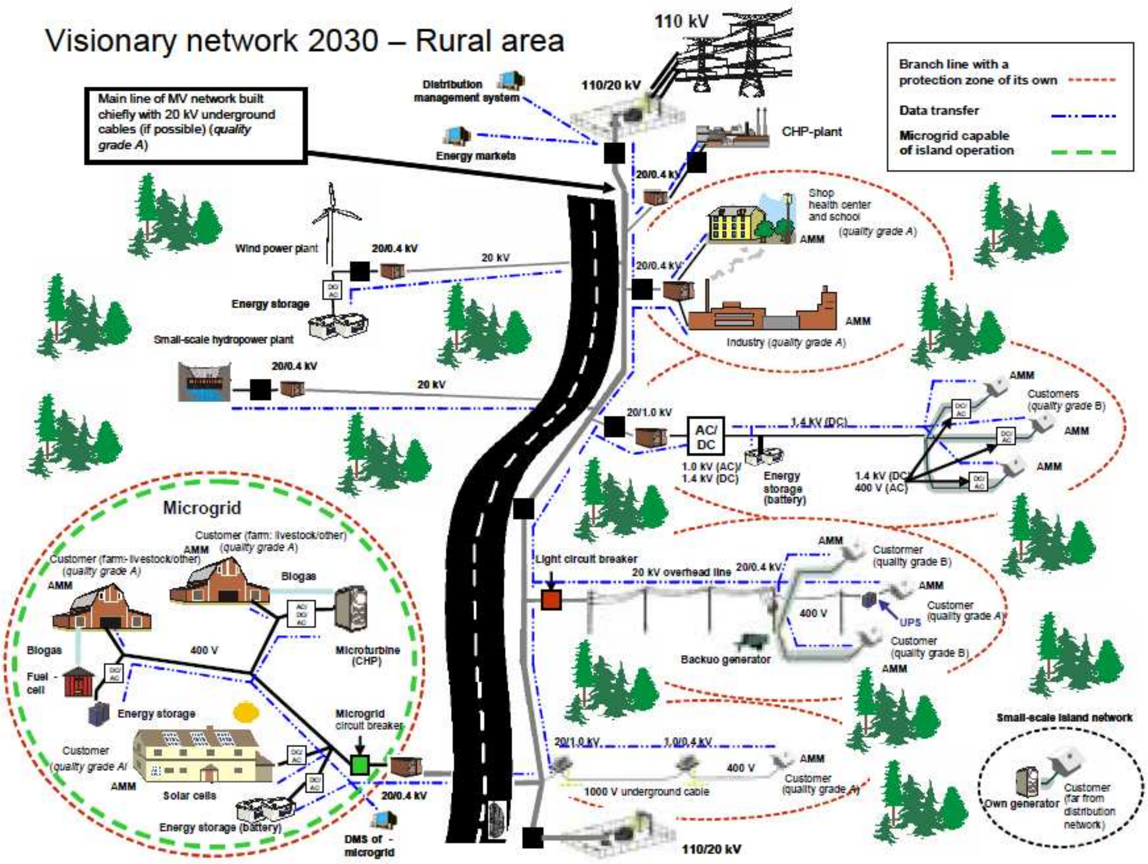

Figure 16. *Visionary network for rural area [26].*

4. NETWORK CONNECTIONS OF ELECTRICITY STORAGES IN SMART GRID

This chapter discusses network connections of electricity storages in Smart Grid in general. At first, general aspects, protection and safety issues are discussed and then connections of electricity storages in AC- and DC-grid.

4.1. General

In practice, electricity storages can be seen as not only storage devices but also as the whole system which is required so that it can be connected and used in the electricity grid. If electric energy is converted to a different form of energy it must be converted back to electrical form. Therefore, each electricity storage technology usually includes a power conversion unit to convert the energy from one form to another. Conversion efficiency plays an important role in how energy can be transferred into or out of the storage device. It depends mainly on the peak power rating of the power conversion system but is impacted by the response rate of the storage device itself. [1, 17]

4.2. Requirements for distribution network connection

The connection of electricity storages into electricity distribution networks allows and by contrast, requires the operating principle of network to be changed from passive to active. The active participation of electricity storages into network operation will enhance the utilization of network assets. Active network management consists of electricity distribution system planning tools, communication, automation, and control systems. [30]

Protection is central part of distribution network operation. Main tasks are protecting people and network components by keeping the power system stable. Potential problems relate to operation of electricity storages protection during reclosings and maintenance operations. Electricity storages must become disconnected during these events because of safety and operation issues. Therefore in the future, protection system and system topology must be planned together to ensure proper protection system coordination for a variety of configurations. [30, 43]

It can be assumed that a large number of standards will be developed in the next few years or are currently under development for the connections of electricity storages to distribution network. Unless, it is today the situation concerning distributed generation. However, these are voluntary unless a specific organization or legislation requires adopting these standards. In practice, this means that there are regional standards requirements, recommendation etc. for the interconnection of DG and also probably soon for electricity storages. International Electrotechnical Commission (IEC) and European Committee for Electrotechnical Standardization (CENELEC) elaborate official standards regarding these issues. Also, parallel to these two organizations and partly in co-operation is the standardization work in the Institute of Electrical and Electronics Engineers (IEEE). [49]

Since there are no official requirements for distribution connections of electricity storages it can be assumed that same requirements are valid than those concerning distributed generation. Generators and other installations which feed electricity to distribution network are not allowed to cause disturbances in distribution network. Also, for example according to Standard EN 50438 microgenerator has to automatically disconnect in certain situations. Loss of main protection must be taken into account and visible disconnection when necessary is also required because of safety reasons. Requirements for the connection of microgenerators are shown more specifically in Standard EN 50438. [52, 53, 54]

4.3. Connection to AC loads and feeder

Most of the electricity storages release power as DC current and current of distribution network is AC. Thus, a power conversion system is needed between the grid and the electricity storage. A power conversion system (PCS) is an integral part of storage application system because it serves as an interface between the storage system and the grid. Electricity from the grid is converted to DC for storage and back to AC when returned to the grid. Consequently, PCS provides bidirectional power conversion between the AC and DC systems. The PCS consists of a voltage source inverter which is designed to operate as either an inverter discharging the electricity storage or as a rectifier when charging. [11, 55]

The main purpose of the PCS is that it matches the frequency of current converted from DC to the frequency of the distribution network and also matches grid demand to power released from, or taken in by the storage device. PCS operates optimally at high frequency, high voltage and high current. The best systems have a fast response, great efficiency, high power quality and reliability. [11]

4.3.1. Integration of electricity storage system into FACTS devices

In general, second generation flexible AC transmission systems (FACTS) controllers are power electronics based devices that can rapidly influence the transmission systems parameters and provide fast control of distribution system. FACTS devices have been used the past two decades mainly in transmission systems but they may be reasonable solution in distribution networks because of improvement and cost reduction of power electronics. FACTS devices include for example static synchronous compensator (STATCOM) and static var compensator (SVC). Use of FACTS devices as electricity storage is based on the fact that energy is stored in the capacitor of DC bus. The amount of stored energy in capacitor is however limited but it is possible to integrate more electricity storages into FACTS devices to improve its performance, as in Figure 17. The integration of electricity storage into FACTS devices can offer greater real and reactive power injection/absorptions from/into the grid. [1, 22]

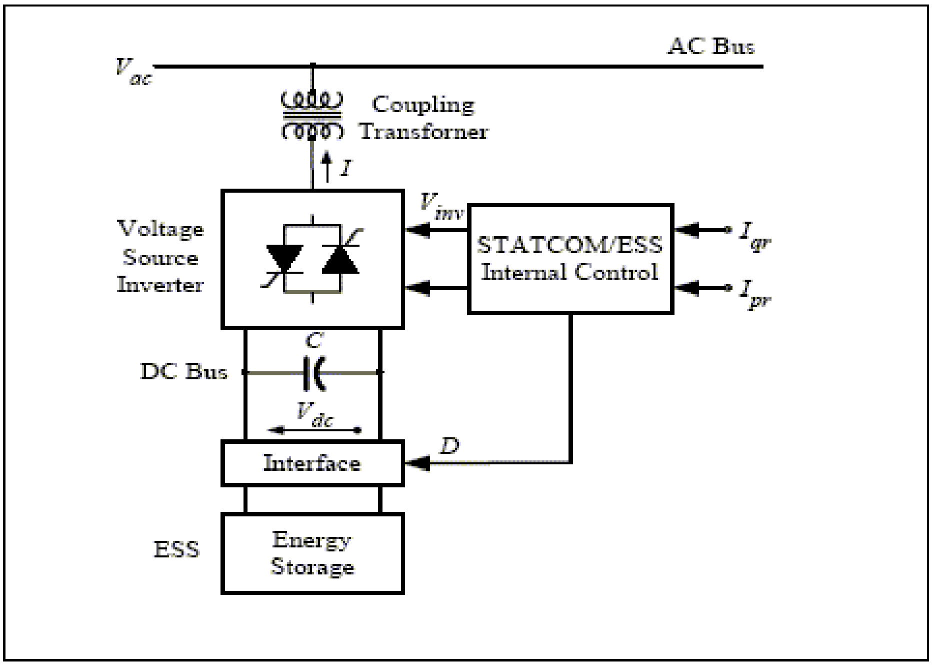

Figure 17. *STATCOM and electricity storage [56]*

4.4. Connection to DC loads and feeder

Traditionally, only AC systems have been used in electricity distribution. Low and medium voltage has been applied only to the AC supply so far while DC supply has received less attention. Recently, there has been more discussion and research about the use of DC systems in distribution networks due to the development and cost reductions of power electronic devices. The DC supply may offer a use potential in the Finnish electricity distribution system and the use of a DC system may bring significant investment cost reductions. [26]

DC distribution has several benefits compared with AC distribution. Supply voltage can be higher due to the definitions of the AC and DC voltage ratings in the low voltage directive. The maximum low voltages can be 1000 VAC and 1500 VDC according to it. Compared to AC, with DC it is possible to transmit higher power. If the protection of DC connection is implemented with line protection devices i.e. circuit breakers, each DC connection forms a protection zone of its own. This would improve significantly the reliability of the distribution system. In addition, customer problems caused by voltage drops will decrease, if the low voltage level is produced directly with an inverter. A further benefit of DC systems is the connectivity of electricity storages and distributed generation, as in Figure 18. [26]

The main benefit from this study point of view is that integration of electricity storages and also distributed power sources into DC systems would be easier compared to AC systems because most of the electricity storages release power as DC. The role of electricity storages in DC distribution is even more important than in AC systems. Instead of just balancing the peak power, electricity storage systems must support the supply voltage. Electricity storage connection to the DC system provides improved response to fast load changes and they have very important role in rapidly changing situations. Small voltage sags can be corrected by the converter controls and the energy stored in the passive elements in the system. But longer lasting voltage sags or interruptions requires some kind of electricity storage in the DC system as well as in the AC systems. The storage device can be interfaced to the DC system through a power converter. The converter will be controlled to keep the storage device charged during normal operation and then supports the DC voltage at a minimum level during a disturbance. [1, 3]

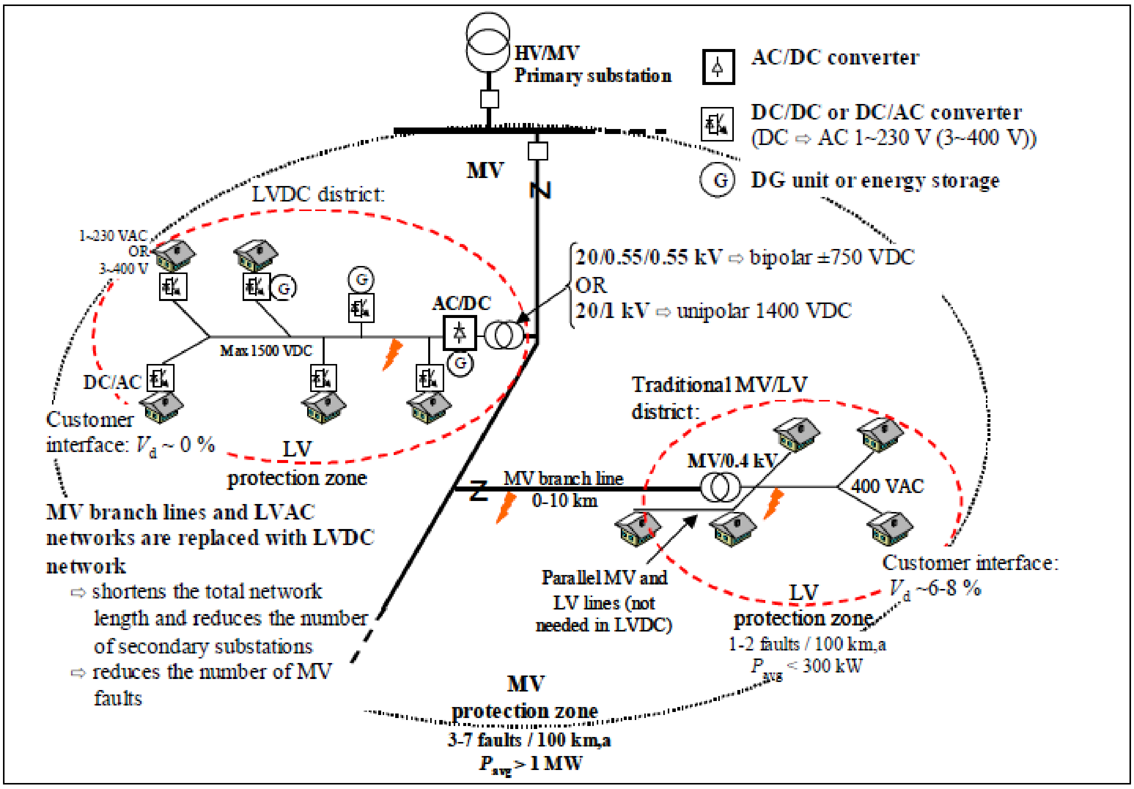

Figure 18. *The role of electricity storages in low voltage DC system [57].*

Although DC supply may seem like a good solution there are also some challenges concerning its utilization. Application of DC voltage in electricity distribution requires inverters and rectifiers at both ends of the DC voltage level. Also, as a result of usage of the converters, there occur harmonics in the distribution network, which are seen in the supplying network and by the consumer as well. Harmonics can decrease the power quality experienced by customers. Despite that inverters replace the low-voltage transformers altogether this increases the number of components in the distribution network. It may lead to a more fault-prone distribution network and may increase the number of interruptions experienced by customers. In addition, the lifetime of power electronics is shorter than the lifetime of the conventional components such as transformers. [26]

5. USE OF ELECTRICITY STORAGES IN SMART GRIDS

Electricity storages can be used for various purposes and different places in Smart Grids, as in Figure 19. The goal of this chapter is to explain use of electricity storages in Smart Grids. Electricity storages can play very important role in maintaining power quality. In subsection 5.2 main characteristics of power quality according to standard EN 50160 are presented. On the other hand, electricity storages can be used for energy management purposes which are discussed in subsection 5.3. After definitions use of electricity storages for different purposes are described.

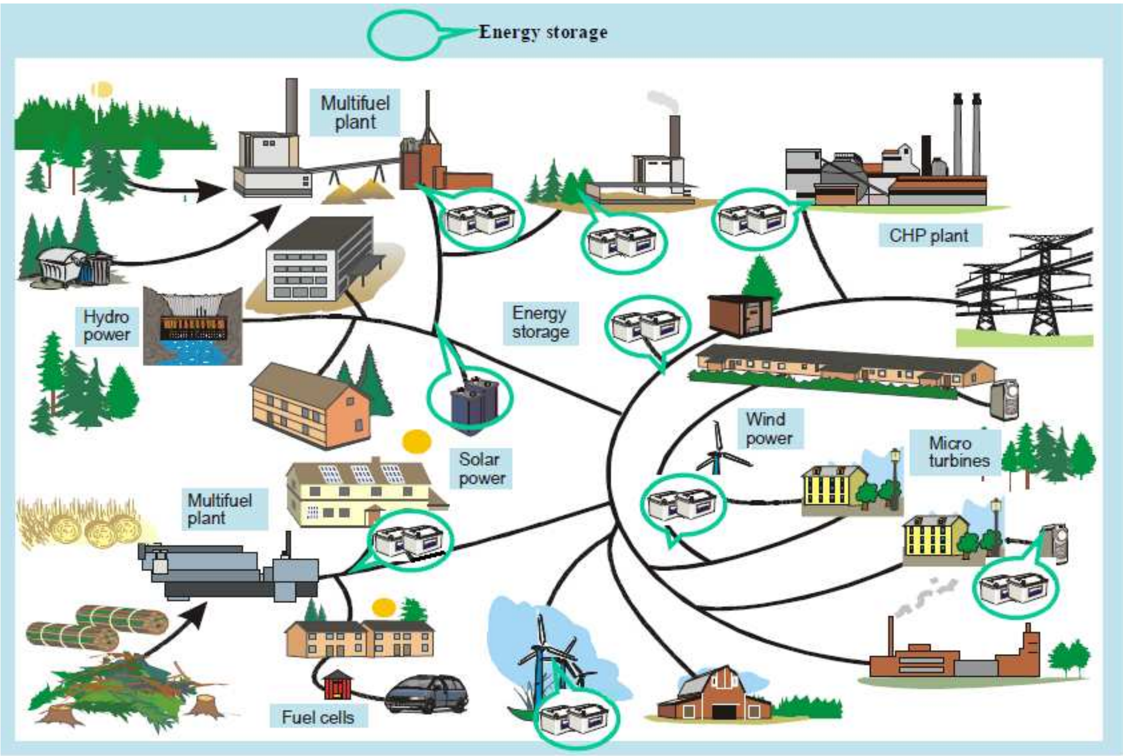

Figure 19. *Use of electricity storages in Smart Grid. [8]*

5.1. General

The applications of electricity storages can be defined on the basis of different parameters like capacity of storages, response time, storing time and discharging time. Electricity storages can be seen in different scales. The applications require electricity discharges from a fraction of a second in high power applications to hours in high-energy applications. Storage technologies can be categorized into two main categories: quality of supply management and energy management technologies.

First category means simply electricity storages that are intended mainly for high power ratings with a relatively small energy content making them suitable for power quality applications. In turn, second category includes electricity storages that are designed for energy management applications which mean both load management and production management. The applications from minutes to several hours can relate to the support of distributed energy generation or load variations. Depending on applications in power systems, the capacities of electricity storage systems can vary from less than 1 kW to nearly 1 GW. [34, 49]

Power quality and energy management applications can be further refined based on how frequently the electricity storage is expected to be used. Frequent discharge of power quality storage implies hundreds of discharges over the course of a year. On the other hand, frequent discharge for long-duration electricity storage implies almost daily use throughout the year. [12, 49]

5.2. Quality of supply management

Customers today expect even better quality of supply than before. Although completely 100% reliability supply would be economically impracticable but electricity storages can be a reasonable way to improve quality of supply. Standard SFS-EN 50160 gives the main characteristics of the supply voltage in medium and low voltage distribution networks under normal operation conditions. The standard defines and describes the characteristics of the supply voltage concerning: frequency, magnitude, wave form and symmetry of the three phase voltages. In this Thesis voltage sags, voltage fluctuations, flicker and both short and long interruptions are handled. [58]

Quality of supply is important because low-quality supply can cause disruptions of customer's devices. The effects of loss supply vary a lot with customer group but for example consumers with sensitive or critical loads need a constant supply voltage with a sinusoidal waveform at nominal frequency and magnitude. Nevertheless, the standard does apply under abnormal operating conditions including for example following situations [58, 59]:

- Conditions arising as a result of a fault when the goal is to keep customers supplied during maintenance and construction work or to minimize the extent and duration of a loss of supply
- In case, customer's installation or equipment is not according to requirements of public authorities or the electricity supplier.
- In exceptional situations outside the control of the electricity supplier, in particular, exceptional weather conditions and other natural disasters.

In general, the most significant and critical quality problems are voltage sags or complete interruptions of supply. Interruptions are classified in two categories:

Prearranged and accidental. Accidental interruptions are occasionally caused by permanent or transient faults. Prearranged are interruptions, for which consumers are informed in advance. Those are execution of scheduled works on the distribution network like maintenance. [58, 59]

5.2.1. Voltage sags

Voltage sags are sudden reductions of the supply voltage to a value between 90% and 1% of the declared voltage Uc, followed by a voltage recovery after a short period of time. Voltage changes which do not decrease the supply voltage to less than 90% of the declared voltage Uc are not considered as voltage sags. Under normal operating conditions the expected number of voltage sags in a year can be from up to a few tens to up to one thousand. In general, voltage sags are caused by faults occurring in the distribution network or in the customers' installations. Also, they are often unpredictable and largely random events whose duration is conventionally between 10 ms and 1 minute. [58]

The power rating requirement for energy storages varies from 1 kW to 20 MW, while stored energy is between 50-500 kWh in voltage sags situations. Supercapacitors, SMES, flywheel can respond very rapidly in providing needed power to the grid and thus stabilizing voltage. Batteries cannot respond as quickly as others but are still fast enough. Therefore they suit also for this purpose. Supercapacitor has very low energy storage capacity but it suits very well in applications where a relatively high peak power is needed because the high power is possible to obtain from it very fast. [1, 10]

5.2.2. Rapid voltage changes and flicker

Voltage fluctuations are rapid changes of voltage. In general, rapid voltage changes of the supply voltage are caused either by load changes in customers' installations or by switching the system. It can be systematic variations or a series of random voltage changes. However voltage fluctuations are systematic variations in the envelope or a series of random voltage changes with a magnitude which does not normally exceed the voltage range of 0.9 to 1.1pu. Also, voltage fluctuations can cause changes of the luminance of lamps which can cause the visual phenomenon called flicker. Above a certain threshold flicker becomes disruptive grows very rapidly with the amplitude of the fluctuation. [58]

Requirements of electricity storages are almost similar than concerning voltage sags. Electricity storage for these applications must respond very quickly to fluctuations in demand although they will not need to store large amount of energy. Therefore, SMES, flywheels, supercapacitors and batteries are all suitable also for this purpose.

5.2.3. Short interruptions

Short interruptions are situations in which the voltage is lower than 1% of declared voltage Uc. Maximum duration of short interruptions is less than three minutes caused by a transient fault. Most faults (90%) in medium-voltage network are shorter than three minute interruptions and usually caused by thunders, storms, branches of threes or animals. [22, 58]

Short interruptions require a storage device which is able to discharge in a time between a few seconds and only to several minutes (3 minutes). [58] Short interruptions systems as well as voltage sags and voltage fluctuations can also be handled by relatively small but fast electricity storages. Therefore, supercapacitors, flywheel, SMES and most of the batteries are also suitable for providing backup power during brief interruptions. [60]

5.2.4. Long interruptions

Long interruptions are longer than three minutes caused by a permanent fault, usually external events or actions which are impossible to prevent by the supplier. There is no typical value for the annual duration and frequency of voltage interruptions due to wide differences in distribution networks. [58]

Stored energy, in these applications, is used normally from minutes to several hours. The power rating requirement varies a lot from 100 kW to 200 MW, while stored energy is usually between 1-1000 MWh. In long duration interruption situations response time of electricity storage can be much longer than in short interruptions. Also, amount of stored energy which is required depends on the duration of interruption. Requirements for relatively short interruptions are near to requirements for short interruptions but on the other hand, during long fault situations needs are almost same than concerning energy management applications which are discussed next. Flywheels, supercapacitors, Ni-Cd, Ni-MH and lead-acid are only attractive for power not energy applications thus they can be used only during long interruptions not lasting for more than several minutes. Of the remaining electricity storages NaS and SMES are theoretically suitable if duration of fault is more than several minutes. In addition, lithium-ion battery could be in the future also solution for that purpose. [12]

5.3. Energy management

Electricity has traditionally been used at the time at which it is generated. Despite the fact that electricity storage would allow for the optimization of power generation, it is not usually stored. [16] Consumer demand varies throughout the day as well as seasonally. Expensive spinning reserves have been necessary for this purpose. The problem gets worse when more and more uncontrollable power production is connected in the distribution network. Large amounts of variable generation from renewable resources are not fully forecastable. It causes increasing problems in distribution networks.

From energy management point of view the main purpose of adding electricity storage systems in the electricity grid is to collect and store overproduced, unused energy and be able to reuse it during times when it is needed. In other words, electricity storages are used to decouple the timing of generation and consumption of electric energy. The typical example is load levelling, which involves the charging of electricity storage when electricity cost is low. On the other hand, demand response offers also a way for power supply and demand variability. Demand response can reduce the problems caused by the variable output of distributed generation by using the flexibility in electricity consumption as described in chapter 3. [49, 61]

5.3.1. Production management

Most of renewable energy sources, for example wind power, vary widely in the energy that they can provide to the grid. Electricity storages can smooth out this variability by allowing unused electricity to be stored for later use when generation capacity is too low to meet demand. Thus, electricity storages enable to manage intermittent power production in renewable energy production systems such as wind and solar power plants. [9, 11]

For this purpose desirable storage systems are technologies which offer capabilities of hours to even several days. The amount of stored energy is totally in different scale (100 kWh – 200 MWh) than quality of supply in applications regarding voltage sags and short interruptions. On the other hand, response time does not impose requirements for any electricity storage because it can be allowed to be even seconds. However, NaS battery is only alternative profitable storage in production management. SMES and Li-ion can also be attractive in the future. [1, 4, 11]

5.3.2. Load management

Consumer demand for power varies throughout the day as well as seasonally. Many power plants have limited ability to make rapid changes in their outputs in response to demand-side fluctuations. In addition, the construction and maintenance costs of additional power plants only for this purpose are high and also, environmental impacts of these plants are big. Electricity produced at off-peak hours can be stored and used later on. Thus, electricity storage technologies can provide an effective method of responding to daily fluctuations in demand by filling in demand valleys and shaving demand peaks. [11]

Electricity storages can provide an environmentally and economically advantageous method of responding to fluctuations in demand as long as the electricity storage device is not charged by energy generated from fossil fuel. Replacing gas plants with electricity storages could be a significant benefit to the environment. As said, demand response offers also a way for balancing consumer demand but if electricity storages are used for this purpose requirements of electricity storages are similar than in production management but response time can be even longer and the amount of stored energy higher. [11, 12]

5.4. Conclusions and discussion

Electricity storages have potential for significant environmental, economic and energy diversity benefits. In summary, electricity storages enable following issues [49, 61]:

Quality of supply:

- Improve the quality of supply (voltage sags, flicker and voltage fluctuations) and also, provide supply to customers during prearranged and accidental interruptions (during short and long interruptions) and cut costs of power failures

Energy management:

- Production management: Enabling renewable energy
- Load management: By shifting demand on electricity supply from critical times to off-peak periods and reducing the need of the power plants and spinning reserve

High-power electricity storage technologies are applicable for fast response quality of supply management. High-power applications are electricity storage technologies that can supply a large power but only for a time up to a few seconds or minutes. Today, supercapacitor, flywheel, lead-acid, Ni-Cd, Ni-MH and Li-ion seem attractive for power applications, as in Figure 20. At present, the long-term electricity storage technologies employed on a large scale are only NaS batteries. SMES can be applied mainly in power applications and in some cases in energy management but today it is still too expensive. On the other hand, pumped hydro power and CAES might also be suitable for energy management purposes but they are not considered in this study. [4, 61]

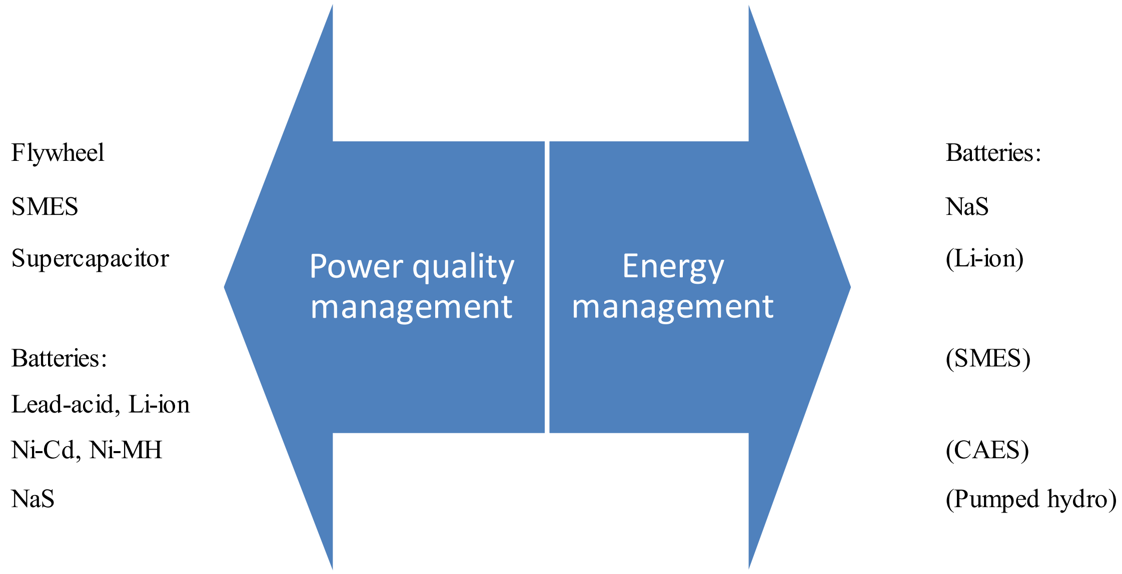

Figure 20. *Electricity storages in two different scales. [11, 12, 34]*

Figure 21 shows usage of electricity storages in power quality and in energy management applications. It also describes positions where electricity storages can be probably used in the Smart Grid. On the left side is the primary substation and on the right side is the customer. In the middle of the graph is the secondary substation.

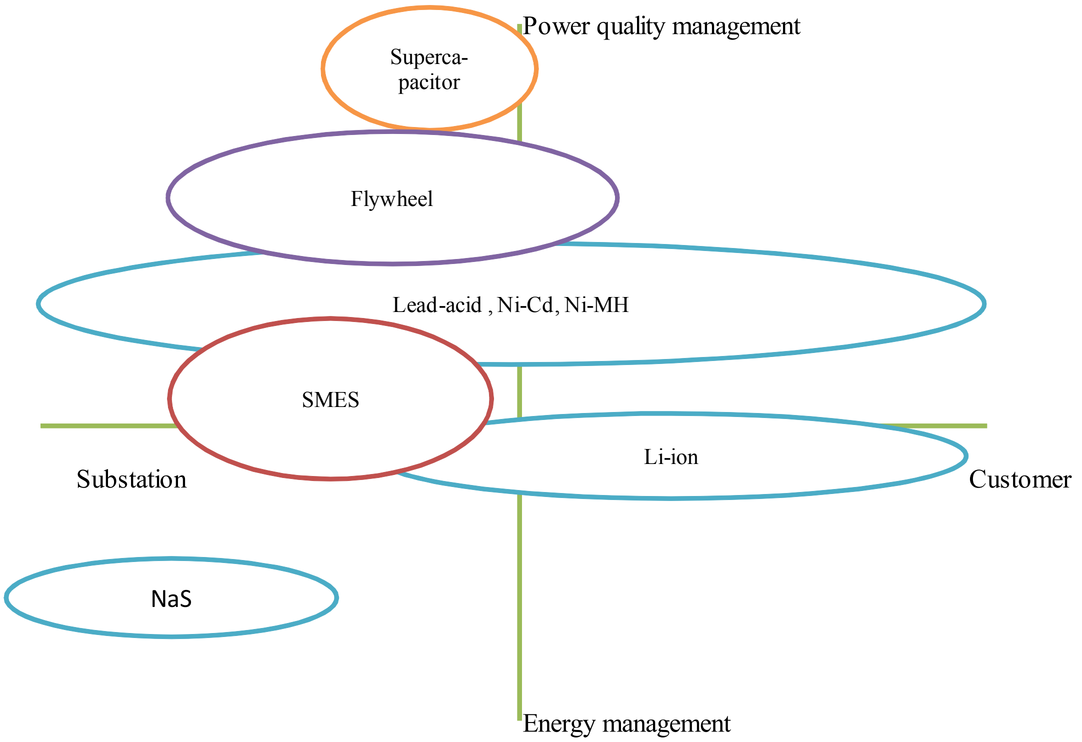

Figure 21. *Use of electricity storages in Smart Grid and positions where electricity storages can be probably used in distribution networks. [1, 10, 21]*

Although some storage technologies can function in large scale, most technologies would not be economical to be applied in all categories. [34] Also, it is obvious that different storage technologies are in some cases in competition with each other. On the other hand, depending on the perspective electricity storage are also in competition or work together with other balancing system like demand response, control power plants and energy import/export. Since there is still limited capacity to store energy, demand response is a good alternative that can be used to balance fluctuations in the supply and demand of electricity.

Although the development of different kinds of energy storages during the last ten years there is still a lack of smart, cost effective and efficient electricity storage. Therefore today costs of storages are still high. The electric energy lost in electricity storages together with the fixed costs of storages drive up overall costs. [9, 20] However, the situation will probably change in the near future due to recent developments and advances in electricity storage and power electronics technologies. [1]

Electricity storages will have also certain implications for system design and distribution network can be designed differently. Thus, construction costs will decrease and moreover, losses will reduce. In some cases, it is possible to avoid large investments in distribution network improvements. [3] For various reasons, it is however difficult to predict the amount of electricity storages and therefore, there will probably be significant differences between different networks. In summary, if these technologies are to be widely adopted, the technologies must be economically profitable. [11]

6. SWOT ANALYSES OF ELECTRICITY STORAGES

The goal of this chapter is to summarize both features of different electricity storage technologies in the form of SWOT analysis and present exploitation of electricity storages in Smart Grid. The SWOT analysis describes strengths, weaknesses, opportunities and threats of different electricity storages.

6.1. Batteries

This subsection presents SWOT analysis of different batteries. In general, most of batteries suit well in power applications, but NaS battery suits also for energy management applications.

6.1.1. Lead-acid battery

Lead-acid battery presents mature low-cost technology but has a lot of weaknesses such as low energy and power density, high maintenance requirements compared to other technologies, as in Table 5. It can be used in quality of supply applications and it is excellent for short duration applications like providing backup power during short interruptions.

Table 5. *SWOT analyses of lead-acid battery [4].*

SWOT: Lead-acid	
Strengths: Mature technology Familiar Low capital cost	Weaknesses: Low energy density Low power density Short life time (years and cycle) Capacity depend on temperature increasing High voltage of deep discharging High maintenance requirements
Opportunities: Performance at low ambient temperatures Depth of discharge	Threats: Environmental hazards

6.1.2. Sodium-sulfur battery

NaS battery with very high energy density serves well for storing large amounts of energy. NaS batteries are only suitable alternative for both power quality and in particular energy management applications because stored energy capacity is big enough. It is still quite expensive but with rapid cost reductions NaS batteries could be a promising technology in the near future for energy management applications. [1, 4, 11] (See Table 6.)

Table 6. *SWOT analyses of sodium-sulfur battery [4].*

SWOT: Sodium-sulfur (NaS)	
Strengths: High energy density High efficiency Mature technology	Weaknesses: Expensive technolgy High temperature of work Safety concerns
Opportunities: Lower cost	Threats:

6.1.3. Nickel-cadmium battery

Table 7 shows that nickel-cadmium batteries are mature technology as well as lead-acid batteries but Ni-Cd contains toxic components which might restrict their usage because of environmental issues which are today more and more important. However, nickel-cadmium can be used also in improving quality of supply. [4, 12]

Table 7. *SWOT analyses of nickel-cadmium battery [4].*

SWOT: Nickel-cadmium (Ni-Cd)	
Strengths: Mature technology High mechanical resistance	Weaknesses: Expensive technology Toxic components
Opportunities: Lower cost Improvement of recycling process	Threats:

6.1.4. Nickel-metal hydride battery

As Table 8 shows, nickel-metal hydride battery presents mature but expensive technology. Ni-MH battery is quite similar to Ni-Cd battery and suits for similar applications. It is more environmentally friendly than nickel-cadmium battery because it has fewer toxic components. However, improvements of recycling process will be opportunity to improve its use. [4, 12]

Table 8. *SWOT analyses of nickel-metal hydride battery [4].*

SWOT: Nickel-metal hydride (Ni-MH)	
Strengths: Mature technology High mechanical resistance Lower number of toxic components than Ni-Cd	Weaknesses: Expensive technology
Opportunities: Lower cost Improvement of recycling process	Threats:

6.1.5. Lithium-ion battery

Lithium-ion has high efficiency and energy density but it has also some weaknesses such as safety concerns. [4, 16] With rapid cost reductions and improvements of temperature gradients independent, lithium-ion batteries can be promising technology in the near future for small-scale applications. (See Table 9.) It can also be profitable for energy management purposes in the future. [12]

Table 9. *SWOT analyses of lithium-ion battery [4, 61].*

SWOT: Lithium-ion (Li-ion)	
Strengths: High efficiency High energy density	Weaknesses: Expensive technology Early-stage technology Safety concerns
Opportunities: Lower costs Improvement of temperature gradients independent	Threats:

6.2. Supercapacitor

Relatively new technology, supercapacitor suits well for power quality applications, because it can respond very rapidly. However it is quite expensive and requires advanced power electronics. (See Table 10.) Stored energy is too low for energy management purposes but with lower cost it can be used for quality of supply applications for example to stabilize voltage and it is excellent for short duration applications like providing backup power during short interruptions. [1, 4]

Table 10. *SWOT analyses of supercapacitor [4].*

SWOT: Supercapacitor	
Strengths: High power density Long life cycle (cycle)	Weaknesses: Low energy density Expensive technology Requires advanced power electronics
Opportunities: Lower cost Higher energy density	Threats:

6.3. Superconducting magnetic energy storage

SMES is theoretically very good solution for quality of supply management and also it can be used for energy management applications because according to Table 11 it has such features as very low standby losses and high power density. Today, it is still too expensive. But with significantly lower costs it might be ideal electricity storage in many levels in the future. [1, 4]

Table 11. *SWOT analyses of superconducting magnetic energy storage [4].*

SWOT: Superconducting magnetic energy storage (SMES)	
Strengths: High power density Very low standby losses	Weaknesses: Low energy density
Opportunities: Lower costs Higher energy density Higher charging speed	Threats:

6.4. Flywheel

Flywheel suits for quality of supply applications and according to Table 12 it has advantages such as high power and long life time in cycles compared other technologies but it suffers relatively large standby losses. However, it can be used for example in balancing voltage fluctuations because it can inject power into the electricity network in milliseconds and it can be recharged very fast. [4, 21]

Table 12. *SWOT analyses of flywheel [4].*

SWOT: Flywheel	
Strengths: High power density Long life time (cycles) Very fast recharge High power	Weaknesses: Low energy density Large standby losses
Opportunities: Lower costs High energy density	Threats:

6.5. Summary

In this chapter SWOT analyses of different electricity storage technologies were presented. All electricity storages have their advantages and disadvantages. It seems obvious that although certain electricity storage technologies can be used for all of the applications, most of the technologies are not practical and economical for both power quality and energy management applications.

7. SUMMARY

The aim of this thesis was to introduce electricity storages in Smart Grids. Batteries, flywheels, SMES and supercapacitors were examined closely in this Master of Science Thesis. As said many times above, electricity storages which are discussed in this study are only one part of energy storages.

Concept of Smart Grid was introduced because e.g. automated metering infrastructure and penetration of PHEVs and EVs will partly enable use of electricity storages. On the other hand, electricity storages will allow the use of microgrids and increase value of distributed generation. Also, it is important to keep in mind that Smart Grid will not treat electricity storages as separate issues. Rather, Smart Grid will integrate functions for example distributed generation, electricity storages, demand response, AMI and distribution automation so that the total benefits are greater than the sum of the parts.

The connection of electricity storages into electricity distribution networks allows and by contrast, requires the operating principle of network to be changed from passive to active network. Since there are no official requirements for distribution connections of electricity storages it can be assumed that same requirements are valid than those concerning distributed generation. Also, a power conversion system is needed between the grid and the electricity storage because most of the electricity storages release power as DC current and current of distribution network is AC. On the other hand, if DC supply becomes common integration of electricity storages into DC systems would be much easier compared to AC systems.

The main goal of this thesis was to examine use of electricity storages in Smart Grid. Electricity storages can improve quality of supply for example by protecting against voltage sags, rapid voltage changes and flicker and providing supply during both short and long interruptions. Electricity storages are also a key enabling technology for managing peak demands and improving utilization of unpredictable renewable generation.

Therefore, in this thesis electricity storages were divided into two categories: quality of supply and energy management applications. First category means electricity storages that are intended mainly for high power ratings with relatively small energy content. In turn, second category includes electricity storages that cannot supply a large amount of power, but can sustain it for a much longer period of time. Lead-acid, Ni-Cd, Ni-MH, Li-ion, supercapacitor and flywheels belong to first category. NaS battery belongs to second one although it can be used also in power quality applications. SMES is theoretically very good solution for quality of supply and in some cases for energy management application but it is still too expensive. Li-ion battery will probably also be used for energy management applications in the future. All in all, although certain electricity storage technologies can be used for all of the applications, most technologies are not practical and economical for both power and energy applications. Also, if these technologies are to be widely adopted, the technologies must be economically viable.

Electricity storages can be highly beneficial to both the grid and the consumer in the future. In the long term, the development in electricity storages may have a strong impact on the construction of distribution networks. Electricity storages will have certain implications for system design and distribution network can be designed differently. In some cases, it is possible to avoid large investments in distribution network improvement.

In the future, impacts of active resources such as controllable loads and also, virtual power plants, aggregators and demand response together with electricity storages require more attention and research. Case studies of impacts of electricity storages on distribution network for example network topology could be very interesting research subject and as well as technical and economical analysis of the use of electricity storage in distribution network.

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