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Power System Flexibility Enhancers – A Patent-Based Analysis of the Current Development Trends

Master’s thesis

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ABSTRACT

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Power system flexibility is becoming a significant topic as increasing amounts of variable renewable energy are being fed into grid. Current power system design has capabilities to provide flexibility to some extent, but alternative designs are needed to minimize variable renewable energy curtailment. In this thesis, flexible power plants and smart grid- and energy storage technologies are discussed as potential technological solutions to improve flexibility and patent analyses are conducted for smart grid and energy storage to monitor development trends in these technology areas. The results of the patent analyses indicate that patent activity is growing in both technology areas. Moreover, a rapid increase of Chinese patent filings has been recognized. Each technology area is dominated by a distinctive group of applicants who have a diverse patent portfolio and strong capabilities to hamper other applicants from patenting related inventions. Smaller key applicants are focusing on certain technologies and might possess significant inventions in the field of interest. Based on the technical content of the retrieved patent data, it can be said that different technologies are in the different stages of their lifecycles, when measured by patenting activity. However, different methods should be used in the future studies to examine the content of patents more precisely.

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Energiamurroksen myötä voimajärjestelmän joustavuuden lisääminen muodostuu prioriteetiksi voimajärjestelmän toiminnan turvaamiseksi. Tässä työssä joustavaan tuotantoon kykenevät voimalaitokset, älykäs sähköverkko ja energian varastointiteknologiat esitetään mahdollisina ratkaisuina lisätä sähköjärjestelmän teknistä joustavuutta. Älykkääseen sähköverkkoon ja energian varastointiteknologioihin liittyviä kehitystrendejä tutkittiin työssä patenttianalyysin avulla. Tuloksista havaittiin, että patentointiaktiivisuus oli ollut molemmilla teknologia-aloilla kasvussa, johtuen pitkälti kiinalaisten patenttihakemusten määrän nopeasta kasvusta. Kummallakin teknologia-alalla oli muista hakijoista selvästi erottuva joukko hakijoita, joilla oli monipuolinen patenttiportfolio ja hyvät valmiudet estää muita hakijoita patentoimasta samanlaisia keksintöjä. Lisäksi huomattiin, että pienemmät hakijat keskittyivät patentoimaan tiettyihin teknologioihin liittyviä keksintöjä, joista osa saattoi olla teknologian kehityksen kannalta merkittäviä. Patenttidatan teknisen sisällön analysointi paljasti, että kummankin teknologia-alan sisältä löytyy patentointiaktiivisuudella mitattuna sekä kypsiä että voimakkaasti kasvavia osa-alueita. Kuitenkin tulevissa tutkimuksissa tulisi käyttää eri menetelmiä, jotta patenttien teknistä sisältöä voitaisiin analysoida eksaktilla tavalla.

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LIST OF ABBREVIATIONS

AFC	Alkaline Fuel Cell
AMI	Advanced Metering Infrastructure
BES	Battery Energy Storage
CAES	Compressed Air Energy Storage
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditure
CPC	Cooperative Patent Classification
CPP	Cites Per Patent
DG	Distributed Generation
DLC	Direct Load Control
DMFC	Direct Methanol Fuel Cell
DSM	Demand-Side Management
EMS	Energy Management System
EPO	European Patent Office
ERP	Enterprise Resource Planning
FLH	Full Load Hour
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IEA	International Energy Agency
IP	Intellectual Property
IP5	Five largest intellectual property offices
IRENA	International Renewable Energy Agency
LCOE	Levelized Cost of Electricity
Li-Ion	Lithium-Ion
NaS	Sodium-Sulphur
NiCd	Nickel-Cadmium
NIOOH	Nickel Oxyhydroxide
MCFC	Molten Carbonate Fuel Cell
MDMS	Meter Data Management System
MW	Megawatt
Modbus/TCP	Modbus/Transmission Control Protocol
MWH	Megawatt hour
PAFC	Phosphoric Acid Fuel Cell
Pb	Lead
PbO_2	Lead dioxide
PCM	Phase Change Material
PEMFC	Polymer Exchange Membrane Fuel Cell
PFS	Patent Family Size
PHS	Pumped Hydro Storage
RPM	Revolutions Per Minute
SCADA	Supervisory Control and Data Acquisition
SOFC	Solid Oxide Fuel Cell
TCM	Thermochemical Material
TES	Thermal Energy Storage
VLR	Voluntary Load Reduction
VPP	Virtual Power Plant
VRE	Variable Renewable Energy
WIPO	World Intellectual Property Organization

1 INTRODUCTION

Power systems are currently on the edge of profound change. This change is driven by three megatrends, decarbonization, digitalization and decentralization, which are accelerating the energy transition from fossil fuel-based energy generation to variable renewable energy (VRE)-based generation. As the share of VRE generation increases, the complexity of power system grows, and balancing supply and demand becomes more challenging. In this kind of environment characterized by uncertainty and variation, power system flexibility becomes a global priority (IEA 2018; IRENA 2018; IRENA 2019). According to IEA (2018, p. 7), power system flexibility refers to power system's ability to reliably and cost-effectively manage the variability and uncertainty of demand and supply across all relevant timescales. As the definition indicates, a combination of technical, political and institutional solutions is needed to ensure that power system functions unremittingly each second at the lowest possible cost. This thesis provides a patent-based overview of research and development (R&D) landscape in technology areas which can be utilized to create more flexible power system design in the future. By first reviewing suitable technologies and then conducting patent analysis on the selected technologies, one can estimate development trends in examined technologies.

1.1 Background

All power systems have been designed to continuously balance supply and demand. Conventional power system architecture assumes that the gap between two variables is mainly caused by load changes, and that these changes follow a certain pattern. The role of demand-side is assumed to be passive, thus flexibility needs to be addressed by utilizing set of supplier-side assets or more specifically, different kinds of power plants (Lund et al. 2015, pp. 786-787). In the current power system design, a major share of energy is generated by so-called baseload power plants. Baseload power plants can produce energy with marginal operational costs, but are uncapable of reacting to sudden load changes, which means that these changes need to be covered with different means. Typically, this is done by deploying peak power plants, which are characterized by fast start-up and ramp-up times.

Growing integration of VRE generation is rapidly changing the old status quo. Wind and solar power can generate electricity with almost zero marginal cost when operating, consequently leading to cheaper electricity prices, but at the same time introduce a net load problem, thereby increasing the need for flexibility (CERRE 2018, p. 18). Net load refers to situations where supply from VRE sources is unable to cover the total electricity demand, thus creating a gap between production and consumption, which needs to be assessed by other means. The net load effect is best demonstrated in Figure 1, which shows the load behavior when a set of wind turbines are connected to the grid (NREL 2014, p. 2). The green area illustrates the available wind energy supply and the yellow area presents the electricity demand at certain period. The orange area between supply and demand presents netload. The graph demonstrates in remarkable way that VRE output can vary significantly even in short period of time.

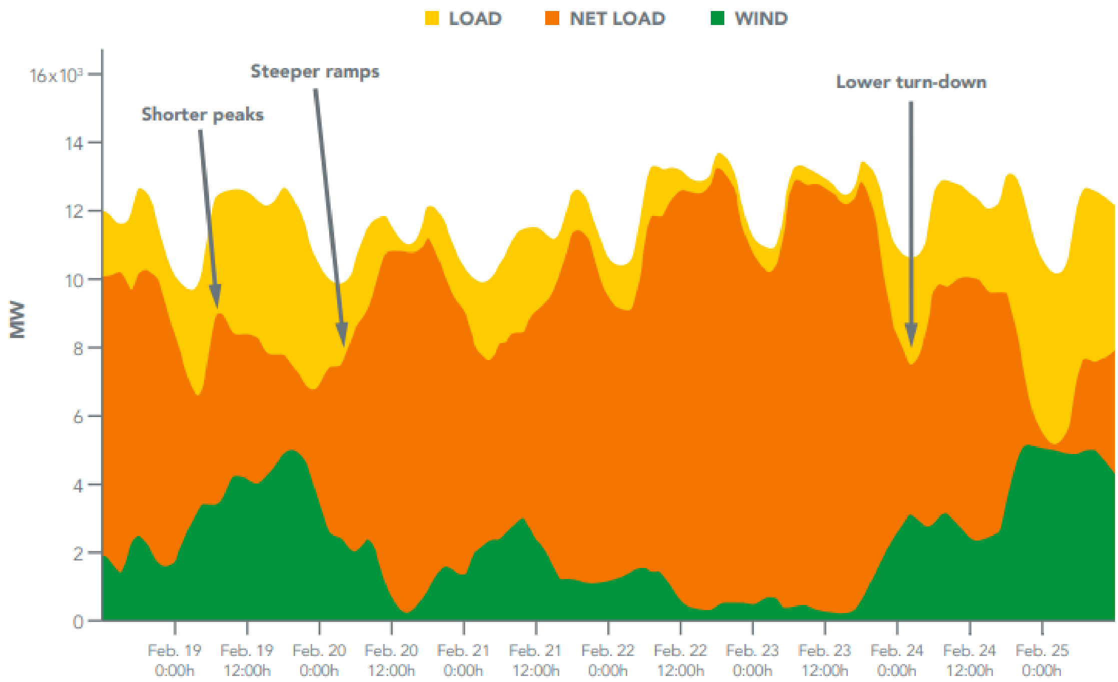

Figure 1 Net load's impact on power system (NREL 2014, p. 2)

The graph also clearly points out the decreasing peak periods, stronger ramp-ups and steeper turn-outs, which impose new requirements for power systems, calling for increased holistic system flexibility to manage the "new normal". As was stated earlier, this does not mean that current power systems would not have the technical capabilities to host these requirements. Gas-fired peaking power plants have already demonstrated their capability to provide power system flexibility rather sustainable way. The main challenge is related to inflexible baseload power plants which are incapable to adjust their minimum generation levels, hence creating a set of environmental-economic constraints in VRE-dominated context (NTEL 2014, pp. 1-3). If the energy outputs of baseload power plants remain inflexible, VRE power will need to be curtailed, which means that a significant amount of renewable energy is lost to either to maintain system balance or to mitigate transmission congestion (IEA 2018, pp. 7). VRE curtailment may not only impede national and international efforts to reach emission targets, but also lead to increased price volatility and negative market prices (NREL 2014, p. 5).

Considering environment-economic constraints, a question how to create a flexible power system that at the same time fulfills IEA's definition and does it in sustainable manner, may arise. A closer look to the existing literature reveals that a flexible power system is an entity of different technological, regulatory and institutional factors, as demonstrated in Figure 2, and therefore being strong in one area may not guarantee robustness of the whole system (IEA 2018, pp. 8-11). Technological factors refer to physical infrastructure of the power system, which form the core of every system. It consists of various supply and demand side technologies that secure energy supply across all relevant timescales. The suitable technical mix is country specific and approaches vary significantly (Lund et al. 2015, p. 786), although it has been identified that successful mix should have at least clear assets' optimization and controlling plans (Salpakari et al. 2016; Haikarainen et al. 2019).

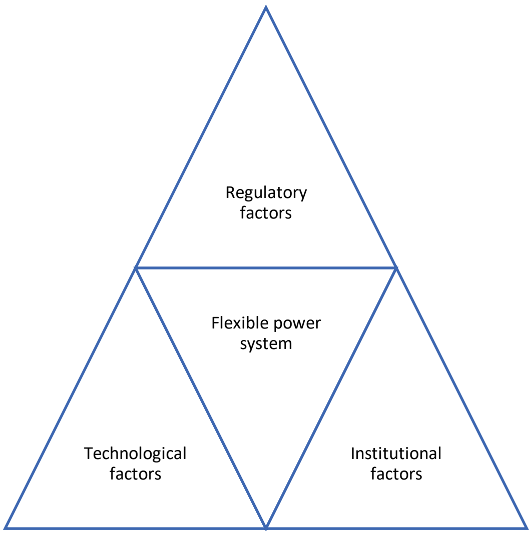

Figure 2 Components of flexible power system

In recent decades liberalization of electricity markets has been one of the major trends in power sector. It has allowed producers and purchasers freely trade electricity in both wholesale and retail markets, which has made the energy operations more efficient but also created new threats, such as California Energy Crisis in 2000-2001 (Honkapuro 2019; Uz 2018). The main task of regulation is therefore to organize market place in such a way that it provides incentives for new investments, encourages for energy efficiency and sets and controls borders of economic activities (IEA 2018, p. 28). In the last years the academic discussion has been oriented towards examining new tariff options, as older energy-based tariffs no longer reflect the true costs of generation for system operators (Thompson 2014; Layer et al. 2017; Narayanan et al. 2018). Holistic regulatory roadmaps have also been created (Papaefthymiou and Dragoon 2016; Child et al. 2018a).

Transparent and well-functioning institutions play a major part in creation of flexible power system. In flexible power system different actors and stakeholders are aware of their roles and responsibilities as flexibility providers. Key issues to solve include the questions of market participation, roles and responsibilities and co-ordination and communication among different players. In the retail side the role of so-called prosumers is gathering growing attention. Prosumers are energy consumers capable of producing energy, usually by utilizing distributed generation technologies such as solar pvs (Nylund 2018, p. 8). The main topic is to clarify how these prosumers are shaping market dynamics and how they can contribute in enhancing power systems' flexibility.

1.2 Research questions and objectives

This study aims to provide an overview of patenting activity and patenting trends in selected technology areas, that can be utilized to provide power system flexibility. To achieve the aim of the study, four research questions presented in the Table 1 need to be addressed. The first research question (RQ1) asks what are the main technology areas that can be utilized to enhance power system flexibility. The objective of RQ1 is to identify possible flexibility provider technologies and this objective is achieved by reviewing available literature. The second research question (RQ2) asks how the patenting activity related to the selected technology has developed, aiming to understand the direction of patenting activity in the selected technology areas. The third question (RQ3) is linked to the leading intellectual property offices and key applicants and tries to disclose where inventions in the selected technology areas are filed and who are filing them. Lastly, the fourth research question (RQ4) asks what are the technological focus areas in the selected technology areas. The objective of RQ4 is to identify what is being filed in the selected technology areas.

Table 1 Research questions and objectives

Research question	Objective
RQ1: What are the main technology areas to enhance power system flexibility?	To identify possible flexibility provider technologies
RQ2: How active the selected technology areas are in terms of patenting?	To understand the direction of activity in selected technology areas
RQ3: Who are the leading IP offices and the key applicants in the selected technology areas?	To reveal where inventions are filed and who are filing them
RQ4: What are the technological focus areas in the selected technology areas?	To identify what is being filed in the selected technology areas

1.3 Scope of the study

Power system flexibility can be enhanced in three different ways as was shown in subchapter 1.1. Institutional level can enhance power system flexibility by dividing roles and responsibilities for entities providing flexibility. On the regulatory level, technical rules and economic incentives are created to ensure well-functioning power system. Technological level includes all physical means that can be used to provide flexibility into a power system. This study acknowledges the importance of institutional and regulatory but focuses solely examining technology level solutions. Institutional and regulatory levels are simply irrelevant, when considering the aim of the study and used data.

This study considers only those technologies which are part of power producing sectors and thus regarded as core part of power system. Hence so-called sector coupling technologies, whose primary function is to connect buildings, transportation and industrial sectors with power producing sectors, are excluded.

1.4 Keyword map

The main keywords used in the information retrieval process are presented in Figure 3. Keywords related to “Energy storage”, “Conventional power plants” and “Smart grids” are used to retrieve material for study’s theoretical part. Keywords linked to “Patent analysis” are utilized to find material for study’s methodological part.

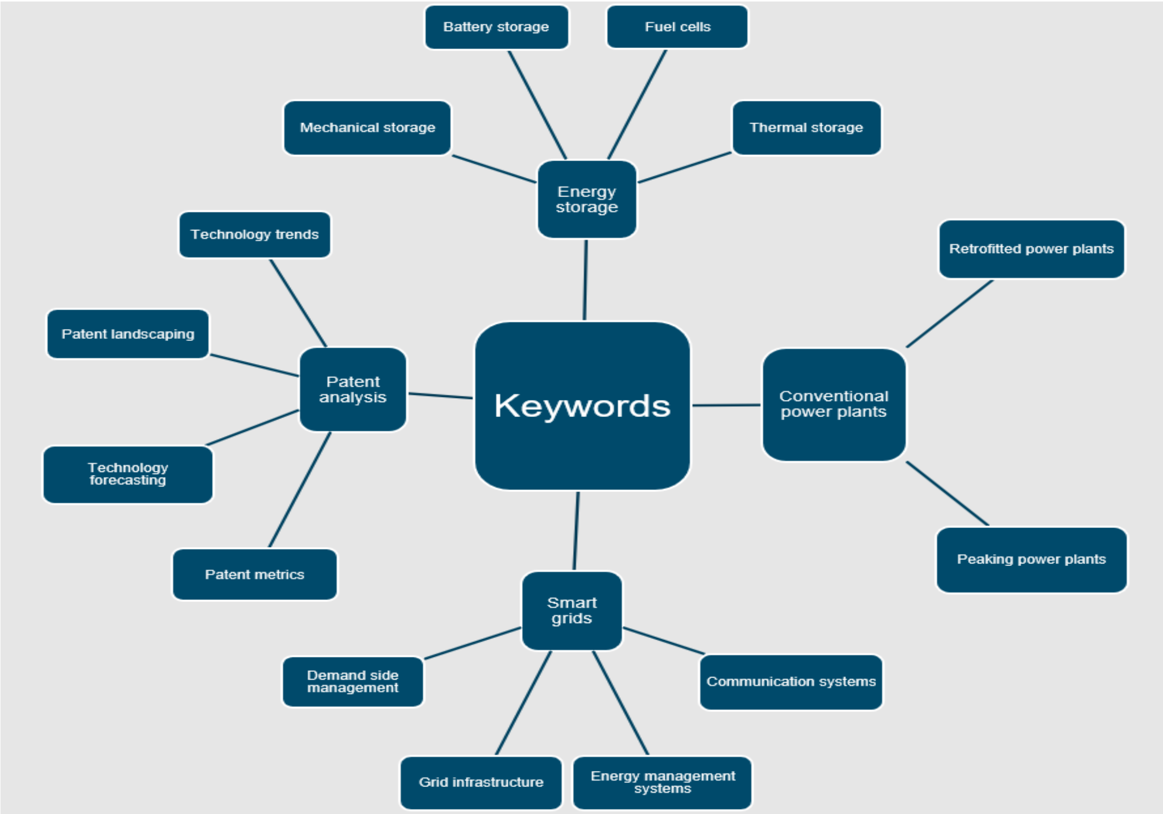

Figure 3 Keyword map

1.5 Structure of the thesis

The thesis is structured as in Table 2, which introduces chapters’ names and briefly describes the main inputs and outputs of each chapter. The study starts with *Introduction* chapter, which provides background for the study, introduces research questions and objectives, discusses scope of the study, and presents keywords and the structure of the thesis. Next chapter, *Flexibility Provider Technologies,* functions as a literature review chapter and provides an extensive overview of the technical means to enhance power system’ flexibility.

Chapter 3 *Methodology* creates a structure for study's empirical part by describing the used research methods.

Table 2 Thesis structure

Input	Chapter	Output
Introduction to the topic	**Chapter 1** **Introduction**	Background of the thesis, research aims, questions, scope and limitations
Theoretical framework for literature review, research questions, scope	**Chapter 2** **Flexibility Provider Technologies**	Overview of technologies which may be used in patent study
Suitable patent data-based methods	**Chapter 3** **Methodology**	Structure for empirical part, description of used methods
Retrieved patent data	**Chapter 4** **Smart Grid Patent Analysis**	Patent analysis
Retrieved patent data	**Chapter 5** **Energy Storage Patent Analysis**	Patent analysis
Results of patent analyses, overview of literature review	**Chapter 6** **Discussion**	Answers to the research questions, limitations, future research
Assessment of the results	**Chapter 7** **Conclusions**	Final assessment

Chapters 4 and 5 form the empirical part of the study. Chapter 4 *Smart Grid Patent Analysis* shows the results of the patent- and trend analysis of smart grid technologies and the following chapter *Energy Storage Patent Analysis* does the same for energy storage technologies. *Discussion* summarizes the results and answers to the research questions. Furthermore, it discusses about limitations and proposes possible areas for future research. Chapter 7 *Conclusions* provides a final assessment for the whole thesis.

2 FLEXIBILITY PROVIDING TECHNOLOGIES

A flexible power system is a power system design in which variability and uncertainty of demand and supply are addressed by deploying set of technologies that are capable of securing the reliable operation of a power system in all relevant time-scales by adjusting the amount of energy in the system. IRENA (2018, p. 23) has listed six features of a flexible power system:

1. Ability to meet peak load and peak net loads without loss of load
2. Capability to maintain the balance of supply and demand at all times
3. Ability to store energy effectively to balance variability in VRE generation
4. Capability for demand adjustment in overgeneration and supply shortage situations
5. Ability to deliver ancillary services
6. Operates under efficient markets

Figure 4 presents three technology areas that have proved to have above-mentioned features and could be utilized to create more flexible power system (Lund et al. 2015; IEA 2018; IRENA 2018).

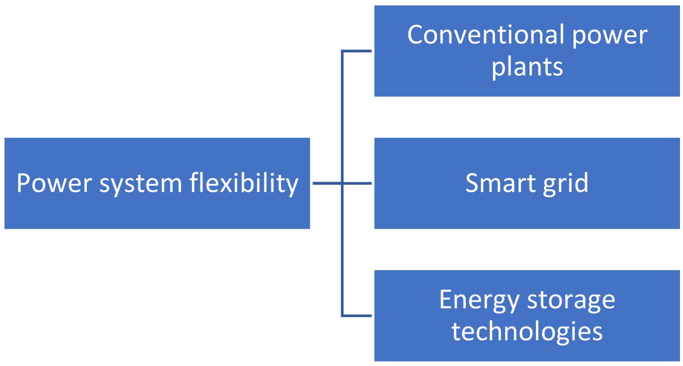

Figure 4 Power system flexibility providers (based on Lund et al. 2015; IEA 2018; IRENA 2018)

Conventional power plants can be utilized to provide flexibility across relevant timescales. Current power systems are based on conventional power plants, hence only a little emphasis is put on introducing them in this thesis.

Smart grid is used as an umbrella term for a set of physical and virtual technologies that connect supply and demand sides to each other and efficiently coordinate the operations between two sides. Different energy institutes see that smart grid will have a significant role in flexible power system as it increases energy efficiency.

Energy storage technologies are vital for VRE based power systems as they can store electricity generated during the overproduction hours and release the energy when needed. Energy storage technologies can also provide ancillary services and help to balance supply and demand. Some scholars see them as the most important part of future flexible power systems.

2.1. Conventional power plants

Conventional power plants are power plants that utilize thermal engines to generate electricity from fossil- or biofuel sources. Traditionally power systems have been categorized according to their input energy and operational design to baseload-, intermediate and peaking power plants. Baseload and intermediate plants have provided the bulk energy, whereas peaking power plants have reacted to the sudden load changes, hence being the major source of power system flexibility in the traditional design (Lund et al. 2015, pp. 796-797; IRENA 2018, p. 25; IEA 2018, p. 23; Irena 2019, p. 71). In the new flexible power system, the old roles do not apply anymore, as wind and solar technologies consolidate as the least cost option in generating bulk energy (IEA 2018; IRENA 2018). Therefore, to remain competitive conventional power plants need to provide greater flexibility more rapidly and frequently (IRENA 2018, p. 27).

There are two technological approaches how power system flexibility can be enhanced with conventional power plants (IEA 2018, p. 31). First one includes retrofitting of the existing inflexible baseload and intermediate plants to meet the targeted flexibility parameters (NTEL 2013, pp. 1-4). In retrofitting process component or operational modifications are done to achieve for example lower minimum load (IRENA 2019, p. 47; Chung et al. 2019, pp. 22-23). The main advantage of retrofitting is that it may help to provide long term flexibility into power systems. The downside of the retrofitting is that it typically includes severe uncertainty related to costs which may turn the investment unprofitable (IEA 2018, p. 31).

The second approach is to deploy more peaking power plants that can operate with part loads and can quickly adjust their power outputs according to the need. Peaking power plants typically operate with gas-fired combustion engines or turbines (IRENA 2019, p. 71). In flexible power system they can be utilized in load following purposes (IEA 2018, pp. 38-39).

2.2. Smart grids

Smart grid refers to a power system structure that combines power grid infrastructure with advanced communication and software technologies to enable two-way power and communication flows between all parties connected to the grid (Bari et al. 2014, pp. 1-2; Lund et al. 2015, p. 799; STEK n.d.). Hasan and Mahfuz (2013, pp. 2-4) have listed several benefits that widescale smart grid integration might have for power system. Firstly, smart grids have an ability to recognize possible malfunction situations in the grid before they even occur and reroute power flows in a way that error area is disconnected from rest of the grid. This may significantly reduce power system's maintenance and repair costs. Secondly, smart grids enhance market integration by allowing bi-directional power flows. This changes traditional provider-consumer approach as consumers become active participants in electricity markets who may sell and buy electricity at the same time. It also forces utilities to create new business models, which may result in improved selection of energy products and decrease the cost of electricity for customers. Lastly, smart grids can be used to host distributed generation (DG), which refers to electricity generation that takes place somewhere else than in large centralized power plant, usually close to customer loads and with VRE sources (Virginia Tech 2007; NETL 2010, pp. 6-8). DG has operational and economic benefits for all market parties. From operational perspective DG reduces transmission loads during peak hours and improves congestion control, as electricity is generated close to load centers and transported via distribution lines. Consequently, the demand of new transmission and distribution lines decreases, and capital can be invested to other projects. Economic benefits come from improved reliability and may be substantial for industries that require uninterruptable power source (Virginia Tech 2007).

2.1.1 Communication and management systems in smart grids

One of the distinctive features of smart grid is the real time communication between different parties of the grid, which enables power system to balance demand and supply instantaneously. Real-time communication feature can be implemented with various technologies, including wired and wireless, and many of these technologies can be used in residential and industrial surroundings. One communication approach is called Advanced Metering Infrastructure (AMI), which refers to an energy monitoring system that allows bi-directional information flows between energy user and utility by connecting user’s meters and utility’s Supervisory Control and Data Acquisition (SCADA) system (Hasan and Mahfuz 2013, pp. 2-3). Typical technologies involved in AMI are smart meters, communication networks, head-end systems and Meter Data Management Systems (MDMS) (US Department of Energy 2016, pp. 9-12). Smart meter is a metering device that collects data from customer’s consumption patterns and sends them to the utility real time (Römer et al. 2012, pp. 486–495). In return, utility can send price incentives and details concerning energy tariffs to its customers (Koponen 2012, pp. 1-5). The information is transmitted via communication network to a head-end system, which works as an information hub and controller. Head-end system forwards information to utility-side’s MDMS, which functions an analytical database that enable interactions with other external systems, like Enterprise Resource Planning (ERP), to perform various actions related to collected AMI data (NETL 2008, p. 9).

Second smart grid technology group that has become increasingly relevant is Energy Management System (EMS). EMS refers to a computer aided control system that manages and optimizes smart grid’s operations in the most reliable and cost-efficient way. EMS can be used to control operations in the whole power system level (transmission approach), but recently the focus has been on developing applications to control individual assets (Aguilera et al. 2018, pp. 1-3). According to Byrne et al (2017, p. 13232) typical application areas include:

- virtual power plant, where distributed generation assets are united by EMS as one, centrally controllable aggregator.

- storage system, where EMS is used to optimize scheduling of grid connected storage systems and to coordinate multiple storage systems based on different capacity and technology
- microgrids, where EMS is utilized in connecting the load centers into distribution network
- electric vehicle, where EMS is used to integrate electric vehicles as part of the grid.

System architectures for EMS may vary significantly according to the application area, but some common subsystems in most of the EMS are power conversion system, device management system and communication systems. Power conversion system is a subsystem that is used for grid interface and controlling power flows in the application. It includes a two-level control hierarchy: secondary level controls system-level power operations (e.g. in energy storage application charging and discharging), while primary level controls that unit functions in a desired way (e.g. right voltage and current inputs). Device management system is used to ensure safe operation of the system. It constantly monitors the state of the system to prevent potential failure states caused for instance by overheating and overcharge and uses active and passive safety means to stop possible damages. Finally, communication interface enables the communication between different subsystems of EMS and is vital to coordinate different tasks between the subsystems. The structure of communication interface often follows standardized commercial protocols, such as Modbus/Transmission Control Protocol (Modbus/TCP), which was developed by Schneider Electronics. (Byrne et al. 2017, pp. 13231-13238.)

2.1.2 Demand-Side Management

Demand-Side Management (DSM) refers to a combination of tools which allow utilities to manage end-users' power loads during peak load hours. Due to ability to shift loads, DSM can increase cost-side flexibility of power system by reducing the need of constructing extra generation and transmission capacity. (IRENA 2013, p. 26.)

DSM include economic and technical dimensions. Economic dimension refers to incentives and pricing schemes that are utilized to modify end-user's consumption behavior. One typical example of DSM incentive would be a lower price that end-user receives when shifting his consumption from peak load hours to off peak hours. In some countries DSM pricing schemes already offer extra flexibility to the power system. In USA markets, for example, there are currently five different time-based programs that are said to better reflect the effect of time variation in the generation costs. These include:

- time of use pricing: Consists of time blocks which have predetermined fixed prices
- real-time pricing: Pricing happens based on hourly prices and consumed energy on that hour
- variable peak pricing: Different periods for pricing are predetermined but pricing for peak hours varies
- critical peak pricing: The price is significantly increased during a specified period to maintain functionality of a power system
- critical peak rebates: Customer receives predetermined amount of refund when lowering electricity consumption in pre-specified period. (US Department of Energy, 2019.)

Technical dimension refers to techniques that are applied to reduce system loads at desired time. Techniques can be divided into three categories. The first, direct load control (DLC) is typically applied with commercial and industrial customers and includes giving utilities a limited control of customer's load. The second technique is voluntary load reduction (VLR) which aims to encourage customers to reduce their loads voluntarily by sending their incentive signals, such as electricity price signal. Lastly, dynamic demand technique can be used to automatically adjust power usage, but this technique is not commonly used due to lack of compensation approaches for customers. (IRENA 2013, pp. 26-27.)

2.1.3 Grid infrastructure

Probably the most self-evident part of smart grid is advanced transmission and distribution infrastructure, which consists of super grids and microgrids. Super grids refer to high-voltage transmission lines whose aim is to enable long distance and high-volume energy trading with minimal losses. Super grids can be created by using high voltage direct current (HVDC) or high voltage alternating current (HVAC) cables, but HVDC is typically preferred due to stability and transmission efficiency issues (Larson 2018). HVDC-based systems consist of two different converter substations at transmission and receiving ends and transmission cables (Rudervall et al. 2000, p. 3). Some authors have presented that HVDC super grids could be used in future power systems for enhancing energy security by establishing continental or even intercontinental transmission networks to balance intermittencies in local VRE production variations (Watson 2012, p. 89; Elliot 2013, pp. 171-173). In theory this could mean that for example Finland could import electricity via intercontinental grid from Sahara where there are plenty of excess energy available. Recent development projects have included inter alia Asia Super Grid, which aims interconnecting electric power systems of several Asian countries, and Desertec, a German-led initiative promoting deeper Europe-North Africa market integration (Renewable Energy Institute n.d.; Desertec n.d.).

Microgrids are small distribution ecosystems designed to supply electricity needs of local customers. Typically, a microgrid ecosystem is designed around a single power generation facility, but may include also other technologies, such as storage and feeder. The main motivation to deploy a microgrid is arguably to promote local community’s energy self-sufficiency, but microgrid may also bring economic benefits, such as infrastructure- and fuel cost savings, and help VRE integration in local scale. (Hirsch et al. 2018, p. 404-405.)

2.3. Energy storage technologies

Energy storage technologies are technologies whose main purpose is to store excess energy generated during low-demand period to convert stored energy into electricity during high demand. Different energy storage technologies provide interesting opportunities for the future power systems due their multipurpose nature and wide range of applications. Some scholars argue that energy storage systems could have a crucial role in achieving the goals of Paris Agreement and making renewable energy cost efficient (Child et al. 2018b, pp. 44-46).

In future power systems, energy storages will have a vital role as they increase system flexibility and can be utilized in mitigation of power variations caused by intermittent renewable energy resources (Amrouche et al. 2016, pp. 20914-20915). In distributed energy system, energy storage technologies can be deployed to avoid local grid bottlenecks in case the energy storage is used to optimally match grid requirements and not according to market opportunities. For power producers and large industrial entities energy storages may offer new ways to provide various grid support functions. Grid support functions are usually classified under second-, minute-, or hour-level response time can be further on categorized divided into seven different categories:

- peak shaving and load leveling: energy storage is used to shave demand peaks and level loads in situation where load and production are imbalanced
- energy arbitrage: Charging storages during the off-peaks to sell energy when demand and prices are high
- renewable energy integration: Energy storage can be used to balance intermittency of variable generation
- voltage and frequency regulation: Stabilize grid frequency in cases when the frequency above or below the nominal by occluding or feeding power.
- harmonic compensation: Storage technologies may be used to compensate decreased power quality that occur in distributed energy systems due to voltage inversion
- reserves: Fast respond energy storages can be utilized as a spinning reserve, replacing conventional reserve generators
- black start: Energy storage is used to provide initial power when starting a power plant after serious grid failure. (Chang et al. 2017, pp. 270-273.)

Energy storages may have geopolitical motivation in some regions to guarantee supply security (Breyer 2018).

Energy storage technologies have different attributes which define their application area. One commonly used categorization method is to divide technologies into physical trait-based classes (Kousksou et al. 2014; Chang et al. 2017). Figure 5 demonstrates physical trait-based classification by dividing energy storage systems into mechanical-, battery- and thermal storages and fuel cells. Mechanical, battery and fuel storages store energy to convert it into electricity, whereas thermal storage technologies store energy for mainly cooling and heating purposes.

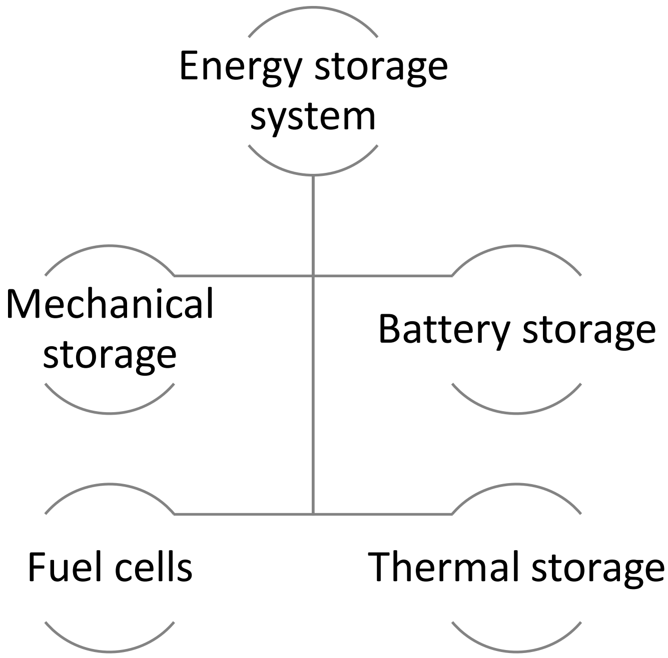

Figure 5 Classification of energy storage technologies based on physical traits (based on Kousksou et al. 2014; Chang et al. 2017)

The following subchapters offer short overviews of relevant energy storage technologies using physical trait-based classification presented in Figure 5.

2.3.1. Mechanical energy storage

Mechanical energy storage technologies store kinetic or potential energy and deliver it when needed in mechanical form (Gogus 2017, p. 2). Mechanical storage technologies are divided into flywheel, Compressed Air Energy Storage (CAES) and Pumped Hydro Storage (PHS) technologies, but typically in distributed storage context PHS systems are disregarded as they are characterized by massive power ratings (ranging from 1000 MW to 3000 MW) and space requirements, making PHS systems rather centralized (Molina 2012, p. 2-4; Amirante et al. 2017, pp. 374-376).

Flywheel energy storage systems convert electric energy to kinetic energy which is then stored in spinning mass (Amirante et al. 2017, pp. 377-378). A typical flywheel system (Figure 6) consists of an electric motor, a variable-speed power converter, a power controller and bearings (Amirante et al. 2017, pp. 377-378). The working principle is quite simple:

motor powers the crankshaft which rotates flywheel-mass that then stores the kinetic energy received.

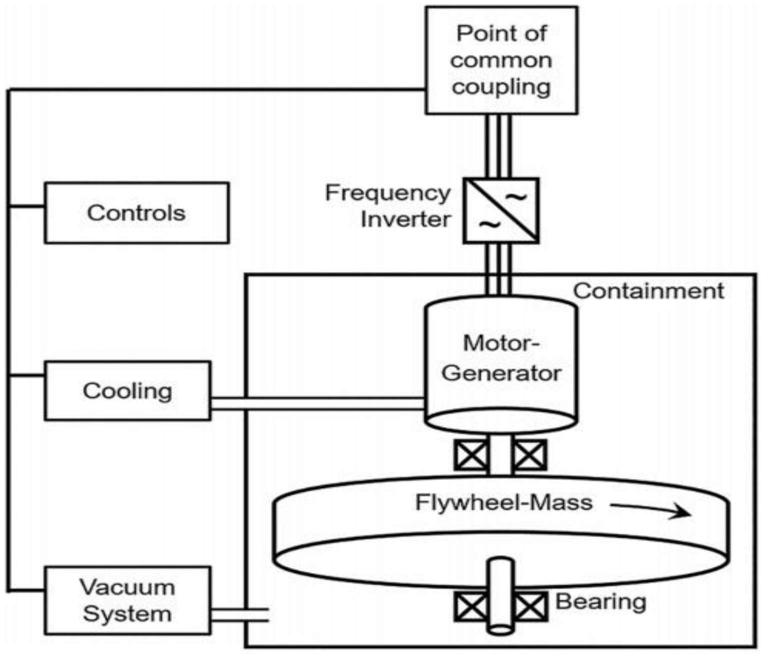

Figure 6 Flywheel system (Schaede, cited in Wicki and Hansen 2017, p. 1120)

The amount of energy stored in flywheel depends on the combination of mass, rotational speed and used material (Kale and Secanell 2018, pp. 576-577), and can be calculated by using following equation:

$$E = \frac{1}{2} J\omega^2,$$

Where E is kinetic energy, J is moment of inertia and ω is velocity.

Flywheel technologies are divided to low- and high speed categories based on their spinning speed. Low speed technologies have operational speeds up to 10000 rpm, utilize heavy steel components and achieve specific energy ratings around 5 Wh/kg (Hadjipaschalis et al. 2009, p. 1514). High speeds are novel technologies, in which very high rotational speeds (up to 100000 rpm) are achieved by utilizing state-of-art materials, such as carbon fiber. Compared to low speeds, they have high energy density but lower power ratings and are restricted by high material costs that can be up to 5 times higher than in low speeds. (Mousavi et al. 2017, pp. 479-485.)

Flywheel technologies have several benefits compared to other storage technologies. To begin with, their operational life time is up to 20 years and charge-discharge cycle times up to hundreds of thousands of cycles without degradation, making it by far the most long-lasting storage technology available (Sebastián and Peña Alzola, 2012, pp. 6804). In addition to long life times, flywheels have excellent response times, high round trip efficiencies and low operational and maintenance costs (Amirante et al. 2017, pp. 377-378). Because of their ability to release high power outputs in rapid manner, high-speed flywheels could be used in peak shaving, black start and voltage/frequency control operations in flexible power systems. (Wicki and Hansen 2017, pp. 1118-1121). Finally, flywheels are easily scalable as its energy output can be modified by adjusting engine power and size (Sebastián and Peña Alzola 2012, pp. 6803; Amiryar and Pullen 2017, pp. 10-11). The main disadvantage of flywheel energy storage systems is the high tendency for self-discharge, which may result to energy losses up to 20% of stored capacity (Kousksou et al. 2014, pp. 68-69).

CAES systems convert electricity into pressurized air by utilizing electrically driven compressors. The idea is that during the demand peaks stored potential energy can be converted back to electricity by first heating the pressurized air and then feeding it to turbine-generator combination (Budt et al. 2016, pp. 253-254). Round trip efficiencies of CAES systems seem to be controversial as estimates range from 50% to 90% (Komarnicki et al. 2014, p.141). The amount of energy which can be stored depends on the available space. The main benefit of CAES systems is that it is capable to deliver very high amounts of power with very short respond time. The fundamental constraint is related to location as typically CAES requires a lot of space and deep salt caverns to ensure minimal pressure losses and disadvantageous chemical reactions. (Wang et al. 2017, pp. 4-5).

In flexible power system, power utilities could utilize CAES for energy arbitrage and to provide operational reserves when the prices are high. In their comprehensive study on the value of CAES in energy and reserve markets, Drury et al. (2011, p. 4964) demonstrated that by providing operating services together with exploiting high day ahead prices could increase annual net CAES revenues by 10 to 28 $/kW.

2.3.2. Battery energy storage system

Battery Energy Storage (BES) systems utilize electrochemical reactions to produce electricity in desired voltage. The working principle is relatively simple and is presented in Figure 7: a set of electrochemical cells is connected either in series or parallel and each cell contains one anode and cathode electrode with an electrolyte. A cell switches the form of energy bi-directionally between electrical and chemical, depending on situation. When battery is discharged, the electrochemical reaction occurs in anode and cathode electrodes simultaneously in a way where anodes functions as an electron provider and cathodes as an electron collector. In charging situations, a reverse reaction occurs and battery is charged by using external voltage to the anode and cathode. (Luo et al. 2015, pp. 516-517.)

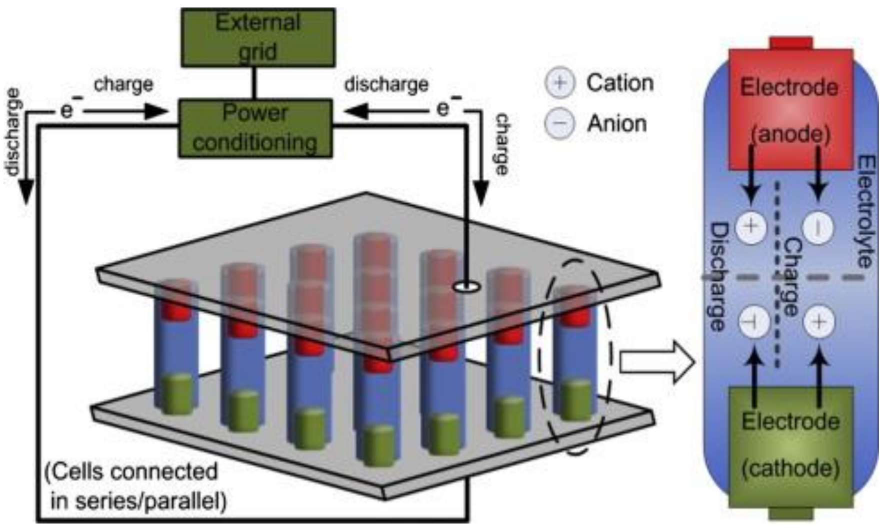

Figure 7 Schematic diagram of a battery energy storage system operation (Luo et al. 2015, p. 517)

Chatzivasileiadietal et al. (2013, pp. 815-816) have proposed the following technologies to be applied in stationary storage applications: lead-acid, sodium-sulphur (NaS), lithium-ion (Li-Ion), nickel-cadmium (NiCd) and flow batteries.

Lead-acid battery is currently the most used battery storage technology globally and it has already been successfully applied in medium and small-scale distributed energy storage systems for grid support purposes. Lead-acid is a mature technology that uses lead dioxide (PbO_2) cathodes and lead (Pb) anodes together with sulfuric acid-based electrolyte to create electrochemical reactions (Luo et al. 2015, pp. 516-517). The main advantages of lead-acid batteries are fast response times, low self-discharge rates, decent cycle efficiencies and low capital expenditure (CAPEX) compared to other battery technologies (Aneke and Wang 2016, p. 364). Disadvantages are related to poor cycle times, low energy density and to poor ability to stand temperature changes (INEEL, 2017, pp. 3-4). Advanced lead-acid batteries, which utilize to carbon plates to achieve supercapacitor qualities, are expected to significantly extend cycling times and response times (Zhang et al. 2018, pp. 3094-3095).

Li-Ion battery technology is a novel technology which has been mainly used in electronics and automotive industries. It consists of lithium metal oxide-made cathode, graphitic carbon-based anode and an electrolyte, which is typically lithium salt-based organic liquid (Zhang et al. 2018, p.3095). During discharge electrons force lithium ions to move from negative anode to positive cathode creating an electric current and vice versa, when battery is charged. Li-Ion battery has several beneficial features from power system flexibility perspective. These attributes include short response time (milliseconds), high energy/power densities (75-200 Wh/kg) and excellent cycle efficiencies (Suberu et al. 2014, pp. 503-504). Unfortunately, Li-ion are sensitive for overheating and therefore require a thermal runaway system, which increases CAPEX of a large-scale system. In addition, Li-Ion batteries may raise environmental and societal concerns, as the batteries contain hazardous chemicals and resources are concentrated into unstable regions, where mining profits could be used to finance regional conflicts. (Oliveira et al. 2015, pp. 355-360.)

In NiCd batteries the electrochemical reaction happens between nickel oxyhydroxide (NiOOH) cathode, metallic cadmium anode and aqueous alkali electrolyte (Luo et al. 2015, p. 518). Compared to lead-acid batteries, the main advantages of NiCd batteries are high energy densities, long life cycle and low operation and maintenance costs (Kousksou et al. 2014, p. 70). Compared to other battery technologies, NiCd's special trait is stability at deep discharge stages, which means that NiCd battery can be stored in discharge stage for long periods without damaging the capacity (Sino Voltaics 2015). The main weaknesses are related to environmental hazards and high self-discharge rates (Aneke and Wang 2016, p. 364). Environmental hazards are resulting from both cadmium and nickel which are toxic heavy metals, hence special attention should be paid on disposal process (Sino Voltaics 2015).

NaS batteries are high-temperature technologies that use beta-alumina solid material as an electrolyte and sodium and sulphur as electrodes (Komarnicki et al. 2017, pp. 142-144). The operational temperatures of NaS batteries range from 270 to 350°C and specific thermal insulation is needed to ensure the liquid state of electrodes (INEEL 2017, pp. 5-6). According to Aneke and Wang (2016, pp. 360-361), NaS batteries are characterized by high energy density, high energy efficiency, long cycle capability and low maintenance costs. The main disadvantages are high capital costs, challenging temperature requirements and toxic components (INEEL 2017, pp. 5-6).

Flow batteries differ from the rest of battery storage system, as they combine elements from battery and fuel cell technologies (Larcher and Tarascon 2015, p. 25). A typical flow battery consists of two electrolyte containing liquids, storage tanks and electrochemical cell. In discharging situations, liquids flow to through electrochemical cell which converts the chemical energy stored in liquids directly into electricity. The main technologies are based vanadium and zinc-bromine, although there several other chemical alternatives available. Flow batteries have several lucrative features which make them suitable for flexible power systems. Flow batteries have rapid response and recharge times as equalization charging is not needed, modifiable layout since power and energy components are separated, and finally long cycle times due to absence of solid-to-solid phase changes. However, the main constraint of flow battery systems seems to be a complex system architecture, which may increase operation and maintenance costs significantly compared to other battery systems. In addition, flow batteries tend to have rather low energy densities and high self-discharge rate, which may limit their usability as single flexibility provider. (Poullikkos 2013, pp. 781-784.)

2.3.3. Fuel cell

Fuel cells are electrochemical devices that convert chemical energy stored in fuels into electricity. The structure of fuel cell system is similar to batteries, as it consists of anode, cathode and electrolyte membrane. The system works by transmitting fuel through the anode of a fuel cell and oxygen through cathode. Fuel's molecules are split into electrons and protons: protons go through electrolyte membrane and electrons are pushed through a circuit, consequently creating an electric current and excess heat. Unlike batteries, fuel cells do not need to be charged, as these direct systems continue to provide electricity as long as continuous fuel supply is provided. (Fuel Cell & Hydrogen Energy Association n.d.)

Fuel cells consists of various technologies, which generally differ in terms of electrolytes used, operating temperature, design and field of application. The major technologies in terms of technical development are

- Solid Oxide Fuel Cell (SOFC), in which solid ceramic electrolyte is utilized. Can be used in large industrial systems.
- Molten Carbonate Fuel Cell (MCFC), where molten carbonate salt functions as an electrolyte with fossil-based fuel:
- Direct Methanol Fuel Cell (DMFC) utilizes hydrogen from liquid methanol directly
- Alkaline Fuel Cell (AFC), in which alkaline electrolyte is fueled with pure hydrogen and oxygen
- Polymer Exchange Membrane Fuel Cell (PEMFC), that consists of H_2O-based polymer membrane and platinum-catalyzed electrodes. Currently the main fuel cell technology with 97% market share
- Phosphoric Acid Fuel Cell (PAFC), which utilizes phosphoric acid as an electrolyte. (Umberto 2014, p. 165.)

The main advantage of fuel cell systems is versatility. There are several technologies available with different power ranges and fuel cells can be used for both grid and off-grid power systems. Downsides are high CAPEX costs and low operational lifetime, which may make the investment unprofitable. (Ibrahim et al. 2008, pp. 1232-1233.)

2.3.4. Thermal energy storage

Thermal Energy Storage (TES) systems can be divided into sensible heat storage, latent heat storage and thermochemical energy storage. Sensible heat storage systems are the most common and the most economic form of thermal storage. They are used in various industrial and residential applications e.g. in space heating/cooling and industrial process management (Guney and Tepe, 2017, p. 1192). The function mechanism is simple: energy is stored by heating storage material to a higher temperature (Luo et al. 2015, p. 523). The energy is stored without phase transitions and stored amount of energy is proportional to the material density, specific heat value, volume and temperature difference (Huggins 2016, p. 22). Sensible heat storage system consists of reservoir, storable material and inlet/outlet devices (Kousksou et al. 2014, p. 61). The used materials can be divided into liquid and solids, both groups having their own special characteristics. The most popular material is water, which has high heat value, good availability and is usually cheap compared to other materials. The main advantages of sensible heat systems are low operational costs and high operational reliability. Disadvantages are linked to size requirements and temperature swings, which occur when ambient temperature changes (Huggins 2016, p. 22-24).

In latent heat storage technologies latent heat is stored to storage medium by utilizing so called Phase Change Materials (PCM). These materials can change their form without changing their chemical structure and have high latent heat potential compared to their non-changing counterparts (Aneke and Wang, 2016, p. 367). PCMs are classified either to organic or inorganic materials, where organic materials can be fatty acids, waxes, polyglycols or aromatic, whereas inorganic materials consist of i.e. different salts and metals (Huggins 2016, pp. 23-26; Aneke and Wang 2016, p. 367). Phase transition can be either solid-liquid-gas-liquid- or solid-solid-based and occurs when PCM is heated and reaches the required temperature (Huggins 2016, p. 23). Absorption continues at a constant temperature while the material changes its state. Stored energy can be released by changing material’s phase from liquid to solid again (Barbour n.d.). Working principle is demonstrated in Figure 8 in which solar collector/molten salt system is presented. Figure 8 illustrates that external energy is used to transform solid salt to its liquid form. When electricity is needed, molten salt is driven via super- and reheaters to steam generator and thereon to power block which converts energy back to electricity. Leftover salt is directed to cold salt tank where it changes its phase from liquid to solid and is then stored in receiver part.

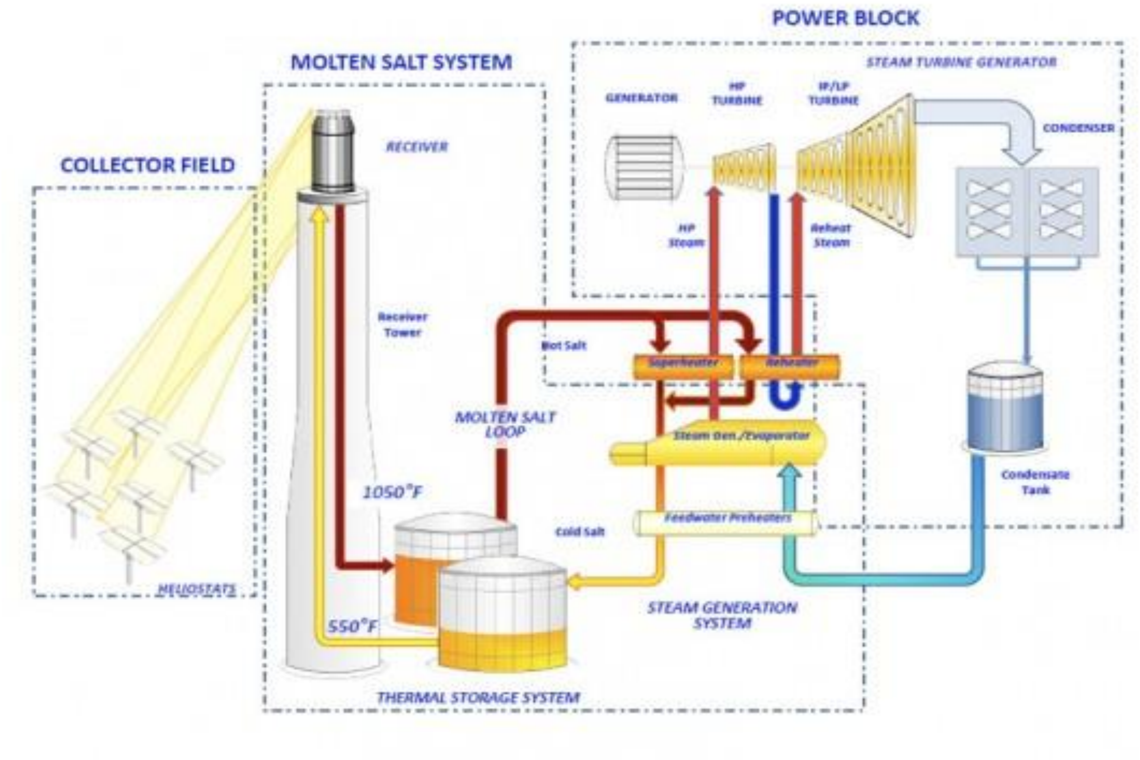

Figure 8 High latent heat energy storage system utilizing solar collectors and molten salt (Sandru 2010)

According to Medved et al. (2010, pp. 3-4) latent heat storage systems have two major benefits. Firstly, they have a high storage density, which enables them to store larger quantities of heat with minor temperature changes. Secondly, latent heat energy storage systems have high discharge times, meaning that they can provide stable energy outputs for long periods of time. The main disadvantage is related to low thermal conductivity of PCMs which causes slow transient response and makes it difficult to rapidly charge and discharge the system (Zarma et al. 2017, p. 9).

The third thermal heat technology group consists of storage technologies that utilize reversible reactions and thermochemical material (TCM) to store absorbed heat in chemical form. Thermochemical storage is discharged when TCM is converted back its original form. (Guney and Tepe 2017, p. 1188.)

3 METHODOLOGY

The methodology chapter is divided into two parts according to the principle presented by Saunders et al. (2009, p. 535). The search methodology part explains how patent data was collected and the data analysis methodology part answers how the collected dataset was analysed. The purpose of methodology is to provide the means to evaluate study’s reliability and validity (USC 2019).

After discussion session, it was decided that the study should focus on finding and analysing smart grid- and energy storage related patent families, as these topics were thought to be hot topics at the time when the study was conducted.

3.1 Search methodology

The search methodology presents the used search tools and databases, discusses about data coverage limitations, formulates the search query and introduces search tool’s query logic.

3.1.1 Search tool and database selection and data coverage limitations

According to Ozcan and Islam (2017, p. 948) patent search process should start by carefully considering and defining the available search tools and patent databases, as both have a significant impact on the coverage and validity of the retrieved dataset. Thesis utilized Patsnap, commercial patent search and analytics tool, in the retrieval process. Patsnap offered multiple advantageous features from the thesis standpoint. Firstly, it had a large coverage of databases, which minimized the need of utilizing multiply search tools. Secondly, Patsnap had INPADOC patent family sorting function which meant that it automatically grouped all patent documents related to same invention as a one entity. This reduced searcher’s workload and minimized the impact of counting duplicate patent documents. Thirdly, Patsnap enabled dataset exporting to XLS format, which was an essential prerequisite for further patent analysis.

Although Patsnap offered over 100 databases from different authorities, using all of them was neither possible or even necessary. Data collection was limited to the databases of so-called IP5 offices, which is formed by European Patent Office (EPO) and national IP offices of Japan, China, Korea and United States of America. As IP5 offices covered approximately

80 per cent of all global patent applications in 2017, it was justified to assume that most of the major inventions were filed at least in one of these five offices (FiveIPoffices n.d.).

To retrieve valid patents from the selected databases, two data coverage limitations were considered. First limitation was related to application period, which was eventually restricted to the years 1999-2019. This was done because patent rights expire after 20 years and the study wanted to retrieve only those patent families that were, at least in theory, still protected by law. After defining the timespan, an issue raised concerning data grouping. It was known that when a search query is conduct, Patsnap retrieves every individual patent document that fits into predefined search frames. This created a risk of counting same invention multiply times, which could have decreased the reliability of the study. To address this risk, Patsnap's settings were changed in way that only one representative per INPADOC patent family was displayed.

3.1.2 Search strategy formulation and search results

A hybrid search strategy consisting of a mixture of patent classifications and keywords was selected to retrieve relevant patent documents. The strategy was selected due to successful prior studies, which offered a clear process model for search string formulation (Chang et al. 2014; Ranaei et al. 2014; Altuntas et al. 2015; Karvonen et al. 2016; Karvonen and Klemola, 2019). The main assumption was that combining technology specific keywords with Cooperative Patent Classification (CPC) patent classes would drastically increase the validity of a dataset.

The actual search query formulation was based on the process featured in multiply earlier patent studies (Chang et al. 2014, p. 1485: Solomon and Bhandari 2014, p. 25). Figure 9 shows that the process started with preliminary search where technology specific terminology was utilized to discover patent documents related to this technology. The search area was limited to patent documents' titles, abstracts and claims and the outcome was then manually screened to identify patents of interest which were then clustered and further examined to extract CPC classes. New advanced search query was created based on these results. The last stage in the search process was data filtering which aimed to erase off-topic documents. The filtered sample served as an input for analysis parts.

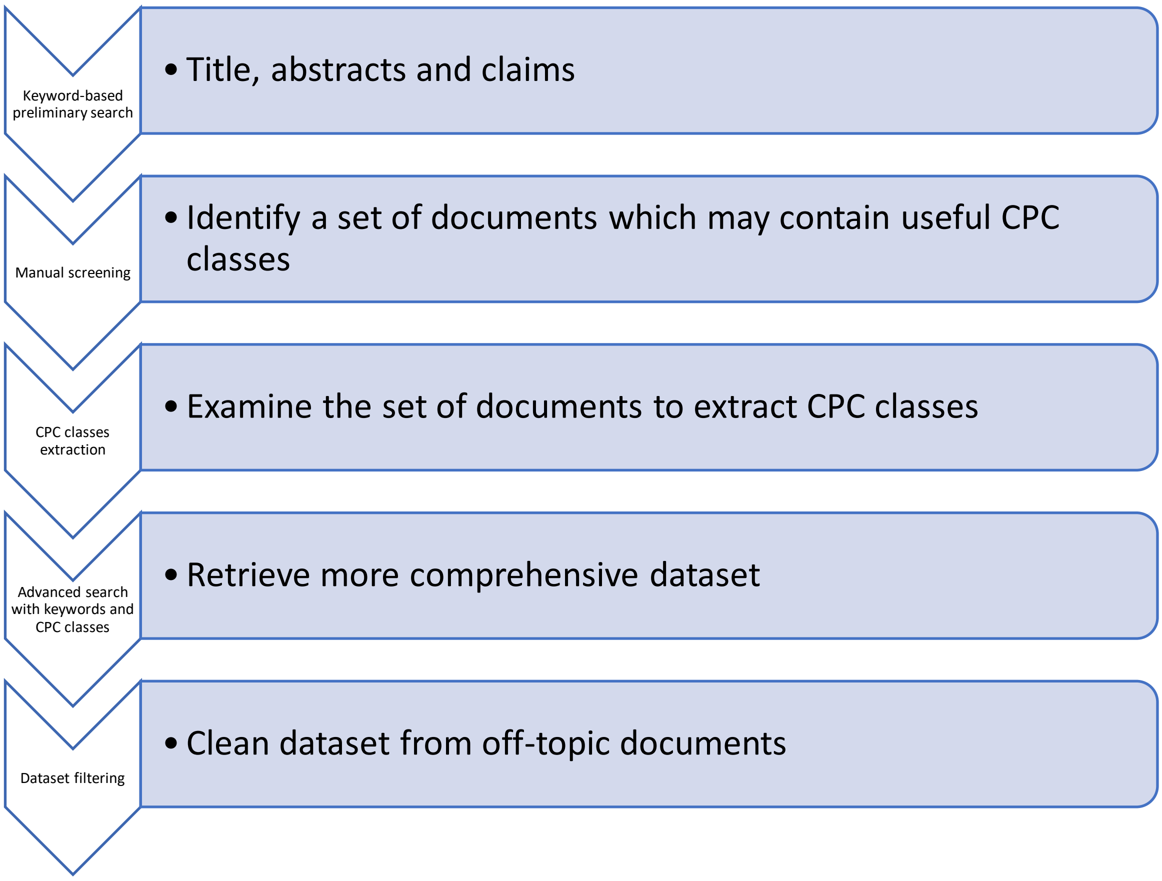

Figure 9 Search process (based on Chang et al. 2014, p. 1485)

Search strategy was first applied to identify patent documents related to smart grids, paying special attention on finding patent families related to EMS systems. Initially a dataset comprising of 6117 documents was retrieved, which was then filtered and grouped to 3171. INPADOC patent families. The search of energy storage patents proved to be more complicated than smart grid search. First, a common search query combining all energy storage technology categories was created and ran, but query turned out to be unsuccessful as the search retrieved 78567 patent families, which was too large dataset for the analysis. Thereby, it was decided to create separate search queries for each energy storage category, which were mechanical energy storage, battery energy storage, fuel cell and thermal energy storage. Eventually, the results of each search query were combined to a one dataset that consisted of 6020 INPADOC patent families.

3.1.3 Introduction to Patsnap query logic

To build efficient search queries, patent searcher should be aware of the query logic that his Intellectual Property (IP) software utilizes (WIPO, 2011). Patsnap uses similar query syntax than other IP software, which made the query formulation relatively easy. The relationships between different terms were expressed with Boolean operators “AND”, “OR” and “NOT”. The logic behind the operators was the following:

- AND: retrieves patents that contain both terms e.g. energy AND storage
- OR: retrieves patents that contain either or both terms e.g. energy OR storage
- NOT: retrieves patents that contain the first keyword but not the second e.g. energy NOT storage

Besides basic operators, study utilized quotation marks and wildcards to formulate more precise search. Quotation marks allowed to combine two individual terms as one phase, which was necessary as study was interested in retrieving patents containing technology terms that were made of two or more words. Asterisks and question marks were used as wildcards to cover different combinations of characters in terms and phrases.

3.2 Patent analysis methodology

Patent analysis consisted of four different analysis, which aimed to answer the research questions presented in the subchapter 1.2 “Research questions and objectives”. The four analysis were named as “Activity analysis”, “Market analysis”, “Key applicant analysis” and “Technology analysis”.

3.2.1 Activity analysis

Activity analysis examined how patent activity was developed over the time and how data was distributed based on their legal statuses. Patent activity was traced for both patent applications and granted patents. Typically, patent activity is measured by number of INPADOC patent families per earliest priority year, as earliest priority year is fixed: different authorities may have different procedures for patent publication and therefore earliest priority year may be the only objective indicator of innovation activity associated with certain year. Due to inconsistencies in priority years in the retrieved dataset, it was decided to use patent application year as measure for patent activity.

Compound annual growth rate (CAGR) and average pendency time were also calculated. CAGR, which functions as numerical presentation for trend line by measuring the growth over time intervals, was calculated for both patent applications and granted patents in ten years interval between 2007-2017, whereas average pendency time measured the time between application filing and final decision of examining office. Following equations were used:

$$CAGR = \frac{Number\ of\ applications\ in\ the\ end\ period}{Number\ of\ applications\ in\ the\ start\ period}^{\frac{1}{n}} - 1,$$

Where n = number of time periods.

$$\begin{aligned} Average\ pendency\ time \\ &= average\ publication\ year\ in\ the\ dataset \\ &- average\ application\ year\ in\ the\ dataset \end{aligned}$$

In addition to before-mentioned, simple legal statuses of the retrieved patent families were disclosed. Patent families can have three different simple legal statuses. Firstly, patent family receives an active status if the invention has been approved by a patent examiner and is legally protected. Secondly, a patent family receives a pending status, if the invention is under the examination and no decision has been made. Finally, a patent family receives an inactive status if the invention has failed to receive patent rights or if the applicant has withdrawn the patent family. The main assumption was that the shares of simple legal families were connected to the technological maturity of technology area. Notably high shares of active and pending families would indicate that technology area is rather novel, whereas high shares of inactive patent families would suggest the opposite.

3.2.2 Market analysis

Market analysis was straightforward and aimed to answer where inventions related to smart grid and energy storage were filed. The analysis included three stages. First it was discovered how patent families were distributed among IP5 offices by just simply counting how many patent families they possessed. Then the patenting trend of each office was revealed to see how the patenting activity had developed between 2007-2017. Finally, compound annual growth/decrease rates between 2012-2017 were identified to create an understanding of the rate of change in each office.

3.2.3 Key applicant analysis

Key applicant analysis followed similar structure than prior patent analyses (Cho et al. 2017; Thissandier and Baron, 2016). The study identified the patent portfolio sizes of key applicants and discovered when and where key applicants had filed their inventions. In addition to the standard metrics, a patent portfolio comparison was conducted for these companies of interest to compare their internecine positions from intellectual property perspective. The comparison consisted of three different analysis, which were IP leadership, IP blocking potential and patent quality/market security ability.

IP leadership was examined as the relationship between applicants' pending patent applications and granted patent families. The model introduced by Thissandier and Baron (2016, p. 22) in their study on microbatteries. Granted patent families signalled the current competitive position of the patent applicant by assuming that high number of granted patent families would result in stronger patent rights enforcement. Number of granted patent families per applicant was extracted from the input data sheet by using equation shown below:

$$\begin{aligned} &Number\ of\ granted\ families\ per\ applicant \\ &\qquad = Granted\ patents + granted\ patent\ applications \\ &\qquad + granted\ utilities \end{aligned}$$

Pending patent applications per applicant were utilized to model future aspects of an applicant in the given technology area. It was assumed that an applicant, who had a high number of pending applications, had also high expectations concerning the technology area and aimed to strengthen its future position by filing patent applications. The number of pending patents per applicant was calculated by counting the number of patent families that had a simple legal status "Pending" and a legal status "Examining".

IP blocking potential was used to estimate companies' capability to disturb other applicants' efforts to patent similar inventions. Blocking potential was assumed to increase when company's portfolio receives high number forward citations from various applicants. Forward citations per company were calculated by summing the forward citations of each patent family. Number of different applicants citing the patent portfolio were calculated manually by examining representative patent document of each individual patent family. Duplicates and self-citations were excluded to increase validity.

Patent quality level and market security ability of the main applicants was analysed using Patent Family Size (PFS) and Cites Per Patent (CPP) as was done in Cho et al. (2018, p.148) patent analysis on high-rise building construction technologies. Two different parameters, average patent family size (PFS) and average citation per patent (CPP) were used. The main assumption in former one was that as patenting procedure usually generates significant costs for patent applicant and as patent families need to be filed in each target market either separately or via intergovernmental special IP agencies, such as World Intellectual Property Organization (WIPO), to gain the protection provided by law, patent applicants avoid large-scale patenting of those inventions that are thought to have only minor commercial impact. Therefore, as patent families represent family of patent documents related to the same invention, it was assumed that a high number of patent families per invention would reflect applicant's high commercial interest related to a specific invention and help in efforts of securing better market position compared to similar type of inventions. The average PFS was calculated as in the following equation

$$Average\ PFS = \frac{The\ number\ of\ patent\ families}{The\ number\ of\ family\ reprentatives}$$

The second parameter, average CPP, was used as a metric to estimate the average patent quality of applicant's patent portfolio. It assumed that applicants with high number of forward citations have more significant patents than applicants with less forward citations. CPP was calculated as in the following equation:

$$Average\ CPP = \frac{Number\ of\ forward\ citations}{Number\ of\ patent\ families}$$

3.2.4 Technical analysis

The purpose of technical analysis was to gain insights of technical content related to retrieved datasets to evaluate the direction of development in the given technology area. Before the analysis was started, the taxonomies for both technology areas were defined. Taxonomies are used to describe relationships between technology areas and sub-technology areas, therefore a significant attention should be paid that taxonomy is logically linked to the field of interest (DePoy and Gitlin 2016, pp. 311-323; Sureka et al. 2009, pp. 644-645). In this study, taxonomies for smart grid and energy storage systems were based on the literature review conducted in Chapter 2. For smart grid analysis, the following main categories were created:

- Integration of power generation technologies
- Grid infrastructure
- Communications and energy management systems
- Energy storage
- Electric vehicle
- Demand response

Energy storage dataset consisted of various technologies and more fine-grained grouping was needed. The following list of sub-technologies was established:

- Energy storage
- Fuel cell
- Flywheel
- Battery components
- Thermal heat storage
- Battery storage system
- Compressed air energy storage
- Flow battery

The analysis was conducted with Excel, using relevant search queries and patent abstracts as an input for data extraction. Document could be categorized under multiple categories in case its abstract included words that matched the terms used in several search queries. The technical analysis identified the most active technology groups and how they were distributed amongst the main players, and development trend between 2012–2017 using CAGR method.

4 SMART GRID PATENT ANALYSIS

This chapter introduces the results of smart grid patent analysis, by following the four-stage analysis procedure introduced in Chapter 3. Dataset of 3171 patent families was analysed. The average patent family size in this dataset was 3.7.

4.1 Activity analysis

The results of patent activity are presented in Figure 10, which shows a timeline of annual patent activity related to smart grid between 1999-2017 for both patent applications and granted patents. Timeline for patent applications is marked with blue line, whereas timeline for granted patents is marked with orange line. Figure 10 demonstrates that the number of applications and granted patents had increased drastically from 2009 onwards, and that smart grid-related patenting was experiencing a period of rapid growth during the time when the study was conducted. Compound average growth rate (CAGR) between 2007-2017 was calculated for patent applications and granted patents. CAGR for patent applications during that period was 37.2% and for granted patents 34.9%. The average pendency time for the whole dataset was 15.4 months and for the granted patents 20.5 months.

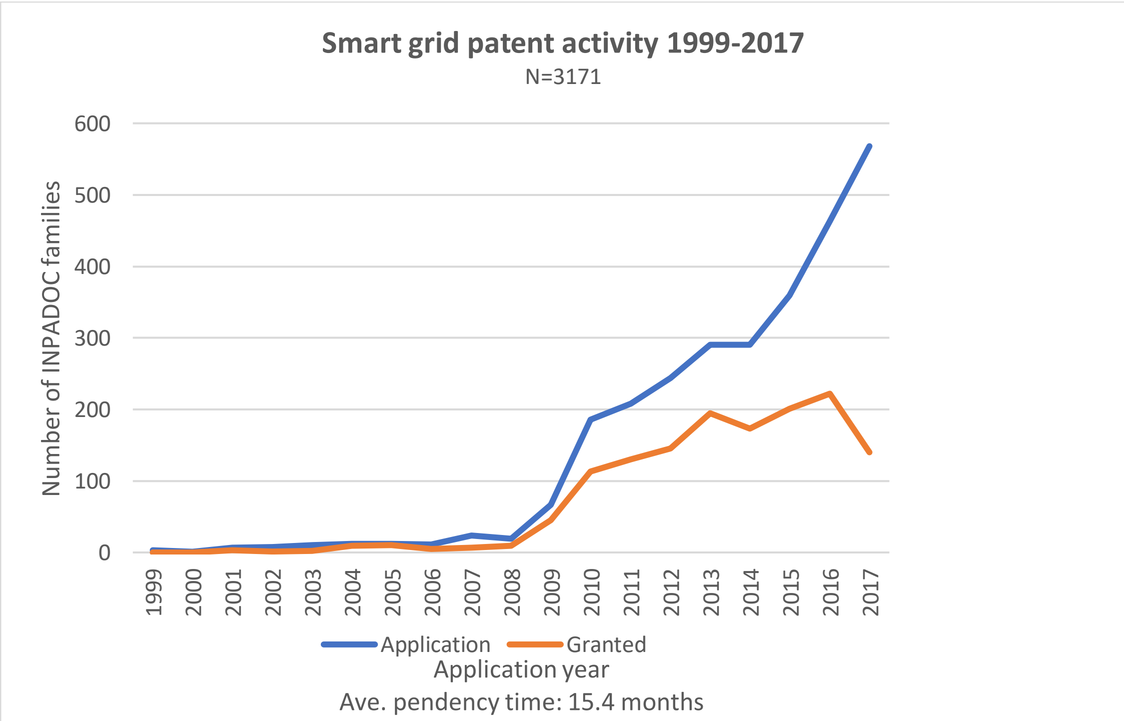

Figure 10 Smart grid patent activity 1999-2017

Simple legal status of smart grid dataset is presented in Figure 11. In this graph inventions were clustered according to whether they were granted and protected by a law (active), they were under examination (pending) or they had been rejected or withdrawn (inactive). From the total of 3171 patent families in the retrieved data sample, 1437 patent families, representing 45% of the whole sample, had an active legal status.

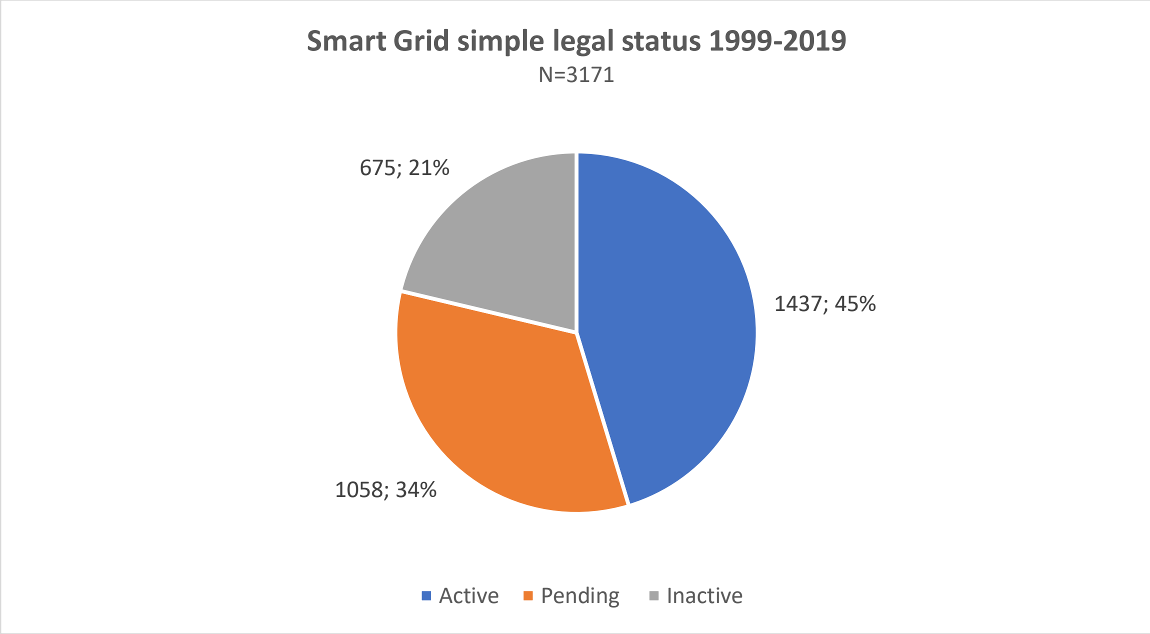

Figure 11 Simple legal status of smart grid patent families 1999-2019

Pending cluster consisted of 1058 patents families, which represented 34% of the data sample. Inactive patents were a minority in this dataset as 675 families had been withdrawn or rejected, standing for 21% of the dataset.

4.2 Market analysis

Figure 12 shows how smart grid patent families were distributed between IP5 offices during the examined period 1999-2019. Chinese national patent office was the most active intellectual property office, as it accounted 1527 patent families which represented approximately 49.5% of the whole sample. USA and Korean patent authorities had major activity related to smart grids as they were responsible for 748 and 530 patent families at data retrieval date. Japan and EPO had significantly less filed patent families. Japan recorded only 197 patent families, while EPO's numbers sank to 169 families.

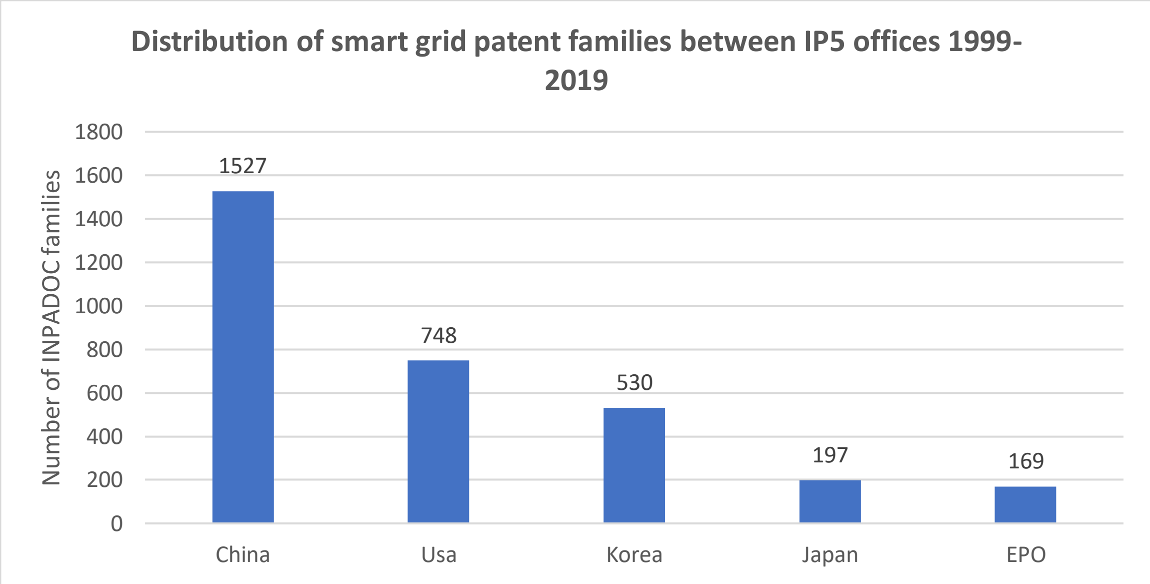

Figure 12 Distribution of smart grid patent families between IP5 offices 1999-2019

The filing trend of IP5 offices between 2007-2017 is modelled in figure 13. The development of each office is demonstrated with colourful linear. It can be seen from the graph that patent documents were relatively evenly distributed until year 2012, USA being the major source of innovation related to smart grids. However, after 2012 Chinese patent filings exploded, making country the main source of smart grid innovation. At the same time the growth in other offices seems to be rather stagnated over last 5 years, although Korea had managed to increase incoming filings and strengthen its position as lucrative innovation hub.

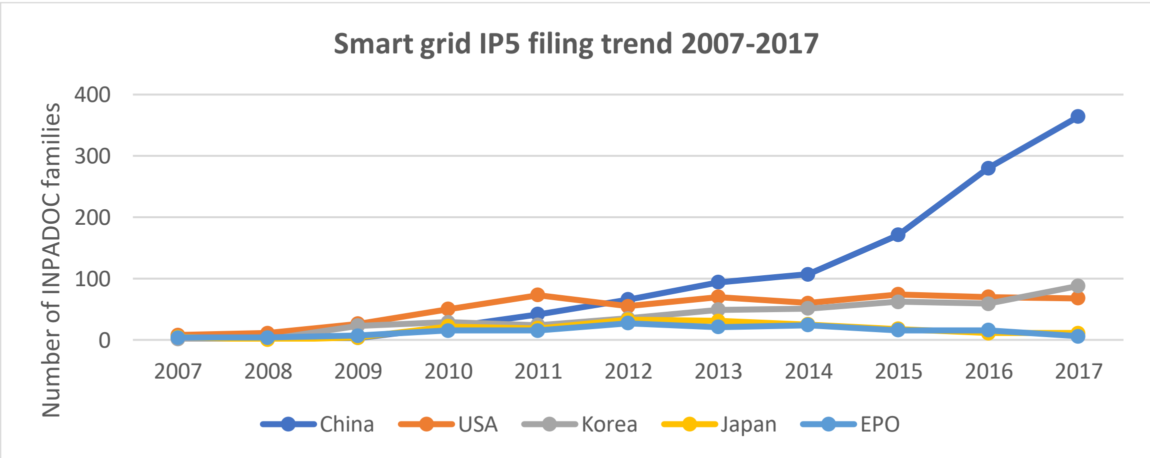

Figure 13 Smart grid IP5 filing trend 2007-2017

Compound annual growth/decrease rates, which were calculated for years 2012-2017 and demonstrated in presented in Figure 14, seems to strengthen conclusion made in Figure 13. China was the fastest grower during 2012-2017, reaching CAGR of 41.8 %, while Korea recorded CAGR of 17.4%. USA had conservative annual growth rates during the inspection period as CAGR hit 1.4%. Finally, Figure 14 clearly expresses the downfall in Japanese and EPO patent filings. Between 2012-2017 Japanese filings decreased on average -22.6% annually, while EPO filings sank on average -22.7% annually.

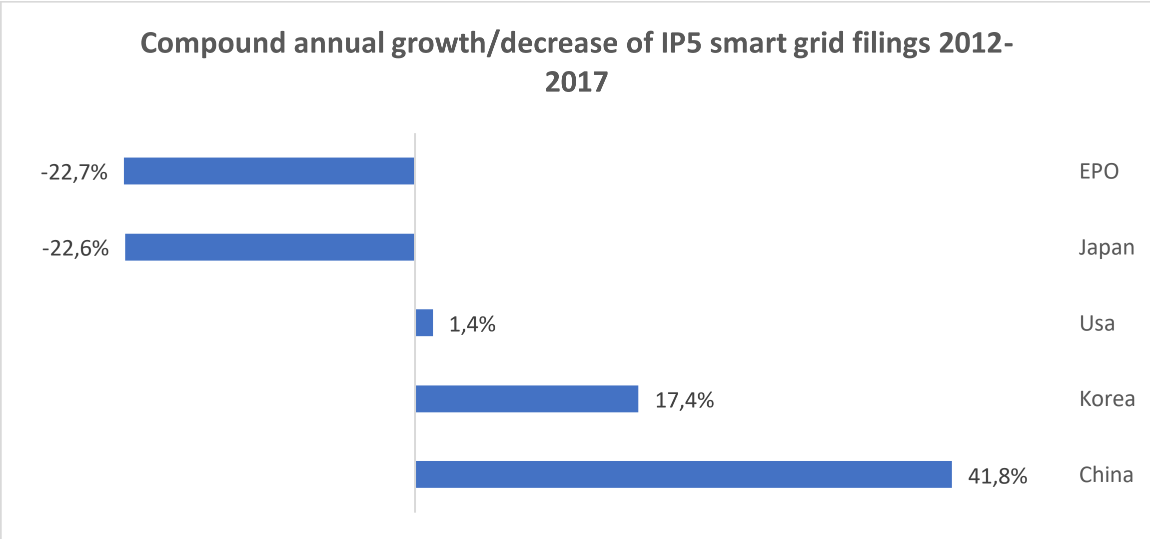

Figure 14 Compound annual growth/decrease of IP5 smart grid filings 2012-2017

4.3 Key applicant analysis

Figure 15 presents how the smart grid related patent families were distributed among applicants of interest in retrieved data sample. The graph revealed three different patent clusters based on number of patent families. The first, large applicant cluster was formed by seven applicants that had more than 20 patent families. These applicants were Samsung SDI (57), General Electric (54), Toshiba (48), NEC (43), LG (40), Siemens (38) and ABB (30). Second, intermediate applicant cluster hold seven companies whose portfolio ranged between eight and 5 patent families. The third cluster, named small applicant cluster, consisted of 12 applicants that had patent portfolios ranging between three and one patent families.

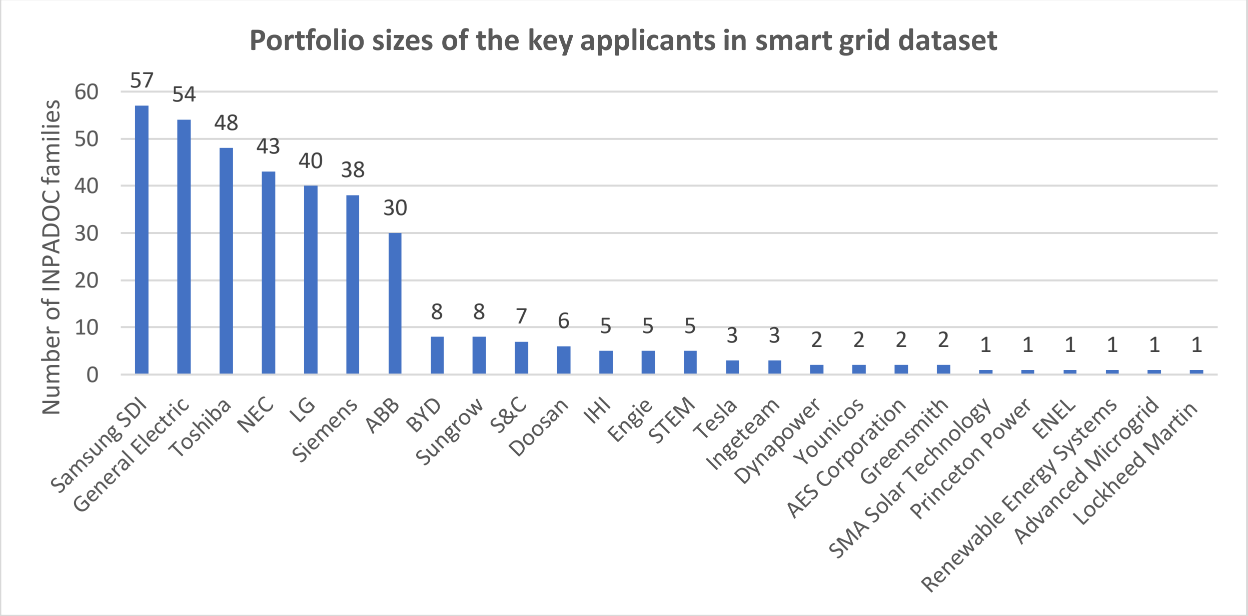

Figure 15 Patent portfolio sizes of key applicants in smart grid dataset

4.3.1 Patent activity of key applicants

Key applicants' annual patent activity based on application year was modelled in the form of heat map, which is demonstrated in Table 3 below. Table 3 suggests that applicants' patenting behaviour have followed the general patenting trend found in the dataset, 2009 being the first year of mass patenting interest towards smart grid technologies. Total number of inventions among the selected companies was 351, whereas the busiest application period was between 2013-2016, when on average 41.5 inventions were filed annually. Besides the generic information, Table 3 also reveals the filing patterns of individual applicants. In general, it can be said that large companies had been filing steadily from 2009 onwards, whereas medium- and small portfolio companies had been rather active since 2014.

Table 3 Patenting activity of the key applicants in smart grid dataset 2008-2018

Year/Company	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Samsung SDI	0	11	13	4	12	7	5	2	2	0	1
General Electric	1	8	3	4	4	2	3	12	6	4	3
Toshiba	0	3	4	6	8	14	8	5	0	0	0
NEC	0	0	1	2	2	4	10	5	6	8	5
LG	0	2	14	1	0	3	6	5	4	5	0
Siemens	1	1	1	4	4	2	5	7	3	9	1
ABB	2	2	1	2	3	1	6	4	4	3	0
BYD	0	1	1	0	0	1	1	1	2	1	0
Sungrow	0	0	0	0	0	0	1	0	1	4	2
S&C	0	0	0	0	1	1	0	0	5	0	0
Doosan	0	0	0	0	0	1	0	0	4	0	1
IHI	0	0	0	0	0	1	2	0	0	1	1
Engie	0	0	0	1	3	0	0	0	0	1	0
STEM	0	0	2	0	0	1	0	0	1	0	0
Dynapower	0	0	0	0	0	0	0	0	0	0	2
Tesla	0	0	1	0	0	0	0	0	2	0	0
Ingeteam	0	0	2	1	0	0	0	0	0	0	0
Younicos	0	0	0	0	0	1	0	1	0	0	0
AES Corporation	0	0	1	0	1	0	0	0	0	0	0
Greensmith	0	1	0	0	0	1	0	0	0	0	0
SMA Solar Technology	0	0	0	0	0	0	1	0	0	0	0
Princeton Power	0	0	0	0	0	0	0	1	0	0	0
ENEL	0	0	0	0	0	0	0	0	0	1	0
Renewable Energy Systems	0	0	0	0	0	0	0	0	1	0	0
Advanced Microgrid	0	0	0	0	0	0	0	0	1	0	0
Lockheed Martin	0	0	0	0	0	0	0	0	0	1	0

4.3.2 Most popular IP offices

Figure 16 presents how key applicants' patenting activities were distributed among the IP5 offices. The figure 16 demonstrates the dominance of US Patent and Trademark Office as major IP office for leading applicants in smart grid field. USA filings included 155 patent families, which represented 45% share of 351 families related to examined companies. The top 3 filing companies in the USA were General Electric (55), NEC (30) and Siemens (12). USA was also the major filing office for 12 other companies examined the study.

Korea was the second largest filing office with 68 patent families presenting 20% of all examined families. Korean patenting was largely dominated by Samsung SDI (41) and LG (18), who were responsible for nearly 87% of all filings in the office. Third large patent applicant in Korea was Doosan who had filed five patent families. Besides the beforementioned, three other applicants were present in Korea with minor patent portfolios, as the number of patent families in these portfolios ranged between two and one.

European Patent Office (EPO) collected 55 patent families which formed 16% of the total families and was the third most popular filing office. 12 applicants were present in Europe, ABB and Siemens being the most active applicants with 21 and 12 patent families. Toshiba, LG and NEC had the third largest portfolios in Europe, each recording four families.

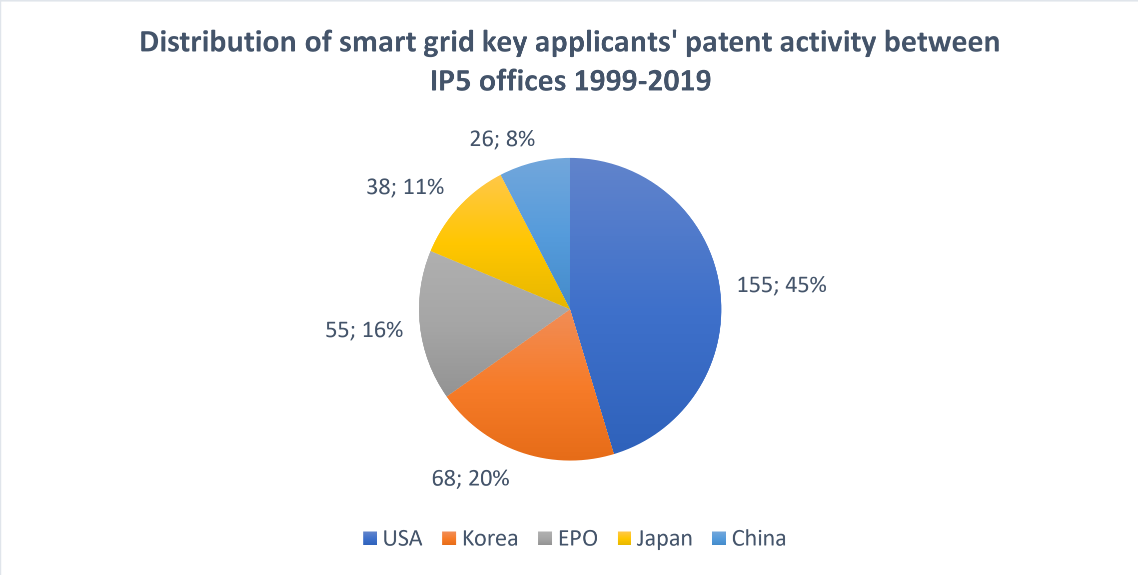

Figure 16 Distribution of smart grid key applicants' patent activity between IP5 offices 1999-2019

Japan and China proved to be the least popular filing offices among the selected applicants. The first totaled 38 patent families which represented 11% of all families, while the latter one collected 26 families that formed 8% of 351 relevant families. Japanese patents were almost solely applied by one company, Toshiba, who had applied patent for 28 patent families. Chinese filed families were more evenly distributed, domestic BYD and Sungrow being the major applicants with eight and seven patent families.

4.3.3 Key applicants' patent portfolio comparison

The key applicants' Intellectual Property (IP) leadership in terms of patent portfolio was discovered by analyzing the relation between applicants' pending and granted patent families. Only applicants who had at least one granted patent family and one pending patent family were considered to have current capabilities to gain IP leadership. The results of modelling are presented in Figure 17. According to the graph, applicants formed three different groups based on their activity.

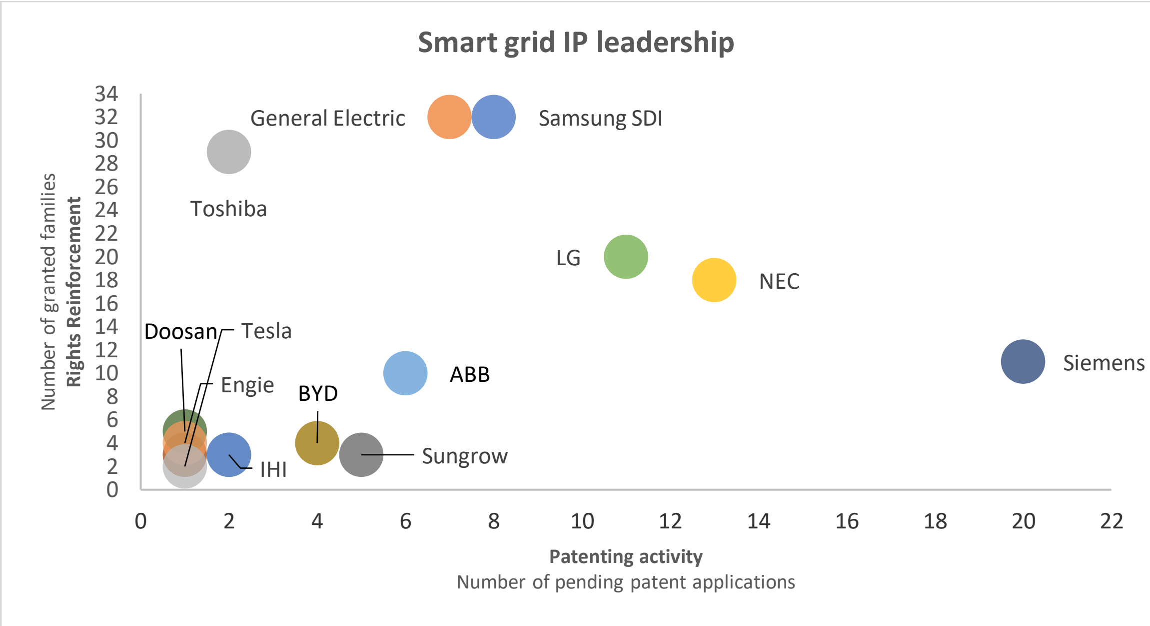

Figure 17 Smart grid IP leadership

The first group was formed by the current "IP leaders" which in this dataset were Samsung SDI, General Electric and Toshiba. These three companies had strong portfolios of granted patent families: Samsung SDI and General Electric shared the number one spot with 32 granted families and were closed followed by Toshiba who had 29 families. However, the data revealed that these companies had only medium or low patent activity compared to their competitors.

Siemens, NEC and LG formed the second, so called "IP challenger group". These companies did not have as many granted patents as the IP leaders had, but they had a higher number of pending patent applications, therefore possessing possible future threat for IP leaders. From the "IP challenger group", LG had the most granted patent families (20), but lowest number of pending patents (11), whereas NEC's portfolio consisted of 18 granted patents and 13 pending patent applications. From the challenger group, Siemens had the lowest number of granted patents (11), but the highest interest towards smart grid as it had 20 pending patent applications.

Majority (9/15) of the companies considered in IP leadership chart were located on bottom left corner. They had both low amount of granted patents and minor patent activity towards smart grid technologies, hence had relatively weak positioning considering patent reinforcement. ABB was the major applicant in this group with 10 granted patents and six pending applications.

Figure 18 compares IP blocking potential as a relationship between number of different patent applicants citing company's patent portfolio and number of forward citations excluding the self-citations. Companies that had either less than 20 different patent applicants citing their patent portfolio, or less than 40 forward citations were thought to have limited blocking capability and were therefore excluded from the comparison.

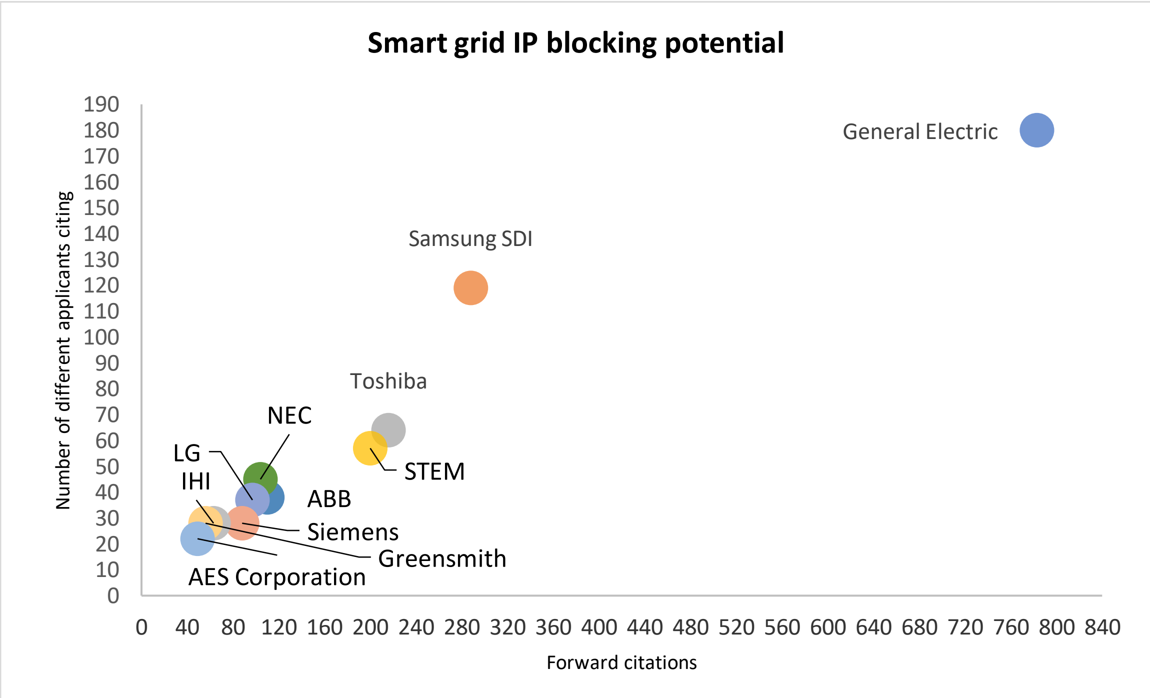

Figure 18 Smart grid IP blocking potential

The results showed that General Electric, Samsung SDI and Toshiba, which were the IP leaders, were also the leaders regarding the number of forward citations and different applicants citing the portfolio. From these three companies, General Electric had a clear advantage as it had more forward citations and almost as many different citers than Samsung SDI and Toshiba combined. General Electric superior citation rate was mainly due to fact that it had been active longer than other applicants.

The challenger group consisting of Siemens, ABB, LG and NEC was relatively evenly positioned, when it came to blocking potential. NEC had the most applicants citing their portfolio (45), while ABB seemed to the most influential publications as it collected 110 forward citations in total. Based on the results Siemens and LG were less influential and had weaker blocking potential, but on the other hand drawing top-notch conclusion was not relevant as the differences between these applicants were minor. Figure 18 disclosed three new applicants that were not shown in IP leadership matrix. These companies, STEM, Greensmith and AES Corporation, had a lot of forward citations and multiple applicants citing their inventions, although their patent portfolios were small. These inventions were most likely considered important in their field and therefore above-mentioned applicants had a significant capability to block similar inventions.

The average patent quality and commercial interest of the key applicants was examined and compared with the average values of the whole dataset. In the calculations it was assumed that average CPP (Citation Per Patent) indicates the average quality and technical significance of the key applicant's patent portfolio, while applicant's average interest to exploit his patent portfolio was measured with the average PFS (Patent Family Size). The results are demonstrated in Figure 19. The average PFS for the whole dataset was 3.7 and average CPP 5.7.

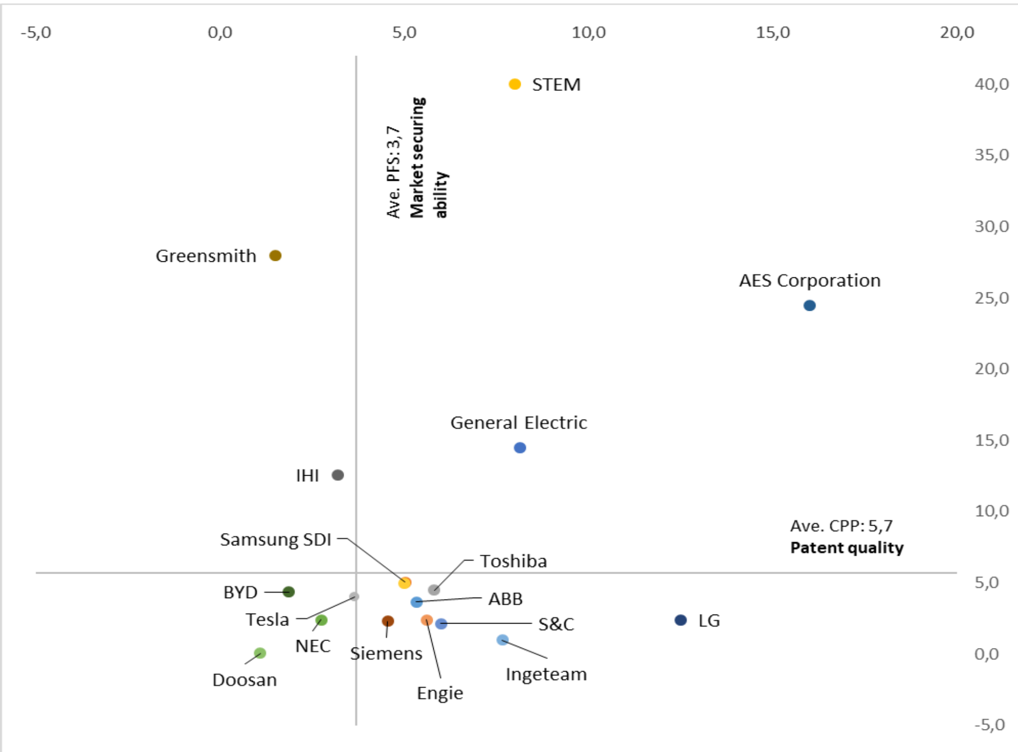

Figure 19 Smart grid patent quality/commercial interest matrix

The graph suggests that majority of key applicants had generally a higher commercial interest than the average in terms of patent family sizes. However, at the same time they filed lower quality inventions than average in terms of forward citations, as only five applicants out of 18, AES Corporation, STEM, Greensmith, General Electric and IHI, had a higher CPP than dataset average. From these five, STEM, General Electric and AES Corporation were aggressive filers.

4.4 Technical analysis

Figure 20 illustrates how patent families were distributed based on their content using predefined taxonomy and figure 21 shows the average annual development pattern of these categories between 2012-2017. Figure 20 suggests that terms linked to category "energy storage" occurred the most frequently in the dataset. In total 1944 patent families representing 61.3% of the whole dataset were somehow related to energy storage. The energy storage group had also shown a robust growth rates over the last five years with CAGR of 19.4% as seen in figure 21.

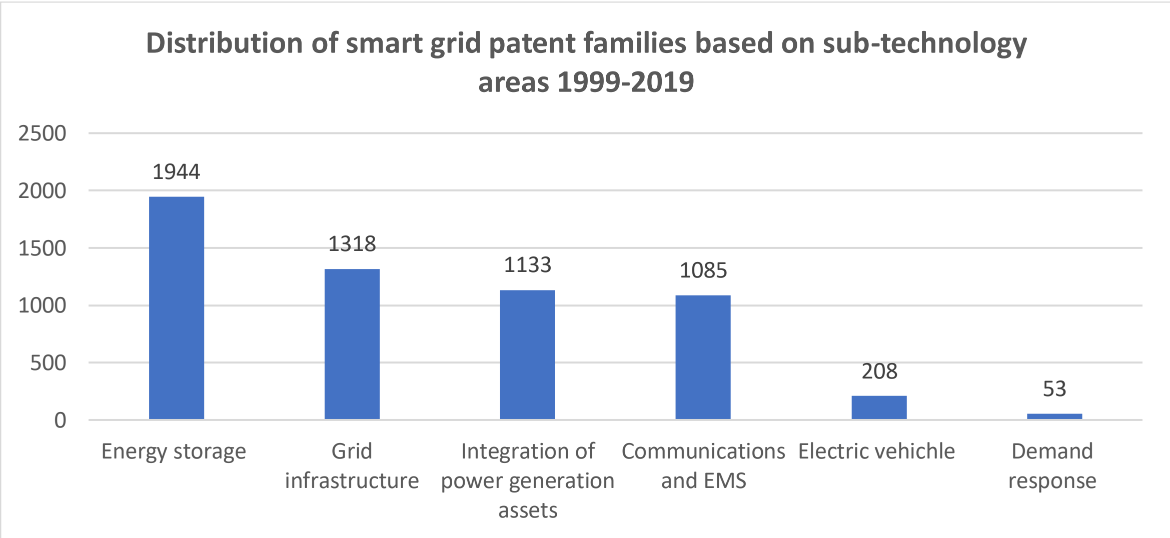

Figure 20 Distribution of smart grid patent families based on sub-technology areas 1999-2019

Terms related to grid infrastructure occurred the second most frequently in the data sample with 1318 patent families. In addition, this technology area had the second highest growth annual growth rate (20.5%) after technology area "Integration of power generation assets", which grew on average 26.0% annually. The latter collected 1133 hits with given query and was placed third, just before energy management system technology area, under which 1085 patent families were classified. Communications and EMS showed CAGR of 20.4% in the interval 2012-2017.

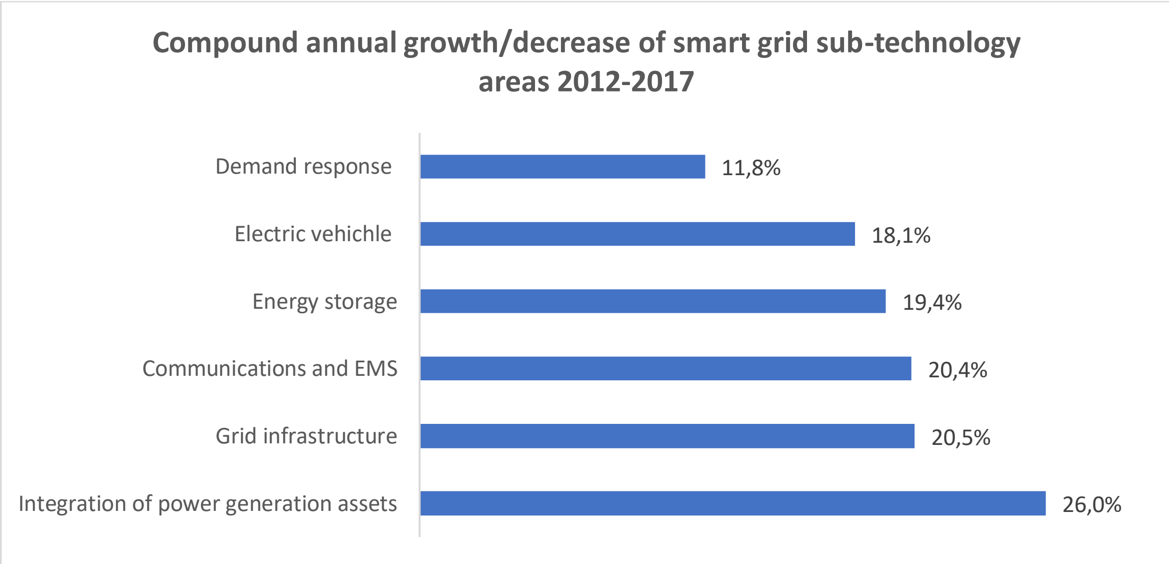

Figure 21 Compound annual growth/decrease of smart grid sub-technology areas 2012-2017

Electric vehicle and demand response were the least patented categories in this dataset when measured by occurrence and growth rates. Terms related to the first one occurred in 208 patent families, while terms related to the second one gathered only 53 hits. Despite low occurrence both groups showed positive growth rates between 2012-2017 as CAGR for electric vehicle was 18.1% and CAGR for demand response was 11.8%.

Table 4 depicts key applicants' technological focus by showing how the patent families were distributed among the predefined sub-technology areas. According to the graph, energy storage category was the main patenting field for 16 out of 26 companies, whereas four companies were focused their filing mainly on communications and EMS category. Grid infrastructure was the main area for six applicants as well, but these applicants had rather limited portfolios, number of families ranging from one to four in this sector. Despite the group "Integration of power generation assets" collected the second most hits in the whole dataset, it was not the major patent area for any of the applicants. The results for electric and demand response were not surprising considering the number of patent families they collected. They were minor patent areas for nine and six applicants.

Table 4 Technology focus areas of smart grid key applicants

Company	Energy storage	Integration of power generation assets	Grid infrastructure	Communications and EMS	Electric vehicle	Demand response
Samsung SDI	29	18	14	19	5	1
General Electric	27	11	13	25	5	0
Toshiba	22	16	18	24	5	0
NEC	19	6	16	21	3	2
LG	20	4	13	10	1	1
Siemens	19	6	14	17	0	1
ABB	20	3	8	11	2	0
BYD	6	5	5	2	1	2
Sungrow	5	2	4	2	0	0
S&C	4	1	4	2	0	0
Doosan	1	0	0	2	0	0
IHI	3	1	3	1	0	1
Engie	3	0	0	3	0	0
STEM	4	1	1	2	2	0
Dynapower	2	1	1	0	0	0
Tesla	3	0	2	1	1	0
Ingeteam	0	1	2	1	0	0
Younicos	1	0	1	0	0	0
AES Corporation	2	1	2	1	0	0
Greensmith	2	0	0	1	0	0
SMA Solar Technology	0	0	0	0	0	0
Princeton Power	1	0	0	0	0	0
ENEL	1	0	0	0	0	0
Renewable Energy Systems	1	0	0	0	0	0
Advanced Microgrid	0	0	1	0	0	0
Lockheed Martin	0	0	1	0	0	0

5 ENERGY STORAGE PATENT ANALYSIS

In this chapter the results of energy storage patent analysis are presented by following the four-stage analysis procedure presented in Chapter 3 The results were based on the analysis of the dataset consisting of 6020 patent families. The average patent family size in the dataset was 4.6.

5.1 Activity analysis

Figure 22 shows general patent activity in energy storage dataset between 1999-2017. Based on the graph, dataset has experienced two distinctive growth periods. The first growth period occurred between 1999-2013, during which an increasing number of patent applications were filed and granted. The compound annual growth rate of the patent applications during that time was 12.0% and for granted patents 22.2%. The long growth period ended in 2014, when IP5 received 27.2% less applications compared to the previous year. Decline in patent applications was reflected in number of grants which sank 24.9% compared to 2013. The distinctive growth period occurred between 2015-2017 and CAGR for patent applications during that period was 14.3% compared to 2014. According to the graph, a robust growth in applications was not reflected in patent grants, as they continued to decline by 2.4 percent compared to 2014 values. The average pendency time for the whole dataset was 20.0 months and for the granted patents 23.7 months.

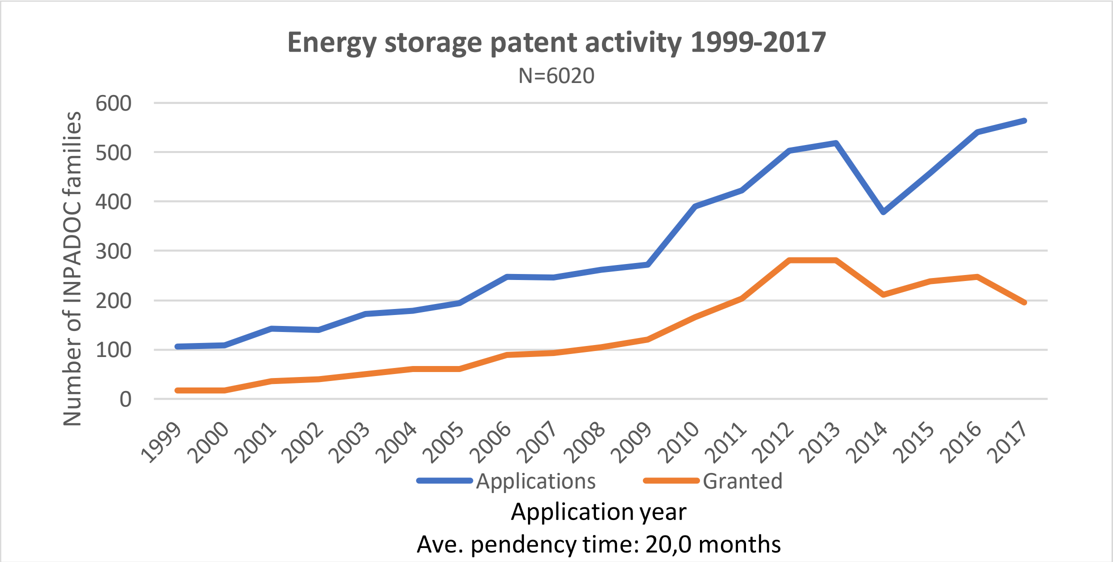

Figure 22 Energy storage patent activity 1999-2017

From the simple legal status perspective energy storage dataset was relatively evenly distributed as seen in Figure 23. Inactive patent families formed the largest group with 2626 patent families, which resulted in 44% share of the total. 2538 patent families were protected by the law at the time when the data was retrieved, therefore receiving Active status and forming the second largest group with total share of 42%. The 14% of the dataset's families, or 853 families, were either under examination or were published but had not entered substantive examination phase.

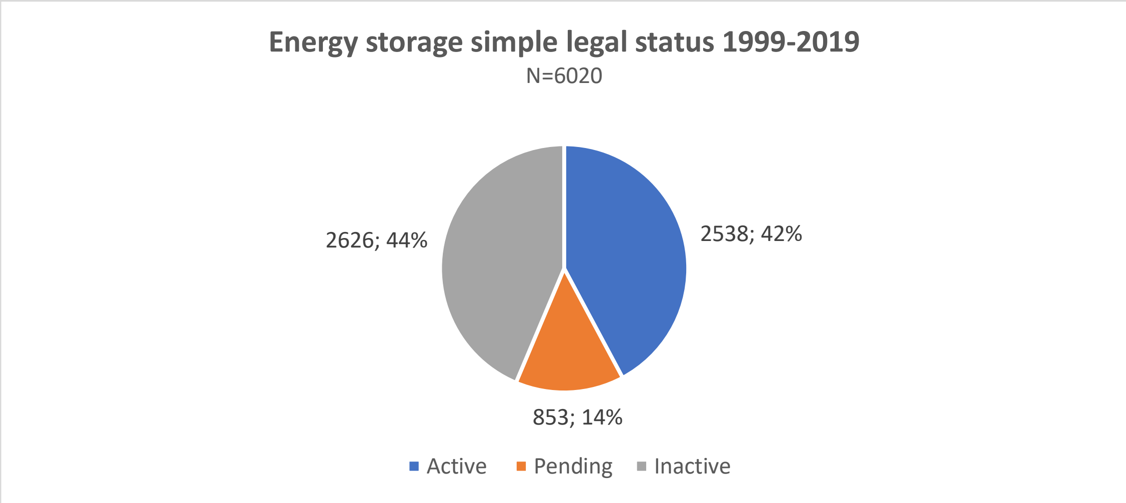

Figure 23 Simple legal status of energy storage patent families 1999-2019

5.2 Market analysis

Chinese intellectual property office seemed to be, like Figure 24 presents, the most active intellectual property office in patent filings related to energy storage inventions, as the it grasped the top place with 2270 patent families, representing 37.7% of total 6020 filed families. USA was placed second with 1789 families and was followed by Korea with 815 patent families.

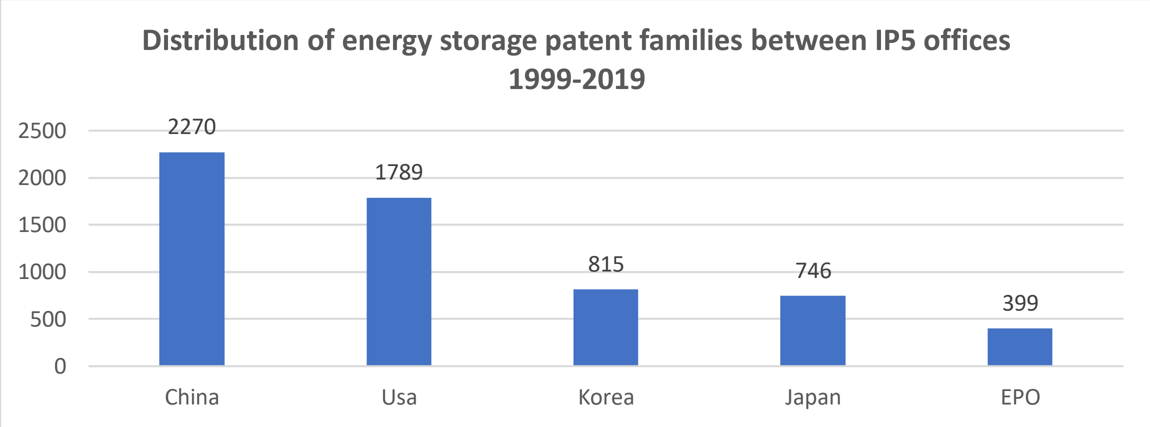

Figure 24 Distribution of energy storage patent families between IP5 offices 1999-2019

Japan and EPO were ranked fourth and fifth with 746 and 399 patent families. Geographic analysis revealed peculiarities related to Chinese and Korean patent practices as their applicants had filed a varying amount of utility models, which compared to patents, have looser patentability requirements but can only be obtained notably short term, typically 5-10 years. Chinese applicants had filed 688 utility models, whereas the Koreans had eight similar filings.

Figure 25 presents the regional filing trends and underlines the growing Chinese influence in the given technology area. USA gathered most patent filings prior 2009, but since that year, Chinese patent officials had been the busiest in processing the upcoming filings. Based on Figure 25, it can be said that filing trend in IP5 offices excluding China has been stagnated or decreasing from 2012 onwards.

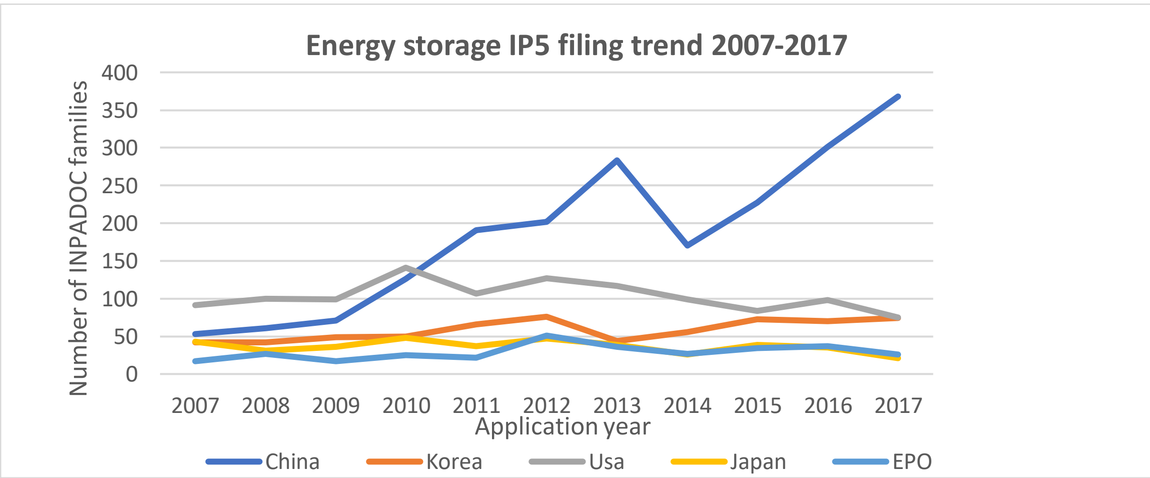

Figure 25 Energy storage IP5 filing trend 2007-2017

Regional compound annual growth rates, which are demonstrated in Figure 26, seemed to support preceding results in two ways. Firstly, figure 26 consolidates China's dominance in energy storage sector by illustrating the high annual growth in Chinese origin filings between 2012-2017. Secondly, the graph demonstrates the downfall of the other offices. From these four offices, Japan, EPO and USA experienced substantial descents in patent activity over the last five years as filings had decreased on average 12.5% annually in these three offices. Korean energy storage inventions stagnated over the period with 0.5 % annual decrease.

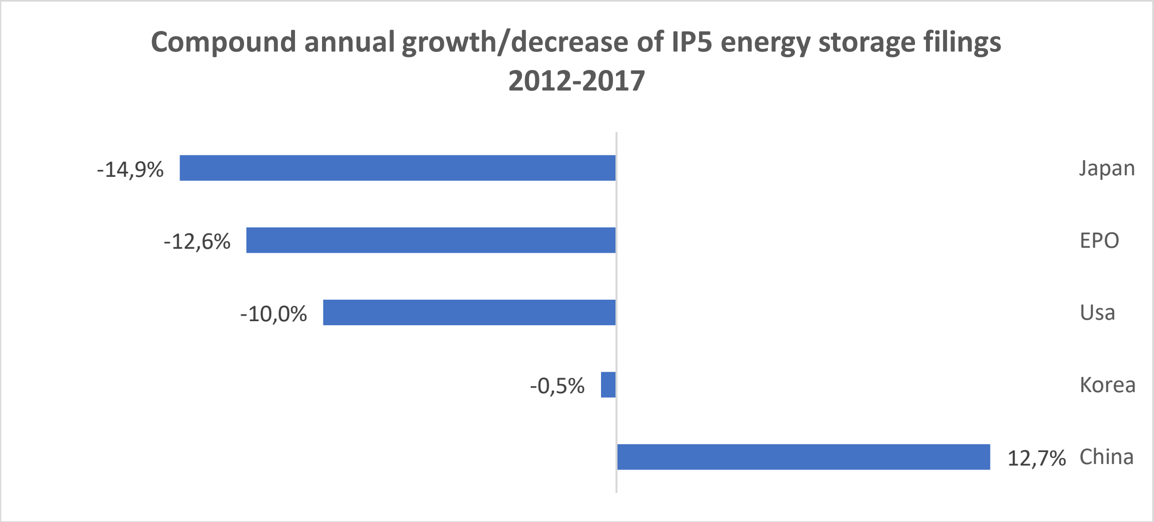

Figure 26 Compound annual growth/decrease of IP5 energy storage filings 2012-2017

5.3 Key applicant analysis

The portfolio sizes of the key applicants in energy storage area are compared in Figure 27. Figure 27 illustrates that when measured by the number of patent families, General Electric (102), Mitsubishi (83), Samsung SDI (68), Doosan (56) and Siemens (55) were the five major applicants in the dataset. LG, LSIS and Nidec were the main challengers for the largest applicants with portfolios of 45 and 37 patent families. Six companies had significantly smaller portfolios, as the number of patent families ranged from 12 (ABB) to four (Wärtsilä).

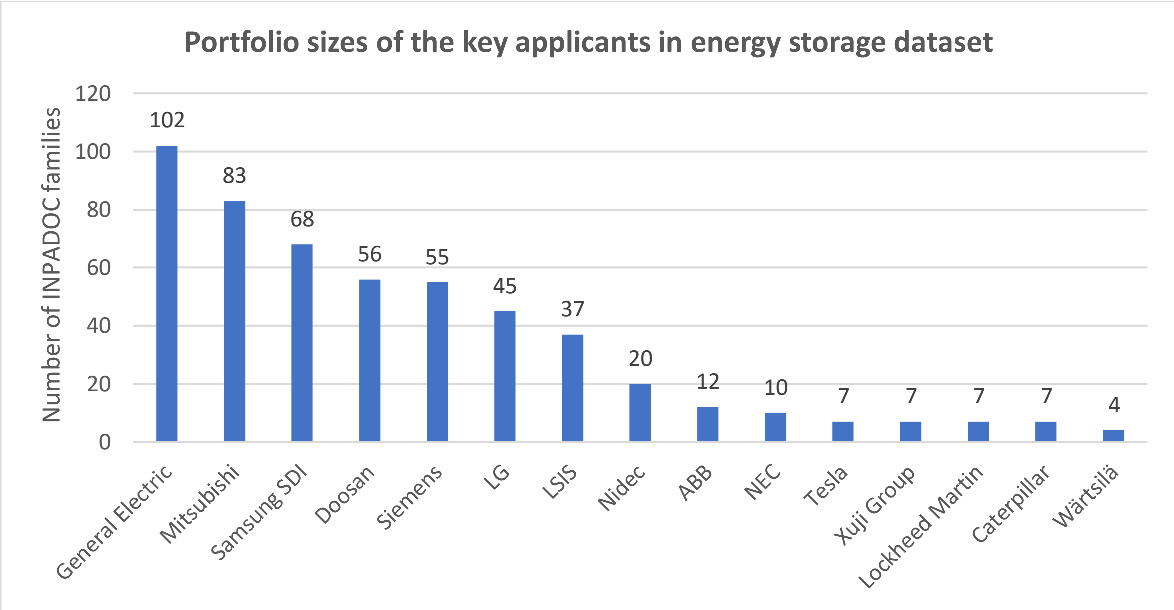

Figure 27 Portfolio sizes of the key applicants in energy storage dataset

5.3.1 Patent activity of the key applicants

Key applicants' patent activity in 2008-2018 is demonstrated in Table 5. Table 5 shows the differences in patent strategies between applicants with large portfolio and applicants with smaller portfolios. According to Table 5, applicants with large portfolio filed majority of their applications between 2008-2013, whereas applicants with minor portfolios tended to be active from 2013 onwards. In addition to patent strategies, busiest application years were exposed. These turned out to be 2015, 2011 and 2012, when 46, 40 and 39 applications were filed by the key applicants.

Table 5 Patenting activity of the key applicants in energy storage dataset 2008-2018

Company/Year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
General Electric	2	10	3	4	7	3	6	8	4	1	0
Mitsubishi	7	4	1	3	4	4	0	1	0	1	0
Samsung SDI	0	5	15	15	14	7	4	4	2	0	0
Doosan	15	5	7	11	6	0	0	0	2	0	0
Siemens	2	4	5	4	2	3	4	5	1	1	0
LG	0	1	0	1	4	2	7	8	11	7	0
LSIS	0	0	0	0	0	4	2	13	5	11	2
Nidec	0	0	0	0	0	0	0	2	4	9	5
NEC	0	0	0	0	0	1	5	1	1	2	0
ABB	2	1	0	0	1	1	3	2	0	0	0
Tesla	1	0	2	0	0	0	0	1	2	0	0
Xuji Group	0	0	0	0	0	0	2	0	3	1	1
Lockheed Martin	0	0	0	1	0	1	0	0	1	2	0
Caterpillar	2	0	0	0	1	0	0	1	0	1	0
Wärtsilä	0	0	0	1	0	1	0	0	0	0	0

5.3.2 Most popular IP offices

Figure 28 shows how the patent activities of key applicants were distributed geographically. United States was the main office with 202 applications representing 39% of all key applicant filings. It was the most significant market also when measured with the number of applicants present, as 14 applicants from 15 applicants had filed an application there. The main applicants in USA were General Electric (91), Siemens (31) and Samsung SDI (18).

Korea followed USA as the second most active filing destination for the key applicants. It collected 174 applications which formed 33% of the total filings. 95.4% of applications in Korea were filed by four domestic applicants, Doosan (55), Samsung SDI (44), LSIS (36) and LG (31). Besides the previously mentioned, four other key applicants were present in

Korea. These applicants had only minor portfolios, ranging from one patent family to four patent family.

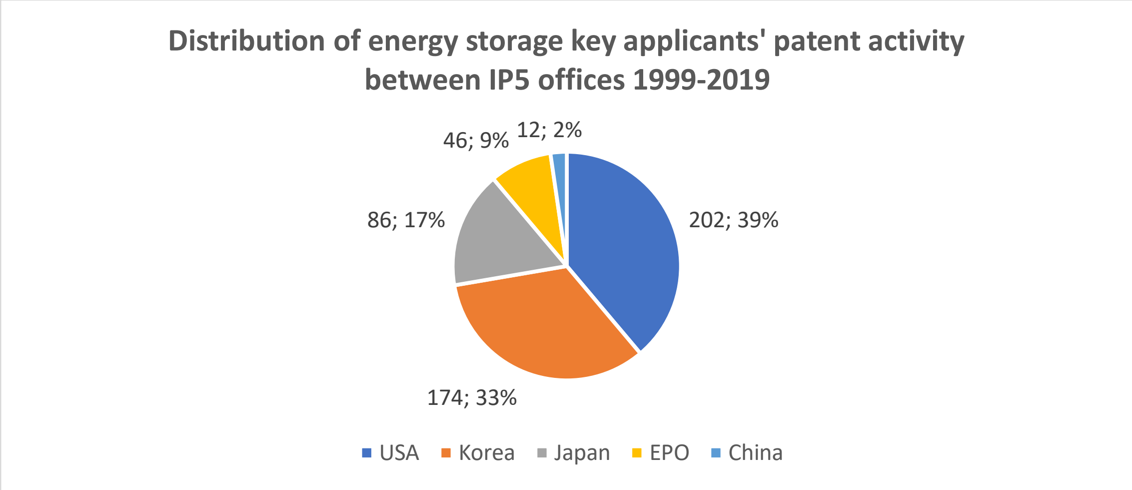

Figure 28 Distribution of energy storage key applicants' patent activity between IP5 offices 1999-2019

Key applicants filed 86 applications in Japan, which presented 17% of total key applicant filings. Japanese energy storage IP landscape was dominated by two applicants. The most active applicant was Mitsubishi, who had filed 64 applications in the country. Domestic electronic component manufacturer Nidec was the second most active applicant with 11 applications. In addition, Japanese IP office received 11 applications from seven applicants, whose portfolio sizes in Japan varied between one and two families. From these applicants probably the most notable were American-origin Lockheed Martin (2), Tesla (2) and Caterpillar (1).

EPO received 46 applications from the key applicants and this number was equal to 9% of total applications. Majority of the applications was filed by large European conglomerates Siemens (23) and ABB (9). General Electric proved to be relatively active in Europe as well, as it filed seven different applications. LG (4), Samsung SDI (2) and NEC (1) were present in Europe, but only with small portfolios.

The results of geographic patent activity revealed that Chinese intellectual property office was not particularly popular among the key applicants. Key applicants applied legal protection only for 12 inventions, which formed 2% of examined applications. The major applicant was Xuji Group, who had filed seven patent applications. Other companies, who tried to protect their inventions in China, were Samsung SDI (2), Mitsubishi (1), LG (1) and Nidec (1).

5.3.3 Patent portfolio comparison of the key applicants

Energy storage IP leadership among the selected companies was modelled and is presented in Figure 29. According to the results General Electric had the strongest patent portfolio at the time of the study. Its portfolio consisted of 63 granted patent families and five pending applications. The major challengers for General Electric were Doosan, Mitsubishi, Siemens, Samsung, LG and LSIS, whose granted patent portfolios ranged between 17 to 45. Based on the graph, Siemens, Samsung SDI, LSIS and LG formed the largest future threat for General Electric supremacy, as they had a large number of pending patent applications, whereas Doosan and Mitsubishi showed no further interest for new energy storage inventions with zero pending patent applications at the time of the study.

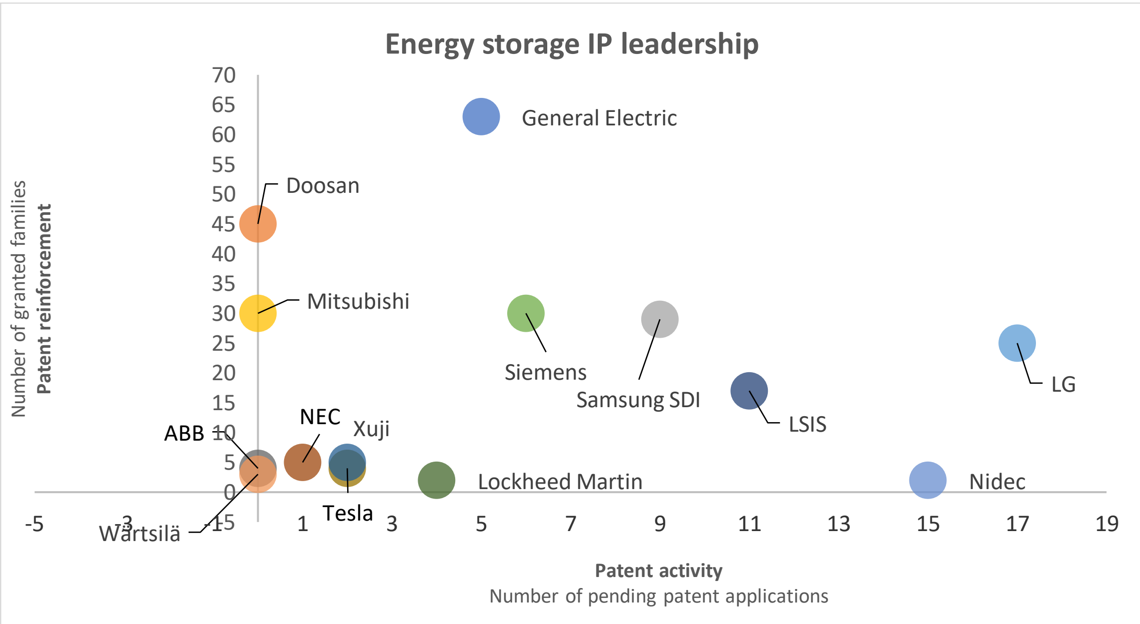

Figure 29 Energy storage IP leadership

Figure 30 illustrates key applicants' IP blocking potential in energy storage field and suggests that in addition of being the current IP leader among the examined applicants, General Electric had the best capabilities to protect its inventions from the similar ones. Its publications gathered 1831 forward citations and 243 different applicants were linked to its inventions. However, a significant percentage (96.2%) of General Electric's forward citations were originated prior 2010.

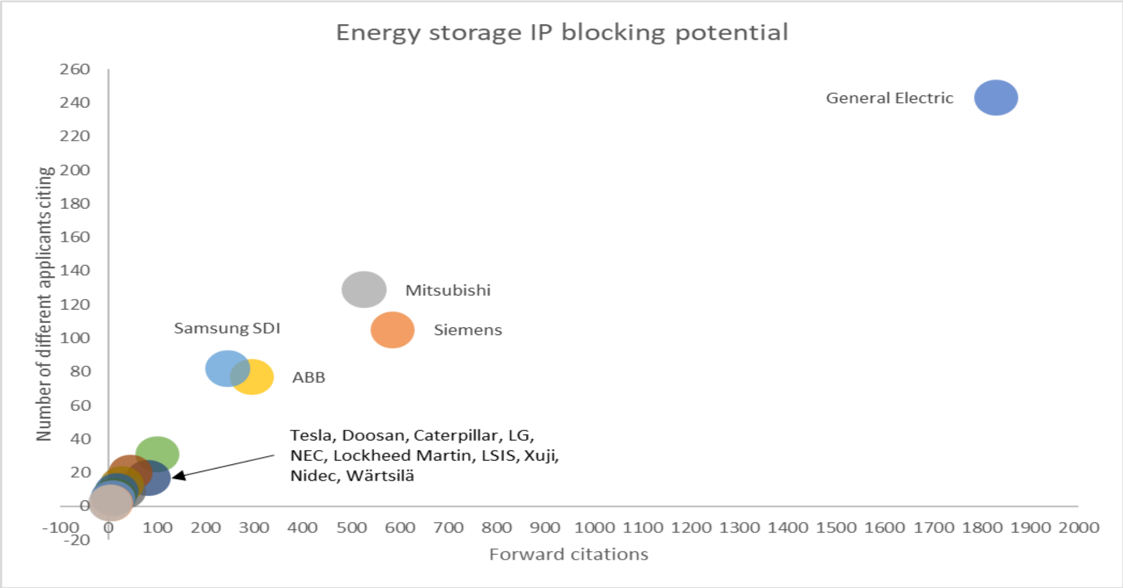

Figure 30 Energy storage IP blocking potential

Mitsubishi, Siemens, Samsung and ABB were General Electric's main challengers in terms of blocking potential. Mitsubishi and Siemens were the strongest from the four, but defining the relative strength proved to be difficult, as Mitsubishi had a boarder selection of different applicants citing its portfolio (129>109), whereas Siemens had more forward citations (586>527). ABB's position was interesting compared to its portfolio size: with a portfolio of 12 families it managed to gather more forward citations and citing applicants than some of its peers who had a much larger portfolio by size.

10 out of 15 were positioned to the bottom left corner of the figure 30, hence they were thought to not have obvious blocking advantage compared to their peer applicants. Majority of 10 applicants had a portfolio of less than 20 patent families, but the block also included Doosan, LG and LSIS who were ranked high in IP leadership matrix due to their large portfolios.

Quality and commercial interest related to key applicants' IP portfolios was compared with the average values of the whole dataset compared in Figure 31. The average CPP, which is indicator of invention quality, was 5.8 and average PFS, which is indicator of commercial interest, was 4.6. The figure 31 illustrates that there were four different applicant groups according to applicant behaviour. The first group, which is shown in the top right square of the graph, was formed by the applicants, who not only filed high quality inventions, but also had higher ambitions to exploit these inventions commercially compared to the average dataset. High commercial interest was also a distinctive feature for the applicants in the second group. They had filed rather lowly cited inventions, but saw these commercially important, thus aggressively expanding their portfolios to cover various regions. Lockheed Martin and Wärtsilä, two most active applicants measured with PFS, belonged to this group.

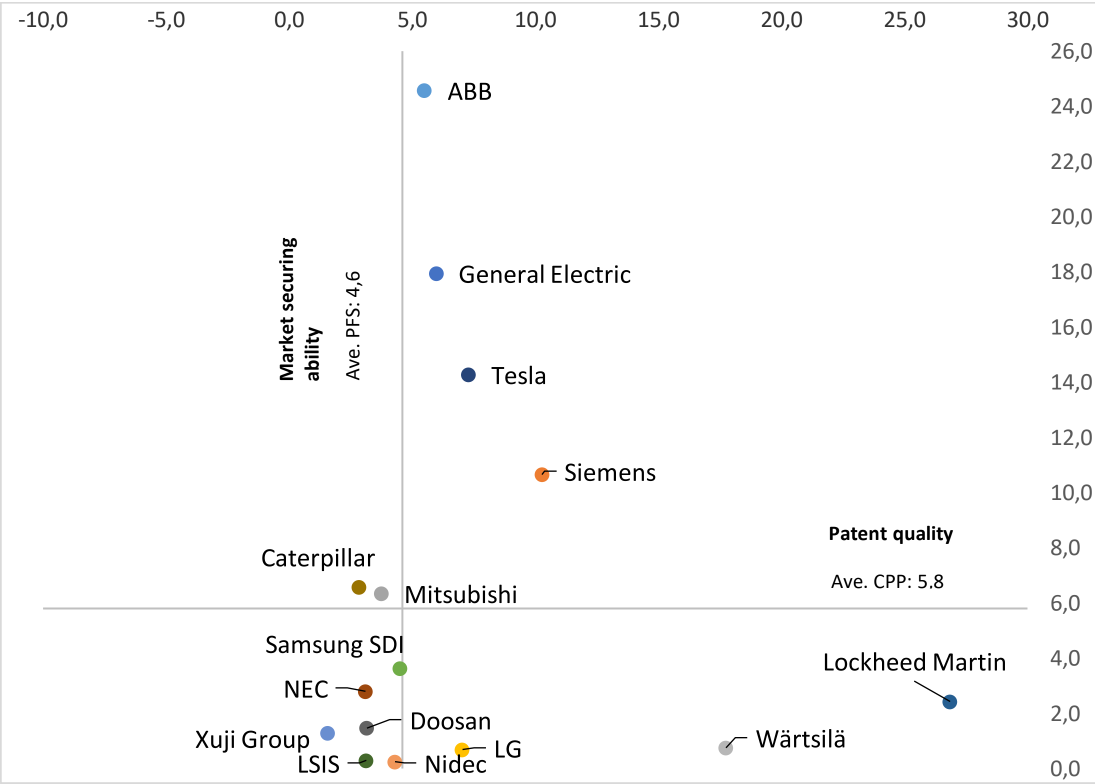

Figure 31 Energy storage patent quality / commercial interest matrix

The third group, located in the top left square of the matrix, included Mitsubishi and Caterpillar, who had good-quality inventions, but for some had less interest on commercializing those inventions. The last group, which consisted of six applicants, had neither high-quality patent families or high interest towards commercialization of those inventions.

5.4 Technical analysis

Figure 32 presents the results of technical analysis of the energy storage dataset and figure 33 shows compound annual growth/decrease rates for each energy storage technology area. Given keywords, it seems that class “energy storage system” had the highest frequency of occurrence, as it collected 2199 patent families, covering 36.5% of the whole dataset. Energy storage system showed positive development in last five years with the second highest CAGR (12.2%) of the given technology areas. In addition to energy storage system, a lot of research and development activity had been put to technologies that were related to fuel cell and flywheel technology areas, as they gathered 1564 and 1474 patent families and covered 26% and 24.5% of the dataset. From the development trend perspective, interest in fuel cell technologies has drastically declined (-25.5%) over the last five years, while flywheel activity seemed to on the rise, as CAGR for 2012-2017 was 3.6%, like figure 33 presents.

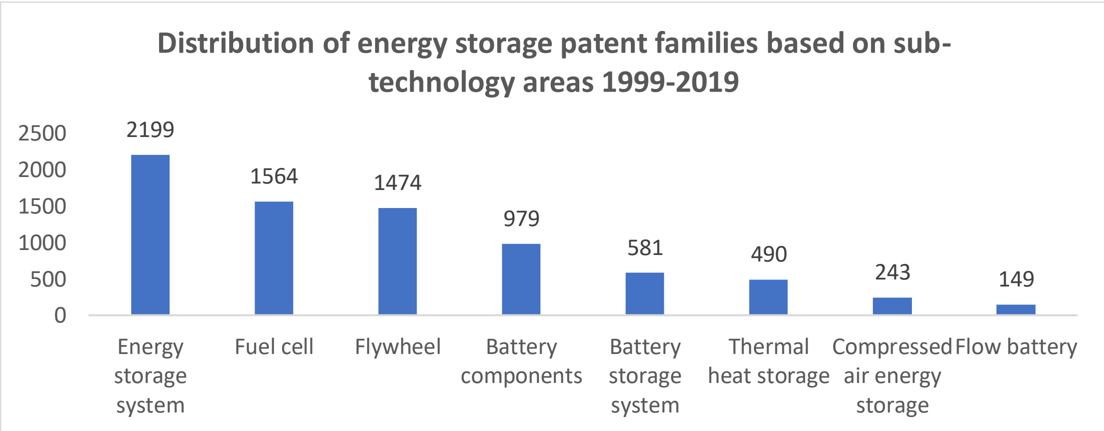

Figure 32 Distribution of energy storage patent families based on sub-technology areas 1999-2019

Fourth storage technology area with significant patent activity was battery storage. The greater part of the patent activity (979) was related to the chemical battery components, while battery storage gathered 581 patent families. However, figure 33 depicts that these two groups had had an opposite development trend in the recent five years. Filings related to battery components decreased on average 11.4% annually, as the applicants showed an increasing interest in filing battery system-level inventions, whose filings increased 10.2% annually in 2012-2017.

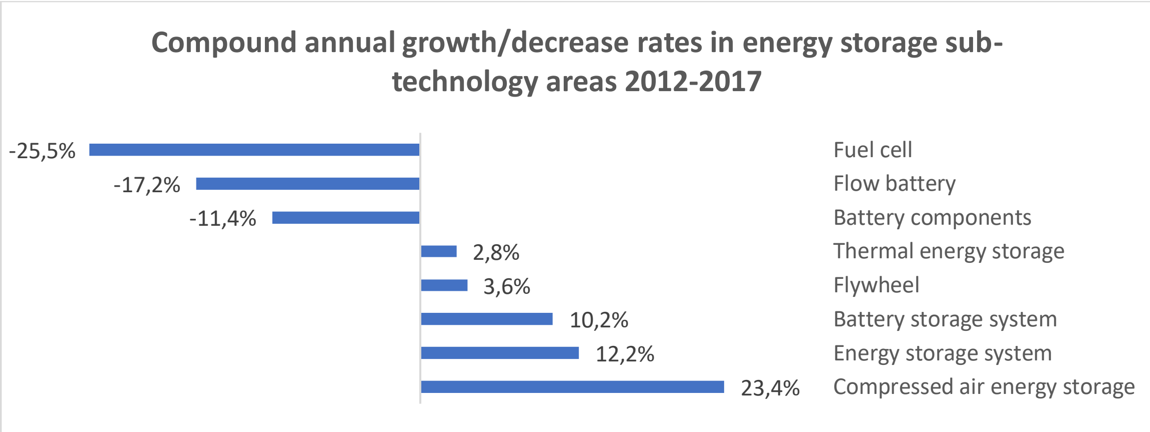

Figure 33 Compound annual growth/decrease of energy storage sub-technology areas 2012-2017

Thermal heat storage (490), compressed air energy storage (243) and flow battery (149) received minor interest from the applicants in terms of filed families. These technology areas were well presented in both spectrums of annual development chart, as compressed air energy storage showed the highest CAGR of all the examined areas with 23.4% annual increase while flow battery activity declined on average 17.2% annually.

Table 6 depicts the technology focus areas of the key applicants using the same taxonomy-based classification. Table 6 reveals that energy storage system and fuel cell were the main technology areas among the key applicants, when measured by the number of applicants. Seven applicants out of 15, most of them having medium or small portfolios, had energy storage system as their main interest. In comparison to previous, fuel cell collected applications almost solely from the large applicants, Doosan and General Electric being the largest with 53 and 46 families. Flywheel and battery components were other technology groups that gathered the main attention from the key applicants.

Table 6 Technology focus of energy storage key applicants

Company/Year	Energy storage system	Fuel cell	Flywheel	Battery components	Thermal heat storage	Battery storage system	Compressed air energy storage	Flow battery
General Electric	45	46	3	19	0	4	18	0
Mitsubishi	5	26	24	5	21	0	3	0
Samsung SDI	27	23	0	5	0	19	0	0
Doosan	1	53	0	21	0	1	0	0
Siemens	20	25	2	3	8	5	1	0
LG	10	8	0	12	0	2	0	2
LSIS	32	0	0	0	0	10	0	0
Nidec	0	0	17	0	0	0	0	0
NEC	8	0	0	0	1	1	0	0
ABB	9	0	1	0	1	4	0	0
Tesla	6	0	0	1	0	1	0	0
Xuji	7	0	0	2	0	0	0	0
Lockheed Martin	3	1	1	1	1	0	0	1
Caterpillar	1	0	5	0	0	1	0	0
Wärtsilä	0	4	0	4	0	0	0	0

6 DISCUSSION

The main aim of this paper was to provide an overview of patenting activity and trends in technology areas that can enhance power system flexibility. This was done by addressing the following research questions: 1) What are the main technology areas to enhance power system flexibility? 2) How active the selected technology areas are in terms of patenting? 3) Who are the leading IP offices and the key applicants in the selected technology areas? and 4) What are technological focus areas in the selected technology areas? The research questions are answered in the order depicted in Table 7.

Table 7 Discussion chapters and research questions

Chapter	*Research question*
6.1 Theoretical findings	RQ1: What are the main technology areas to enhance power system flexibility?
6.2 Empirical findings	RQ2: How active the selected technology areas are in terms of patenting?
	RQ3: Who are the leading IP offices and the key applicants in the selected technology areas?
	RQ4: What are the technological focus areas in the selected technology areas?

6.1 Theoretical findings

The first research question was answered by conducting an extensive literature to identify potential technology areas, which already are or could be integrated into current power system design to provide system flexibility by balancing the impact of VRE. In the end, three different technology areas comprising of several technologies were identified and discussed. These technology areas were conventional power plants, energy storage and smart grid. At the same time, it should be noted that there are also other means to provide flexibility into power systems. These means include sector coupling technologies, such as Power-to-X solutions and vehicle-to-grid technologies. These technologies were not examined in this thesis, which could provide a lucrative opportunity for future study.

Conventional power plants could have a significant contribution in increasing power system flexibility across all relevant timescales. Peaking power plants, which typically operate gas-fired reciprocating engines, were found to possess great flexibility attributes as they are designed start up and shut down quickly and can be operated with part loads. Retrofitting may provide opportunities to harness flexibility from traditionally inflexible baseload and intermediate load power plants. However, retrofitting typically includes significant capital investments and structural changes to the plant, which can make retrofitting efforts unprofitable.

Smart grid was recognized as a second technology area that could help providing flexibility into power systems. Reviewing the literature revealed that smart grid is a broad concept with a complicated mixture of different technologies. Identifying technologies and technology sub-categories that can be exclusively labelled as smart grid technology proved difficult, hence a feature-based categorization was used in the thesis to establish relationships between different components in the smart grid. Three different sub-technology categories were eventually formed. First sub-technology category included communications and energy management system (EMS) technologies, which are used for bi-directional information exchange and to control and coordinate different operations in the smart grid, Secondly, high voltage direct current transmission network technologies and microgrids form the physical infrastructure of the smart grid. Demand-side management applications formed the third category, as they can provide flexibility by allowing power utilities to shift end-user loads when grid is overloaded.

The third flexibility providing technology area was energy storage, which had the largest variety of different technological approaches of the three examined technology areas. The main sub-technology areas considered in the study were mechanical storage, battery storage, fuel cells and thermal storage.

6.2 Empirical findings

The activity analysis suggests that the patenting activity has increased significantly in smart grid and energy storage technology areas, and that smart grid is a novel technology area compared to energy storage. Several indicators support this conclusion. Firstly, the growing trend in both technology areas can be verified simply by examining trend graphs and compound annual growth rates, which both demonstrate the increasing trend. In addition, smart grid and energy storage datasets had fast traditional pendency times compared to USPTO refence value 25.4 months (USPTO 2019), which may indicate that technology area is relatively new as the applications processed faster than average. However, it is the difference in legal status structures that indicates smart grid's novelty compared to energy storage. In smart grid dataset generality of patent families (79%) had either active or pending legal status, while in the energy storage dataset this share was 56%, inactive patent families being the largest single legal status group. These values suggest that majority of smart grid inventions originated to examined period and that smart grid filings had not experienced saturation as the legal shares were unusually distributed. At the same time, energy storages were still growing in terms of filings and granted families, but presumably the energy storage patents had lost some of their commercial lucrativeness as most of the inactive families were inactive because of the right holders' own actions.

The results of the study highlight China's and USA's roles as the main hubs of innovation in smart grid and energy storage fields. To be more specific, China seems to be the main source of innovation quantitatively measured, while USA seems to hold the top place when measured by quality of patent families. The results provide enough evidence for making such a conclusion. In both datasets China had the most patent families and Chinese patent filings were the main reason for increasing patenting activity in smart grid and energy storage technology areas. USA was the second largest patent office when measured by the number of patent families but had highest quality and largest commercial interest when measured by citation per patent and patent family size.

Smart grid and energy storage datasets divulge that both technology areas have seven applicants who have distinctively larger and more diverse patent portfolios than the rest of the applicants. In smart grid datasets these seven large applicants are Samsung SDI, General

Electric, Toshiba, NEC, LG, Siemens and ABB. In energy storage dataset these large applicants are General Electric, Mitsubishi, Samsung SDI, Doosan, Siemens, LG and LSIS. In addition to portfolio sizes, key applicant analysis provides information concerning key applicants' regional patenting patterns and portfolio strengths.

To begin with regional patenting patterns, the study depicts that key applicants are favouring USA over other patent jurisdictions and that China is the least patented region among the key applicants. The results seem to be logical when societal issues are considered. Patents and other forms of IP have traditionally had a major role in USA's competitive markets, which may explain USA high shares. China's poor position may be due to deficiencies in country's IPR system, as Zhang (2016, pp. 3-5) argues. In theory patents and other forms of IPR granted in China should provide similar legal protection than elsewhere, but in practice patent infringements seem to be rather common, which may have affected key applicants' willingness to apply protection for their inventions in the country.

Based on the collected data, it can be argued that patent portfolio size does not necessarily correlate with the patent quality. The results of the patent quality matrix show that many of the large applicants were actually filing low-quality inventions, while some of the smaller key applicants had a very limited portfolio but significantly many citations per patent. Hence, it seems that patent portfolios should rather be viewed as a strategic asset where the value lies somewhere else than in technological advancement. Large patent portfolios can be acquired inter alia to increase company abilities to block competitors from using or patenting certain technology, as was demonstrated in IP blocking potential comparison.

Finally, the results of technology analysis illustrate that different sub-technology areas are at the different stage of their lifecycle in terms of patenting. Some of the sub-technology areas are clearly novel as they have experienced exceptionally high annual growth rates in the recent years. This seems to be particularly the case in smart grid technology area, where all sub-technology areas have shown compound annual growth rates over 10% during 2012-2017. On the other hand, study also depicts that some of the sub-technology areas in energy storage dataset have reached their technological maturity. Three sub-technology areas even showed negative compound annual growth rates during 2012-2017. These sub-technology areas were "fuel cell", "flow battery" and "battery components".

6.3 Limitations of the study

The thesis has several potential limitations that should be considered and addressed before making conclusions based on the study. The first limitation concerns the usage of patent data and its use in monitoring technical development in certain technology field. Timmermanns (2014, pp. 52-54) argues, that distinctive limitation in the use of patent data is that it represents only a fraction of all research and development activity in the given field, as many inventions are not patented due to strategic reasons or simple because they do not meet the requirements of patentability. In addition, patent data may suffer from procedural lag time, which may decrease reliability of the retrieved data. Patent applications are published in most jurisdictions after 18 months from the first filing date, which causes patenting trend to drop as number of patent families may yet not be published (Dapurkar and Telang 2017, p. 3). However, as patents are often seen as indicators of commercially viable inventions, it can be argued that patent data can be utilized to establish a broad overview of general technology trends in the given technology area at relatively limited time span.

The second limitation is linked to the selected search strategy used in the data retrieval. The study utilized a hybrid search strategy consisting patent classes and keywords, which both have features that may possess a challenge for the validity of the findings. Karvonen et al. (2016, p. 3743) acknowledged that use of patent classes may lead to retrieval of significant number of irrelevant patent families. The risk of irrelevant families becomes especially obvious in the studies like this thesis, which are interested in examining large technology areas consisting of various technologies and where the research needs to use a wide range of different patent classes. The risk is often reduced with keywords specific to field of interest, but this approach also possesses a problem, as the terms used by different patent applicants tend to have a high variance. This may result in situation where relevant patent families are excluded and irrelevant families are included. In addition to above-mentioned challenges, it should be regarded that the chosen patent classes and keywords tend to reflect somewhat researcher’s personal preferences. To address these issues in this study, the search process was iterated several times and the findings were discussed with Wärtsilä’s patent professionals to increase the accuracy of the search.

The third limitation of the study is related to the filtering of retrieved patent data. Irrelevant and duplicate documents related to same invention decrease the validity of the study, hence to maximize the relevancy datasets should be manually screened to filter these documents. However, this procedure is significantly time-consuming and requires high level of complex technical knowledge. Considering the constraints set by the high number of retrieved patent families, time limitations and researcher's lack of deep technical knowledge on the examined technology areas consisting of various technologies, manual reading of patent documents was not possible. In the given situation, the patent families were first grouped so that only one patent document per invention was shown, which eliminated the risk of counting the same multiple times. Then, the titles of grouped families were superficially screened, and the most obviously irrelevant patent families were excluded.

Besides three previously discussed limitations, there were limitations related patent indicators. Due to peculiarities of patent data and procedural differences between jurisdictions, a common problem in almost every patent-based study is to select patent indicators that measure what they are intended to measure. To address this issue, the study only used indicators that had been utilized in the similar studies previously.

6.4 Future research

Depending on the selected perspective and desired output, there are several possible alternatives for future research. As this study focused on providing a broad overview of the patent landscape in smart grid and energy storage technology areas, one potentially interesting approach could be to focus specifically on a limited set of technologies and analyse their development. This kind of analysis could be conducted for instance to flywheel and CAES technologies by using already collected datasets as an input data.

Although study analysed the key applicant's patent portfolios from different perspectives, it did not provide insights on the types of claims in the granted patents and pending patent applications. An extensive study on key applicants' claims could provide an extensive knowledge on the current state of art in smart grid and energy storage technology areas for the researchers. From commercial viewpoint, this kind of study could be used to assess the state of freedom to operate or to map the IP related risks in the given field.

The technical content of the collected patent documents was analysed by extracting matching keywords from patent abstracts. To form more elaborate view of the technical content, future studies could include patent classification code analysis, which would allegedly provide an insight of how the patent examiners see the development in smart grid and energy storage technology areas.

7 CONCLUSIONS

This thesis aimed to provide an overview of patenting activity and patenting trends in the selected technology areas which may be used to enhance power system flexibility. After an extensive literature review, smart grid and energy storage were selected as technology areas for patent analysis.

The results of patent analysis indicate that patenting activity related to smart grid and energy storage is on the rise. The positive trend is mainly due to drastic increase of Chinese patent filings, which underlines China's role alongside USA as the main patent hubs in smart grid- and energy storage-related inventions. In both technology areas, IP landscapes are dominated by seven applicants who have significantly larger patent portfolios than other key applicants in the field. Smaller key applicants are focusing on filing inventions related to specific sub-technology areas and some of these applicants may possess significant inventions in the field of interest. Technical analysis of smart grid and energy storage patent data indicates that different sub-technology areas are in different stages of their lifecycles.

Reflecting the results to initial research questions and objectives, it can be stated that the used methodology was able to define the direction of patenting activity, identify key offices and applicants and, to some extent, provide an overview of technical development in smart grid and energy storage technology areas. More importantly, the thesis demonstrated patent data's applicability as an abundant source of information to support decision-making. Study illustrated that patent documents and bibliographic data thereof, are especially viable in situations where a snapshot of development landscape in certain technology area is needed. Moreover, patent abstracts can be utilized to extract information concerning the technical state of art in the specified field, thereby complementing bibliographic metadata.

Despite achieving research objectives, the study had its limitations. Firstly, the study analysed technical development in smart grid and energy storage technology areas using only patent data, meaning that large quantities of relevant non-patent literature were excluded. Secondly, due to inherent defects in search- and filtering strategies retrieved datasets may include irrelevant documents, thereby effecting to the reliability of the study. Thirdly, it can be asked whether patent indicators used in the study actually measure what they are intended to measure. This is especially relevant question in analysis' technical part, where a set of keywords were used to categorize patent families into sub-technology areas.

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APPENDICES

APPENDIX 1: SEARCH QUERY TABLE

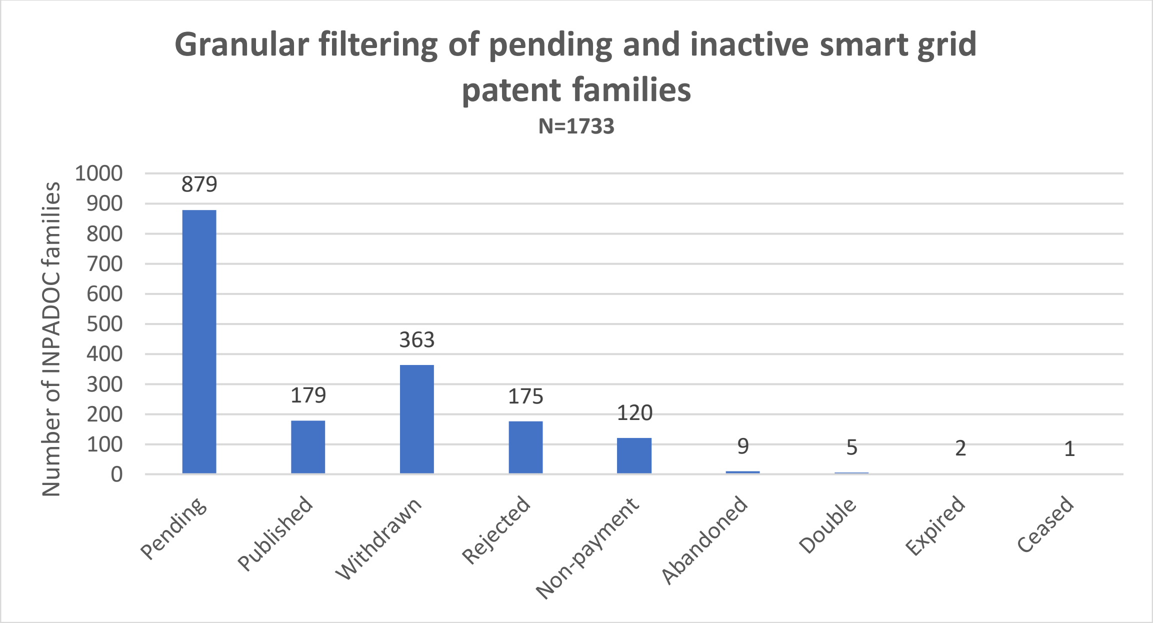
Technology area	**Search query**
Smart grid	TAC:("energy storage system" OR "distributed energy storage?" OR "virtual power plant" OR "energy management system" OR "smart grid") AND CPC:("H02J13/00" OR "G05F1/66" OR "H02J3/382" OR "H02J13/0079" OR "Y02B70/3216" OR "Y02E40/72" OR "Y02E60/7869" OR "Y04S10/123" OR "Y04S20/221" OR "Y04S40/128" OR "H02J15/00" OR "G05B15/02" OR "H02J3/14" OR "H02J3/32" OR "H02J3/381" OR "H02J3/383" OR "H02J7/35" OR "H02J13/0006" OR "Y02B70/3225" OR "Y02E10/563" OR "Y02E10/566" OR "Y02E60/721" OR "Y02E70/30" OR "Y02T90/168" OR "Y04S10/126" OR "Y04S20/222" OR "Y04S30/12") AND APD:[19990101 TO 20190101]
Battery storage	TAC:("Distributed battery storage" OR "flow battery" OR "Battery energy storage system" OR "BESS" OR "battery energy storage" OR "utility scale battery" OR "lithium battery system" OR "alkaline battery system" OR "lead-acid battery system" OR "sodium-sulfur battery system" OR "energy storage system" OR "NaS battery system") AND CPC:(Y02E60/12 OR Y02E60/122 OR Y02E60/124 OR Y02E60/126 OR Y02E40/10 OR Y02E40/34 OR Y02E40/74 OR Y02E60/722 OR Y02E60/726 Y02E60/74 OR Y02E70/30 OR Y04S10/14 OR Y04S10/22 OR Y04S10/24 OR Y04S10/30 OR H01M10/28 OR H01M10/24 OR H01M2220/10) AND APD:[19990101 TO 20190101]
Thermal storage	TAC:("Thermal energy storage" OR "latent heat storage" OR "thermochemical energy storage" OR "sensible heat storage" OR "cold energy storage") AND CPC:("Y02E60/14" OR "Y02E60/142" OR "Y02E60/145" OR "Y02E60/147" OR "C09K5/10" OR "C09K5/12" OR "C09K5/14" OR "C09K5/16" OR "C09K5/18" OR "C09K5/00" OR "F24H7/00" OR "F28D20/00" OR "F28D20/02") AND APD:[19990101 TO 20190101]
Mechanical storage	TAC:("flywheel" OR "high-speed flywheel" OR "low-speed flywheel" OR "Compressed air energy storage" OR "CAES" OR "adiabatic CAES" OR "diabatic CAES") AND CPC:(Y02E60/15 OR Y02E60/16 OR F03G3/08 OR H02K7/02 OR H02K21/22 OR H02K21/222 OR H02J15/006) AND APD:[19990101 TO 20190101]
Fuel cells	TAC:("Solid acid fuel cell" OR "SAFC" OR "Phosphoric acid fuel cell" OR "solid oxide fuel cell" OR "molten carbonate fuel cell" OR "zinc air battery" AND "electricity generation") AND CPC:(Y02E60/50 OR Y02E60/526 OR Y02E60/527 OR Y02E60/528 OR Y02E60/56 OR Y02E60/563 OR Y02E60/566) AND APD:[19990101 TO 20190101] NOT TAC:("car" OR "vehicle" OR "air plane" OR "transportation")

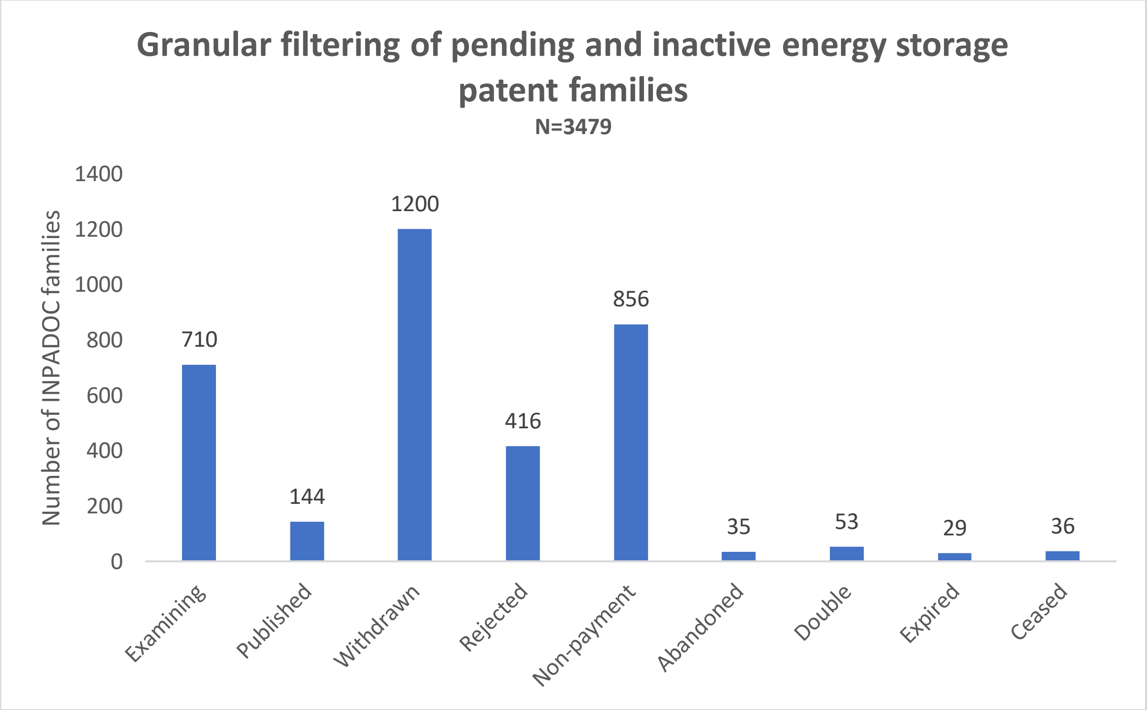
APPENDIX 2: KEYWORDS USED IN TECHNOLOGY ANALYSIS

Sub-technology class	Keywords
Energy storage	“*energy storage*", “*energy system*", “*distributed energy storage*", "*distributed energy*"
Fuel cell	“*fuel cell*")
Flywheel	“*flywheel*”
Battery components	"*electrochemical*", "*anode*", "*cathode*", “*lithium*", "*NaS*”, "*nickel-cadmium*”, "*lead-acid*", "*sodium-sulphur*"
Thermal storage	“*thermal heat*", "*heat storage*”, "*thermal heat storage*", “*latent heat storage*”, “*latent thermal heat storage*", "*latent heat*", "*thermochemical storage*", "*thermo chemical*", "*thermochemical heat storage*", , "*sensible heat storage*", "*sensible thermal heat storage*", "*sensible heat*")
Compressed air energy storage	"*CAES*", "*compressed air energy storage*”, “*compressed air *", "*pressurized fluid*”
Flow battery	“*flow battery*", “*redox flow battery*"

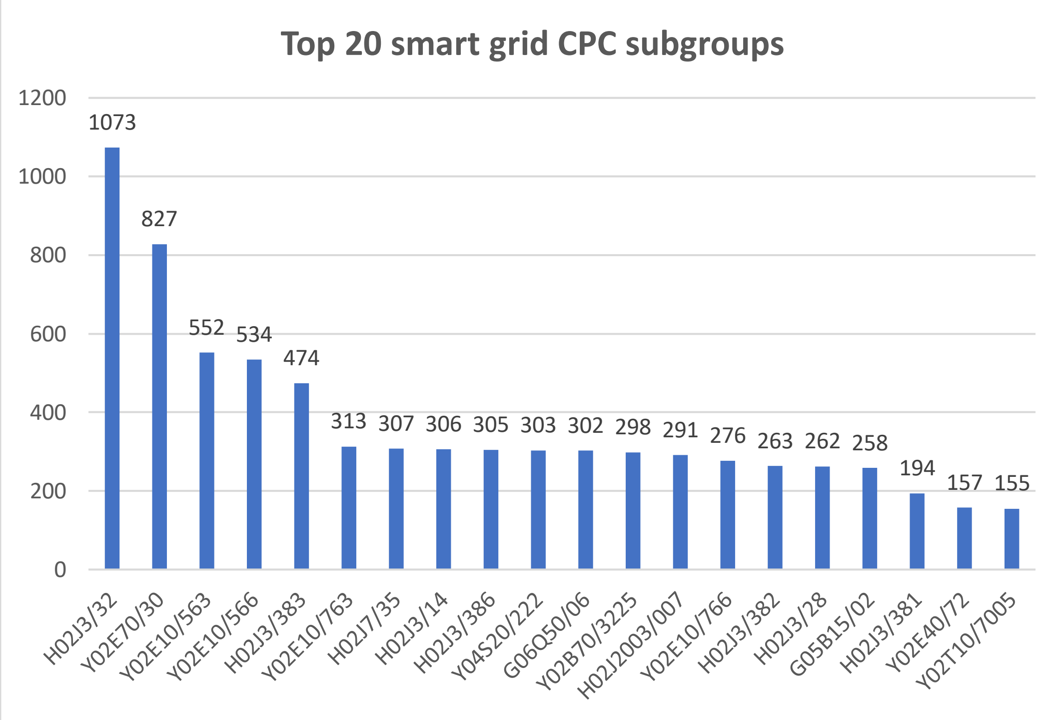
Sub-technology class	Keywords
Integration of power generation assets	“*power generation*", "*electricity generation*", “*integration*", “*wind*", “*solar*")
Grid infrastructure	“*Grid*”
Communications and EMS	"*software*", “*Energy management system*”, “*EMS*, "*energy manager*”, “*battery management*")
Energy storage	“*energy storage*”
Electric vehicle	“*electric vehicle”, “vehicle”
Demand response	“*demand response*”, “*demand management*”, “*demand side*”

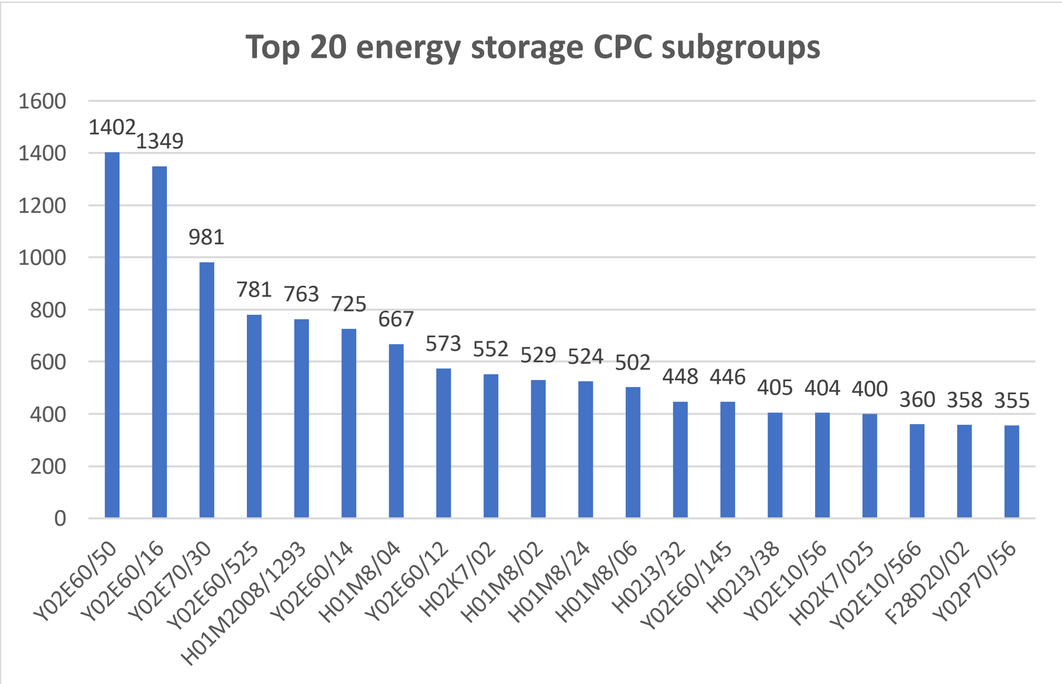
APPENDIX 3: GRANULAR FILTERING OF PENDING AND INACTIVE PATENT FAMILIES





APPENDIX 4: CPC SUBGROUPS





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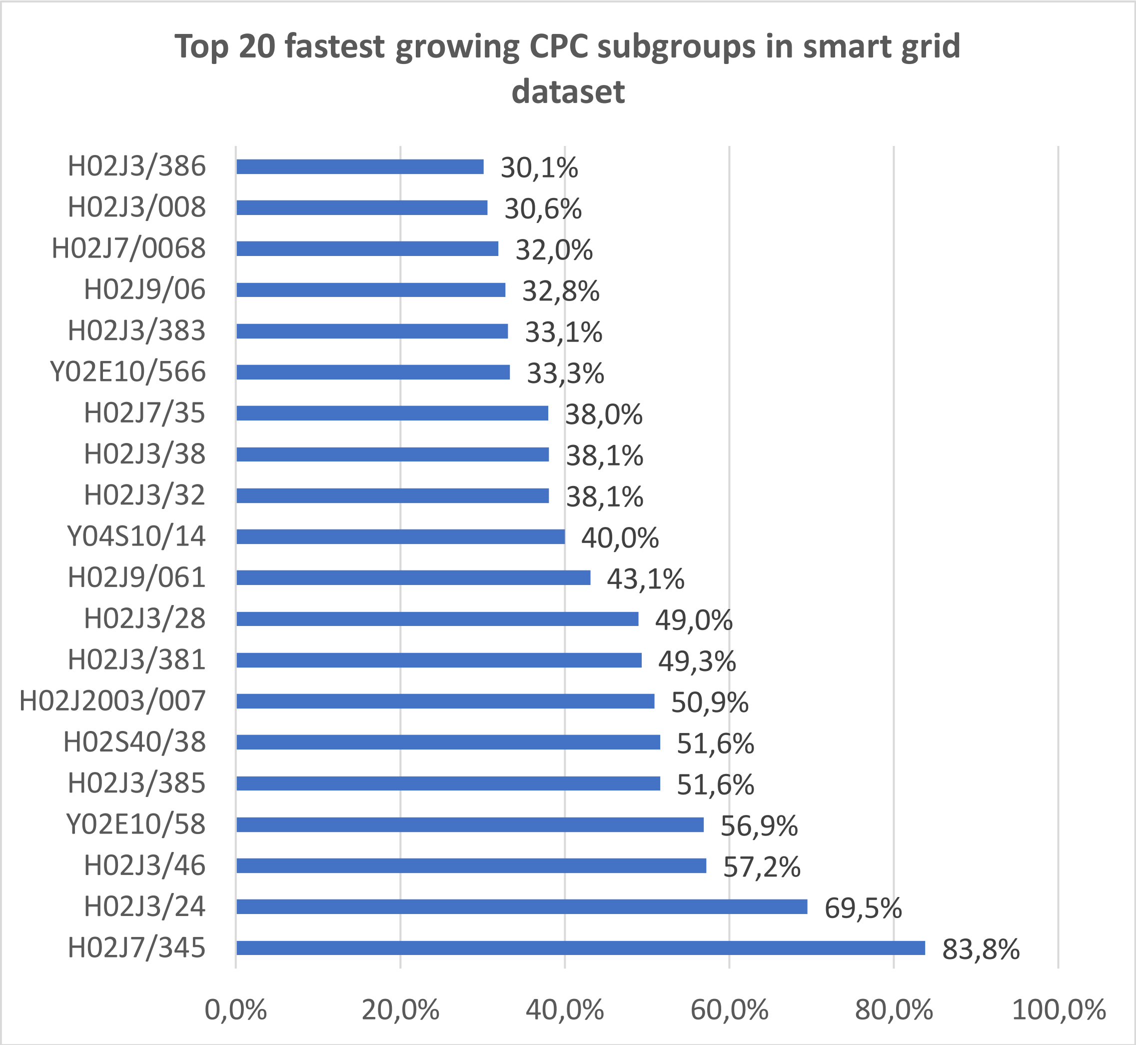
(APPENDIX 4 Continued)



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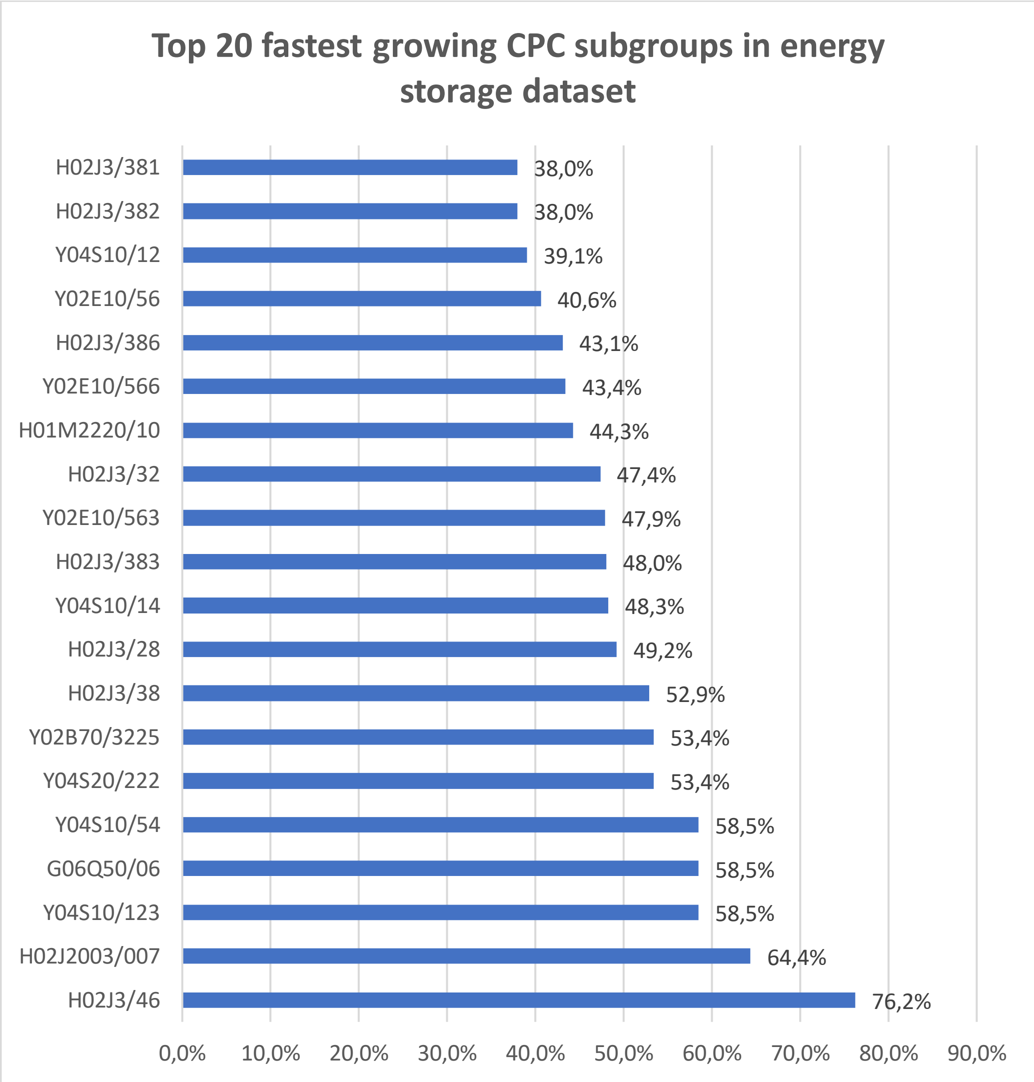
(Appendix 4 continued)



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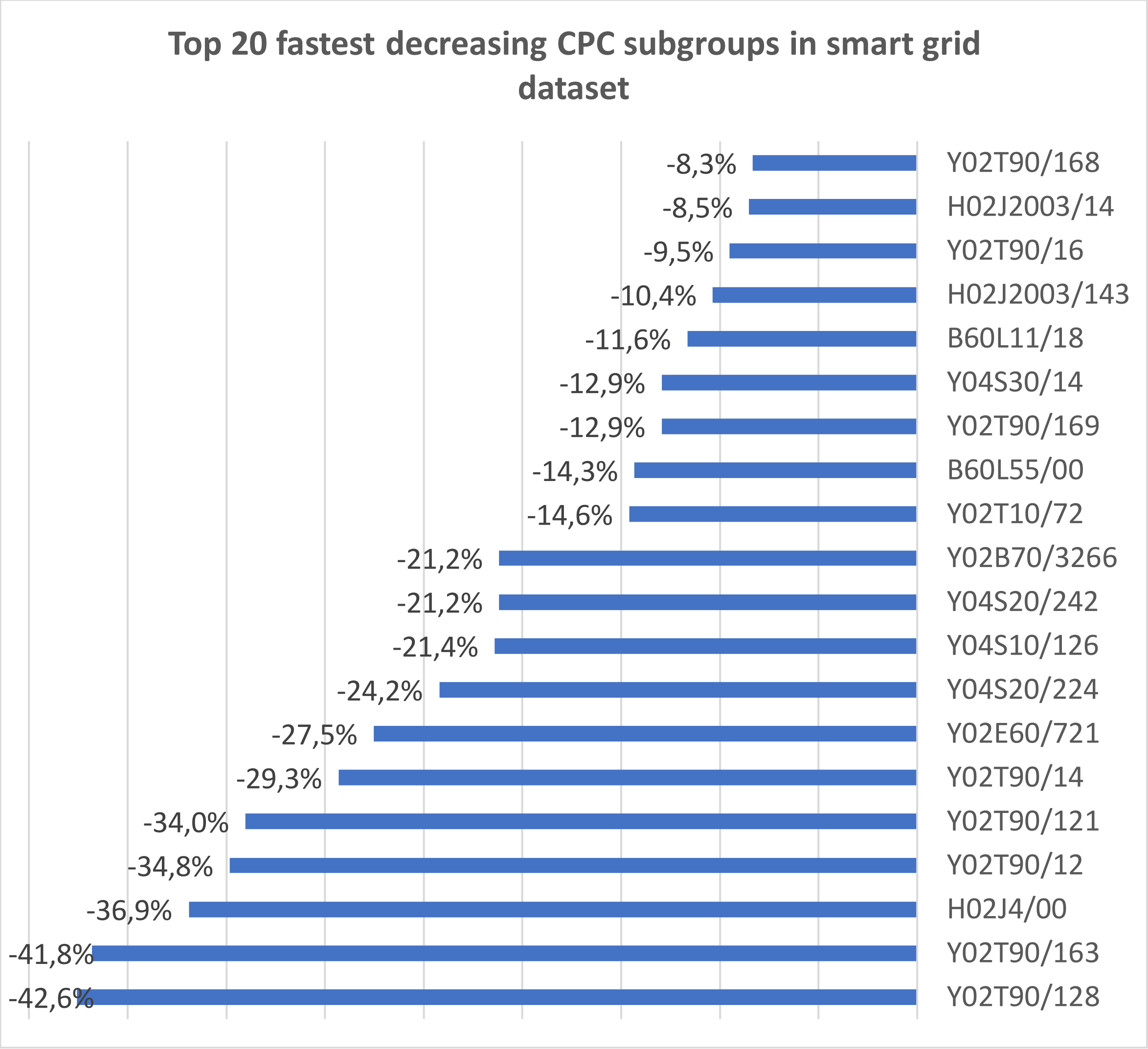
(Appendix 4 continued)



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