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Energy Storage Systems in Electrical Distribution Grids

Analysis and implementations of use cases for service stacking

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Abstract
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This Ph.D. thesis investigates the possibility of using energy storage systems for multiple services by implementing service stacking, with special emphasis on congestion management in distribution grids. The shift towards increased shares of RES in combination with the ongoing electrification of society will create challenges in all parts of the power system. To ensure enough flexibility throughout the power system, energy storage should be part of the discussion as a crucial tool to support balancing and stability, but also to assist in or solve local and regional challenges. One important step in the development of energy storage integration is the forming of more complex business models where multiple services are provided using the same storage unit and is known as service stacking. This increases the availability of the storage capacity towards the power system where value could be generated on both local, regional and system levels. Although, one of the main barriers of energy storage investments have been the high investment and operational costs. By implementing service stacking, the chance of creating a lucrative business case increases and should be considered in all contexts of energy storage implementations.

The targeted research questions focus on mapping the current state of service stacking implementations globally, comparing different methods for implementing scheduling optimization tools, and evaluation of the technical and economic performance for different service portfolios. According to the trends in the results of the appended papers, energy storage systems have the potential to stack services both as large-scale centralized units as well as small-scale distributed units and can be applied to all storage technologies. The higher degree of utilization of the storage units will result in increased degradation due to cycle aging, but the magnitude of this increase strongly depends on the service portfolio composition and allowed cycle intensity. Future work could focus on multi-objective optimization, extended service portfolios, and scheduling over several time scales to include seasonal storage and intraday trading.

Keywords: ancillary services, congestion management, distribution grids, energy storage systems, scheduling optimization, service stacking.

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Thank you for your unconditional support
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Professor AbuBakr S. Bahaj
Chari of the Scientific Committee of ICEC 2021
Head of Energy and Climate Change Division, University of Southampton, UK

List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I **J. Hjalmarsson,** K. Thomas, C. Boström (2023) “Service stacking using energy storage systems for grid applications - a review”. *Journal of Energy Storage*, vol. 60 p.1-25.

II **J. Hjalmarsson**, K. Thomas, C. Boström, A. Berlin, F. Carlsson (2021) “Large scale energy storage in Uppsala, Sweden - an analysis of voltage fluctuations and a service stacked portfolio”. Published and presented at the *2nd International Conference of Evolving Cities,* Southampton, UK.

III **J. Hjalmarsson**, A. Wallberg, C. Flygare, C. Boström, F. Carlsson (2023) ”Optimal Scheduling of Energy Storage Systems in Distribution Grids Using Service Stacking”, Published and presented at *the 27th International Conference on Electricity Distribution (CIRED)*, Rome, Italy.

IV **J. Hjalmarsson**, C. Flygare, A. Wallberg, O. Lindberg, F. Carlsson, C. Boström (2023) “Enhancing the value of large-scale energy storage systems in congested distribution grids using service stacking”, Submitted to *Journal of Energy Storage*, 2023-06-20.

V **J. Hjalmarsson**, A. Wallberg, C. Flygare, F. Carlsson, C. Boström (2023) ”Scheduling optimization of energy storage systems at large sports facilities in congested distribution grids”, Submitted to *Journal of Energy Storage*, 2023-08-16.

VI **J. Hjalmarsson**, A. Wallberg, C. Flygare, F. Carlsson, C. Boström (2023) “Evaluation of centralized and distributed energy storage systems in congested distribution grids with service stacked portfolios”, Submitted to *Applied Energy*, 2023-09-29.

VII C. Flygare, A. Wallberg, **J. Hjalmarsson**, C. Fjellstedt, C. Aalhuizen (2022) “The potential impact of a mobility house on a congested distribution grid - a case study in Uppsala, Sweden”. Published and presented at the *International Conference & Exhibition on Electricity Distribution CIRED - Porto Workshop: E-mobility and power distribution systems*, Porto, Portugal.

VIII J. Leijon, J. Döhler Santos, **J. Hjalmarsson**, V. Castellucci, D. Brandell, C. Boström (2023) ”Analysis of charging and discharging of electric vehicles”, Published and presented at *the 36th Electric Vehicle Symposium & Exposition (evs36),* Sacramento, California, USA. Submitted to *the World Electric Vehicle Journal, September 2023*.

IX A. Parwal, **J. Hjalmarsson**, T. Potapenko, S. Anttila, J. Leijon, J. Kelly, I. Temiz, J. Oliveira, C. Boström, M. Leijon (2020) “Grid Impact and Power Quality Assessment of Wave Energy Parks: Different Layouts and Power Penetrations using Energy Storage”. *IET the Journal of Engineering,* vol 8. p.415-428.

X I. Temiz, A. Parwal, J. Kelly, T. Potapenko, J. Leijon, S. Anttila, **J. Hjalmarsson,** L. Hebert, C. Boström (2019) “Power hardware-in-the-loop simulations of grid interaction of a wave power park”. Published and presented at the *13th European Wave and Tidal Energy Conference EWTEC2019,* Napoli, Italy.

XI A. Parwal, M. Fregelius, D. C. Silva, T. Potapenko, **J. Hjalmarsson,** J. Kelly, I. Temiz, J. G. de Oliviera, C. Boström, Mats Leijon (2019) ”Virtual synchronous generator based current synchronous detection scheme for a virtual inertia emulation in smart grids”. Energy and Power Engineering, vol. 11, p.99-131.

XII T. Potapenko, A. Parwal, J. Kelly, **J. Hjalmarsson**, S. Anttila, C. Boström, I. Temiz (2019) ”Power Hardware in-the-Loop Real Time Modelling using Hydrodynamic Model of a Wave Energy Converter With Linear Generator Power Take-Off’, Presented at *the 29th International Ocean and Polar Engineering Conference (ISOPE)*, Honolulu, Hawaii, USA.

Contents

Abbreviations

AC	Alternating current
ACO	Ant colony optimization
AND	Active distribution network
ASAI	Average Service Availability Index
BAU	Business as usual
BESS	Battery energy storage system
CAES	Compressed air energy storage
CAIDI	Customer Average Interruption Duration Index
CAPEX	Capital expenditure
CHP	Combined heat and power
DC	Direct current
DER	Distributed energy resources
DMS	Distribution management system
DoD	Depth of discharge
DSO	Distribution system operator
DSR	Demand side response
EA	Evolutionary algorithm
EI	the Swedish Energy Markets Inspectorate
ESS	Energy storage system
EV	Electric vehicle
FACTS	Flexible alternating current transmission systems
FCR-D	Frequency containment reserve – disturbance
FCR-N	Frequency containment reserve - normal
FES	Flywheel energy storage
FFR	Fast frequency reserve
FRR	Frequency restoration reserve
GA	Genetic algorithm
G2P	Gas-to-power
HES	Hybrid energy storage
HESS	Hydrogen energy storage system
HIL	Hardware-in-the-loop
HVDC	High-voltage direct current
IEA	International Energy Agency
IED	Intelligent electronic device
IEEE	the Institute of Electrical and Electronics Engineers
IP	Integer programming
IPCC	Intergovernmental Panel on Climate Change

IRENA	the International Renewable Energy Agency
LP	Linear programming
LV	Low voltage
KPI	Key performance indicators
MaREI	the Centre for Marine and Renewable Energy Ireland
MEMS	Microgrid energy management system
MILP	Mixed-integer linear programming
MOO	Multi-objective optimization
MTU	Market time unit
MV	Medium voltage
NLP	Nonlinear programming
NPV	Net present value
NREL	the National Renewable Energy Laboratory
OPEX	Operational expenditure
PDF	Probability distribution function
PHES	Pumped hydroelectric storage
PP	Payback period
PSO	Particle-swarm optimization
PV	Photovoltaic
QP	Quadratic programming
RES	Renewable energy sources
RMS	Root mean squared
RoCoF	Rate of change of frequency
ROI	Return on investment
ROW	Right of way
RV	Residual value
R&D	Research and development
SA	Simulated annealing
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SC	Supercapacitor
SCADA	Supervisory Control and Data Acquisition
SDN	Smart distribution network
SEPA	The Smart Electric Power Alliance
SMES	Superconducting magnetic energy storage
SoC	State of charge
SP	Stochastic programming
STATCOM	Static synchronous compensator
SvK	Svenska Kraftnät
TES	Thermal energy storage
THD	Total harmonic distortion
TS	Tabu search
TSO	Transmission system operator
T&D	Transmission and distribution
VAT	Value-added tax

V2G	Vehicle-to-grid
V2H	Vehicle-to-home
V2X	Vehicle-to-everything
WEC	Wave energy converter
WPP	Wave power park

Nomenclature

A_h	Energy throughput
C	Total cost
c	Cost component of tariff
E^{tot}	Rated energy capacity
f	Objective function
f_{el}	Electrical grid frequency
F	Set of objective functions
g	Set of inequality constraints
h	Set of equality constraints
J	Moment of inertia
k	Cycle intensity constant
P	Active power
P_{st}	Flicker level
Q_{loss}	Estimated capacity life loss
R	Revenue
$\mathrm{SoC_{ini}}$	Initial state of charge
$\mathrm{SoC_{max}}$	Maximum state of charge
$\mathrm{SoC_{min}}$	Minimum state of charge
T	Cell temperature
t	Duration time (endurance)
U	Voltage
X	Set of optimization variables
α	Binary optimization variables
η	Round-trip efficiency
ω_{el}	Electrical angular velocity
π^c	Capacity remuneration
π^e	Energy remuneration
π_{peak}	Cost of peak power
W	Fitness function scaling factor
w	Fitness function penalty

1. Introduction

We live in a time of large and fast changes in our environment: from digitalization and energy system transitions to sustainable development adaptation and societal transformations. A selection of important changes and aspects being adapted to is summarized in Figure 1, and it is clear that a lot of things are going on which affect our everyday life in many ways. The four segments are presented separately in Figure 1, but in reality, they are heavily meshed where e.g., the energy transition is done with great respect to sustainable development and societal aspects while continuously being integrated with the latest advancements and proceedings of the digital revolution.

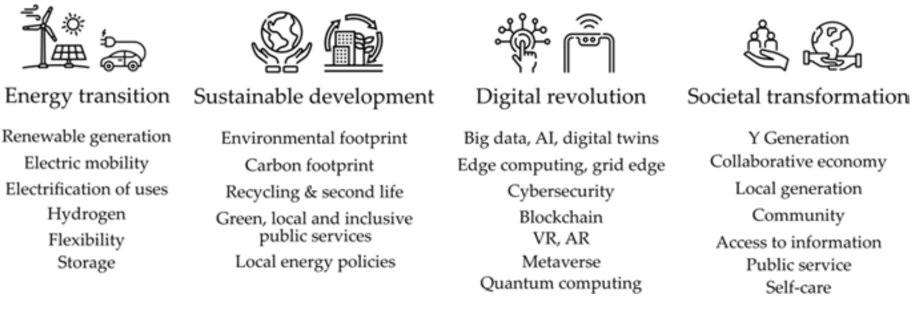

Figure 1. Selection of ongoing changes and adaptations in the world.[1]

It is known that the global emissions of greenhouse gases have to reduce remarkably in order to reach the defined climate targets. In 2015, the Paris agreement on climate change was signed by 190 countries and is one of the most important global climate actions since the Kyoto protocol was agreed and entered into force. As of spring 2022, the Paris agreement has been signed by 195 parties of which 193 are countries. In parallel, climate reports from the Intergovernmental Panel on Climate Change (IPCC) continuously point at the need for climate actions at a faster pace and of larger impact. The conclusions of the latest reports have contributed to a wave of sustainability propagating globally. As more sectors of the society increasingly adapts to current climate policies energy systems worldwide have already or will face major transitions.

[1] This figure has been designed using images from Flaticon.com, by users “Freepik”, “Monkik”, “Eucalyp”, “Nualnoi Kinkaeo” and “Culmbio”

Furthermore, the supply of electricity is also increasing worldwide where people in countries and regions with historically low use of electricity now have access to electric power in their everyday life to a larger extent [1]. This is a natural result of global technology development but also an important result of the hard-working international organizations for human rights and equality. According to Table 1, the global demand for electricity may increase by 21-32 % between 2018 and 2030, which is a noteworthy increase. During the same period, the share of the global population with access to electricity is expected to increase from 89 % to between 93-100 %, depending on the scenarios for climate policies.

Fossil fuels have been used for electricity generation for a long period and are deeply rooted in the energy system. According to the official world energy forecast done in 2019 by IEA, it was concluded that the global levels of CO_2 emissions could be reduced remarkably [1]. Figure 2 visualizes three possible outcomes for the CO_2 emissions as result of different political approaches for the energy system. Considering the "*stated policies*" scenario, the curve for CO_2 emissions flattens by 2040, but with "*current policies*" the curve will keep increasing even by 2040. The scenario "*sustainable development*" is more optimistic and illustrates that it could be possible to make a change once and for all. It can also be noted that the decline of the CO_2 curve can start a few years after 2020 already, indicating that at least some of the required tools are at place as of today. But these tools must be implemented soon – preferably now – to make a difference [1].

The increased use of electricity worldwide and the shift to renewable energy sources (RES) will naturally create challenges throughout the power system: from generation to end-user aspects. Also, according to Table 1, the capacity for electricity generation is expected to increase by 21-32 % between 2018 and 2030, which is necessary to meet the expected increase in demand. During the same period, the capacity of RES is expected to increase by 70-125 % (in comparison, the increase of RES was approx. 140 % between 2000 and 2018). One of the challenges that arise concerns the expansion of the grid, both in areas with and without existing power grid infrastructure. It is a time-consuming and expensive process but still doable and necessary. A second challenge concerns the future roles of involved parties in the power system – a topic that has been discussed frequently last years and probably will be for some time in near future as new challenges and problems arise. Due to the extensive shift towards RES, electrification of transports and digitalization, all involved parties of the power system experience structural changes. Furthermore, another aspect concerns the electrical status of the power system as renewables gain increased shares of the global and regional generation mixes.

Table 1. Global demand and generation of electricity [1].

	Historical data		*Stated policies*		*Sustainable development*		*Current policies*	
	2000	**2018**	**2030**	**2040**	**2030**	**2040**	**2030**	**2040**
Electricity demand (TWh)	13152	23031	29939	36453	28090	34562	30540	37418
Industry	5398	9333	11843	13525	10751	12169	11998	13874
Transport	218	377	1025	2012	1374	4065	725	1091
Buildings	6738	11755	15198	18893	14264	16606	15835	20176
Share of population with electricity (%)	73	89	93	93	100	100	93	93
Electricity generation (TWh)	15427	26607	34140	41373	31800	38713	34988	42824
Coal	5994	10123	10408	10431	5504	2428	11464	12923
Natural gas	2750	6122	7529	8899	7043	5584	8086	10186
Nuclear	2591	2718	3073	3475	3435	4409	3112	3597
Renewables	2863	6799	12479	18049	15434	26065	11627	15485

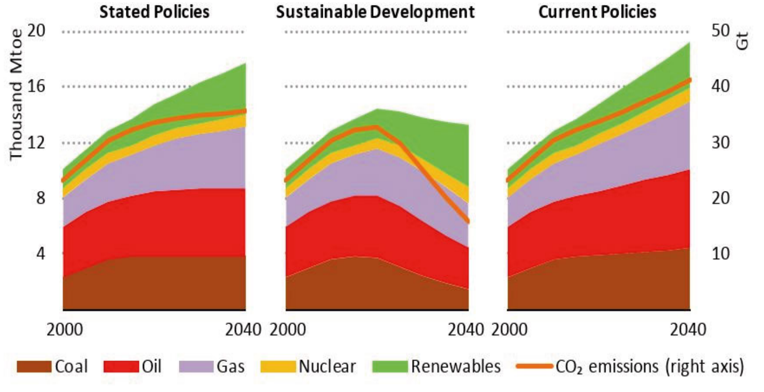

Figure 2. World primary energy demand [1].

The reduced amount of rotating mass of generators which provide inertia to the power system has been highlighted as one of the key issues and may be solved in several ways — but it remains to determine to what extent tools such as synthetic inertia and ancillary services are necessary to maintain a sufficient quality of supply. Additionally, the average size of power plants is expected to decrease as large coal, oil and nuclear power plants are decommissioned, shown in Figure 3. It is also expected that increased shares of the generated electricity will be fed into the distribution grids, which is illustrated in Figure 3 as well. Finally, a fourth aspect concerns how existing grids should be reinforced and interconnected, and to determine how tools such as flexibility and energy storage should be implemented to support the power system. International connections may improve the security of supply and balance between regions but is also a political matter for national security.

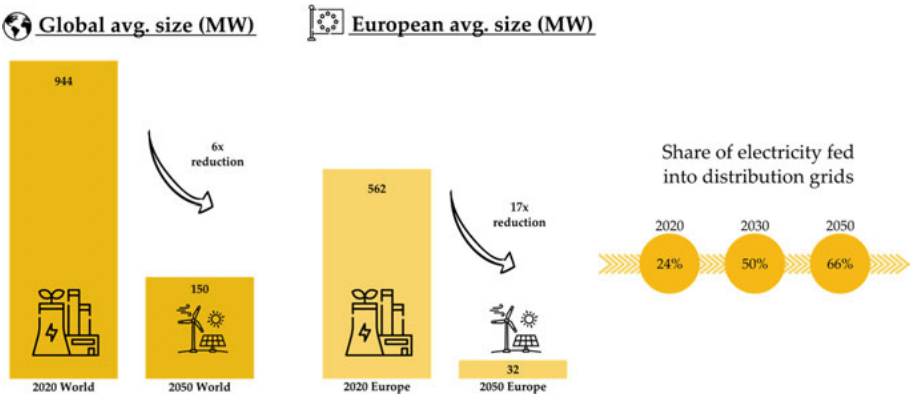

Figure 3. Average size of power plants and electricity fed into distribution grids, reworked with inspiration from [2].[2]

Energy storage has naturally and strategically been present throughout the energy system to enable dynamic balancing of generation and demand, but also as a power and energy reserve. In the Nordic power system, some of the largest reserves are found in hydropower reservoirs and in national oil reserves. Although, applications and services are forming – both old and new ones - which are suitable for other storage technologies to operate actively in as well. These target all levels of the power system: from ancillary services and energy time shift of excess power generation to local challenges of network operators and household energy management.

Not surprisingly, several challenges come with the shift from fossil fuels to RES – but new opportunities arise too. Some of the tools that are being introduced are available for individual users or companies to use - making it easier to affect and adjust the use of electricity than ever before. For example, individuals, companies and even municipalities may invest in local power generation. This enables the possibility for self-consumption of locally generated electricity, thus reducing the demand for electricity from the distribution system operator (DSO). By investing in energy storage systems (ESS), the degree of self-consumption and hosting capacity of RES in distribution grids could be increased even further, by storing excess electricity generation during daytime for later use and by reducing large amounts of power being fed back into the grid. Another tool which most probably will be available for the individual in near future is the possibility to control charging of electric vehicles (EV), either in first-person or by a third party. By using a thoughtful and strategic charging schedule, it is possible for households and companies to significantly

[2] This figure has been designed using images from Flaticon.com, by users “Freepik” and “Culmbio”

reduce the impact from EV charging on the overall electricity use and counteract regional power peaks. Finally, as the digitalization continues in all sectors worldwide, a large number of digital tools has become available. These can be used at home to visualize overall electricity use, show the distribution among household gadgets, and making it possible adjust and even reduce the use of electricity in both short and long-term perspectives. The world of flexible electricity use will change the situation for sure, and it will be very interesting to see what happens when the majority of end-users implement autonomous flexibility tools.

Against this background, there are several reasons why more research is needed in power system analysis, both at transmission and distribution level. Since the power system is vulnerable it requires protection against forces of the nature as well as from human interactions. The energy storage aspect has been discussed frequently last years as more variable RES gain shares of the global electricity mix due to climate change adaptation but also due to increased discussions concerning energy security. Both transmission system operators (TSOs) and DSOs point at storage and flexibility solutions as necessary tools to include and implement even further in all parts of the power system. The forecasts for storage and flexibility implementations are discussed thoroughly in the Nordic and national grid development plans [3], [4] and the role of ESS in distribution grids is visualized in Figure 4. By connecting ESS to distribution grids, in buildings and in communities the power system can benefit from the storage capacity in several ways as illustrated in Figure 4, by e.g., improved security of energy supply, more power and energy flexibility and increased hosting capacity for RES. It should be noted that the need and the possibilities for storage and flexibility applications will differ between transmission and distribution grids and will also differ between network areas.

Lastly, to summarize and form a baseline of the standpoint for the content and analysis found in this thesis, assumptions regarding the development of the energy transition are compiled in Figure 5. Climate awareness and adaptation will be more extensive worldwide and costs for electricity will be considered to a larger extent than before. The already ongoing electrification will remain being considered as a step in the right direction and the transport sector will continue its fundamental shift towards electromobility (e-mobility). Additionally, industry will increase their electricity demand but also contribute with electricity generation through e.g., gas-to-power (G2P) processes or local generation. Furthermore, as renewable energy technologies for generation and storage become more technically and financially available for the standard citizen, households will be considered as energy assets with both generation and storage possibilities. This will result in more devices being connected to the distribution grids and increase the technical challenges for DSOs in combination with the larger energy volumes fed into the distribution grids.

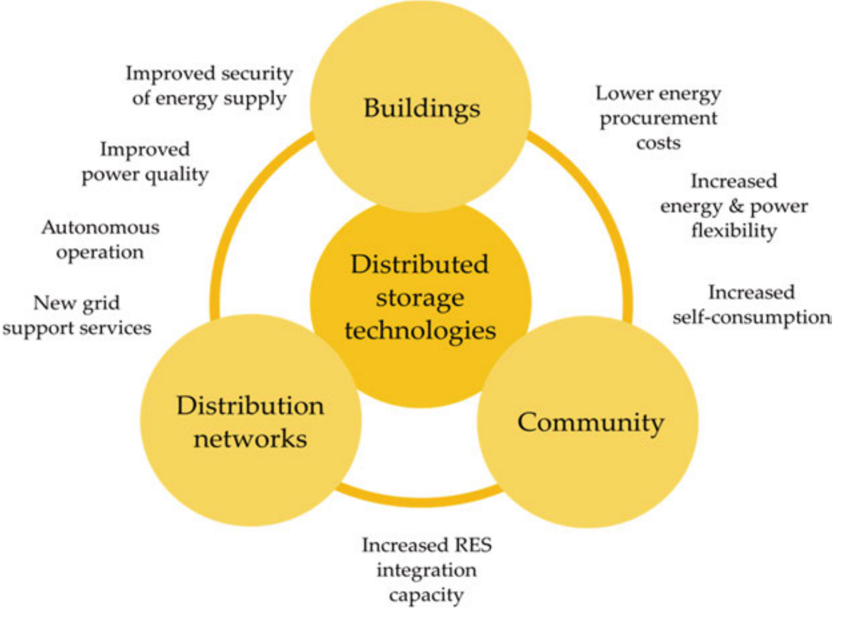

Figure 4. Overview of the role of energy storage systems in distribution grids.

Figure 5. Standpoint and assumptions regarding the energy transition.[3]

[3] This figure has been designed using images from Flaticon.com, by users "Freepik", "Wanicon", "Eucalyp", "bqlqn" and "Aldo Cervantes"

1.1 Research questions

Energy storage systems have been present throughout the power system for a long time using different technologies: from hydropower dams and pumped hydropower facilities that store vast amounts of energy, to smaller units using battery, flywheel or capacitor technologies which can be connected throughout the power system. Until recently, energy storage systems have too often been thought of as components that serve a single purpose – which has led to a discussion of energy storage as an enabler of many services but without financial motivation. In order to deal with some of the challenges that arise from the shift to a power system based on renewable electricity generation there is simply not possible to wait many years before markets for storage technologies mature. Instead, it is more relevant to consider use cases where several services are evaluated in the same service portfolio of an ESS, referred to as *service stacking*. This is a win-win situation as it increases the availability of the energy storage capacity for power system applications while also reducing the financial risk among investors. Thus, there is a clear motivation for why more research should be conducted in this field and answer questions regarding choice of technology, sizing, placement, portfolio design, operational strategies, storage degradation, distribution grid impact, etc.

Furthermore, parallel to the ongoing transition towards renewable electricity generation there is the electrification of the transport sector – which will have a significant impact on the power system and distribution grids. Business models and technical solutions for charging of electric vehicles are still developing, and at the municipality scale several interesting concepts that aim to improve the integration of electromobility to the distribution grids are being tested, e.g., the *mobility house* concept. Conducting research on how energy storage systems can enhance the integration of electric vehicles to distribution grids is highly relevant and should be carefully studied.

1.2 Aim of the thesis

This thesis studies energy storage systems in electrical grids for power distribution, with particular focus on use cases where service stacking is implemented. The main aim of this work is to illustrate, implement and evaluate use cases for energy storage systems connected to various parts of the distribution grid. It has been of special interest to investigate distribution grids with congestion issues, but also to study energy storage systems in the context of electromobility and offshore electricity generation.

1.3 Thesis outline

The first part of the thesis covers a theoretical background regarding power systems and energy storage technologies. Chapter 2 includes information about electricity generation, power transmission and distribution, together with stability and power quality aspects as well as ongoing trends. Chapter 3 presents available energy storage technologies and grid applications and services, partially included in **Paper I**. Furthermore, Chapter 4 focuses on service stacking using energy storage systems and is also part of **Paper I**. The fundamental problem and ideas regarding bundling of services are presented together with optimization theory, and Chapter 4 ends with a summary of the main results from the literature review in **Paper I.** Moreover, Chapter 5 covers the methods and results from **Papers II – VI**, where service stacking has been implemented for several cases with both technical and economic evaluation and includes both the development of a scheduling tool and co-simulation with a distribution simulation software where load flow simulations were executed. In Chapter 6, the methods and results from **Papers VII – IX** are presented and covers energy storage aspects in the context of electric vehicle integration and electricity generation from renewable energy sources. The discussion regarding the main results of **Papers I – IX** and the following conclusions are compiled in Chapter 7, and suggestions for future work are found in Chapter 8.

A summary of the appended **Papers I – IX** are placed in Chapter 9, and the Swedish summary of this thesis is found in Chapter 10. Finally, the author's acknowledgements are located in Chapter 11.

2. The electrical power system

Power systems can be divided into three main sections: *power generation,* where primary energy from e.g., elevated water, blowing wind or incoming solar radiation is turned into electricity; *transmission and distribution* (T&D), where the electricity is transmitted from the generators over long distances all the way to urban areas where people live or to industry facilities; and *the customers* that use the electricity. In this chapter, structural and technical aspects of power systems are explained in more detail together with evolving and ongoing trends with large impact on distribution grids primarily.

2.1 Electricity generation

The palette of available technologies includes conventional as well as more recently developed solutions. Figure 6 illustrates the most common available technologies and separates renewables from fossil sources. Considering the left-hand side of Figure 6, the renewable technologies consist of the bio and geothermal sources, the intermittent sources from wind and solar, and finally the three marine sources hydro-, wave- and tidal power. Considering the right-hand side, the sources based on fossil fuels can be divided in two major groups: those that use various forms of hydrocarbons (coal, gas, and oil), and nuclear power. It should be noted that according to the EU taxonomy and its complementary climate delegated act to accelerate decarbonization, during certain prerequisites, nuclear and natural gas can be accounted for as green energy [5]. The following part of this section briefly introduces the individual energy sources.

2.1.1 Hydropower

In mountainous regions with large differences in elevation, precipitation may result in water assembling and eventually forming rivers. Such rivers are used to run large turbines connected to generators that generate electricity. To create a more efficient and strategic electricity generation, dams are created where the vertical drop (drop height) is sufficiently high. When the control gate is open at the intake of the dam, water will flow through a tunnel (more known as the penstock) down to the turbine. When the water hits the turbine

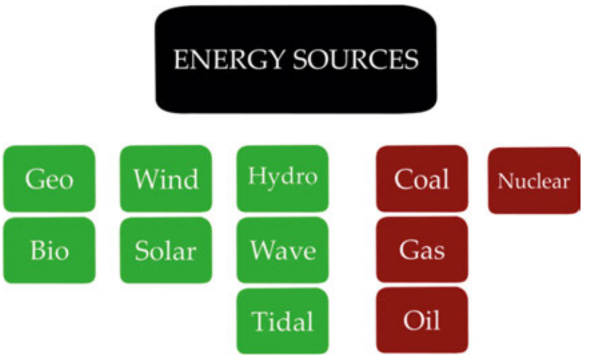

Figure 6. Energy sources, renewables in green and fossil in red.

blades, the turbine starts to rotate. The turbine is connected to a generator via a long shaft, and as the turbine rotates the generator starts to generate electricity. The installed power capacity in hydropower stations varies from small-scale stations (from a few kW up to 1 MW) to the largest power plants in the world with up to tens of GW. The stored water in the upper reservoirs is a very important energy storage since it enables hydropower to provide large amounts of regulating capacity to the power system. A hydropower station is illustrated in Figure 7.

Figure 7. Illustration of a hydropower station[4]

2.1.2 Wind power

One of the most promising energy sources is wind power. This natural source of energy has become very popular as the shift towards renewable electricity production started, since wind is available almost everywhere and it comes for free. To generate electricity from the flowing air, a high tower is placed in a windy area with a turbine and generator on the top, illustrated in Figure 8. The turbine is equipped with large rotor blades which are affected by the aerodynamic force from the flowing air. When the wind speed is high enough, the force on the blades will make the rotor turn. The turbine is connected to the generator via a long shaft, and as the turbine rotates the generator starts to generate electricity. At generation sites, wind power plants are commonly

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placed in groups forming *wind parks* or *wind farms* to capture as much of the kinetic energy from the wind as possible. Until recently, wind power generation has been focused mainly on land, but the wind conditions are very promising at sea as well. Therefore, large investments in offshore wind power are expected during the upcoming period and is further discussed in chapter 2.1.7 [3].

Figure 8. Illustration of a wind power park.[5]

2.1.3 Solar power

Another energy source that has gotten tremendous attention during the last two decades is solar energy. The energy from the sun is, just like the wind, accessible and available for everyone on the planet. The mission is to convert the energy emitted from the sun as radiation to useful electric energy in an efficient way. As of today, this is done using photovoltaic cells, commonly known as PV cells. The basic principle is built upon letting incoming radiation (photons) hit a semiconductor material, most often silicon, where electrons are excited which then give rise to a current. The PV cell consists of two differently doped silicon layers. The silicon layer facing the sun is doped with electron-rich atoms, known as n-type doping, and a common atom for n-type doping is phosphorous. The rear layer is doped with atoms that lack electrons, known as p-type doping, and a common atom for p-doping is boron. When these two layers are placed next to each other, a depletion zone is formed where electrons from the n-doped area move to the p-doped area. This also creates an electric field around the junction of the two materials, preventing further electrons from moving between the two sides without external excitation. Finally, as the PV cell is exposed to sunlight and incoming photons hit the front layer, electrons are freed (excited) and move through the depletion layer to the p-type layer. If the two silicon layers are connected via an external conductor, there will be a flow of electricity as the cell is exposed to sunlight. When creating a solar panel, several PV cells are connected in series to form strings, and several strings may form a PV panel, illustrated in Figure 9. The solar panels are then connected in various configurations to form PV systems

[5] Credits: designed by *petovarga*, published in Adobe Stock, used according to terms for standard license.

together with one or several inverters and a set of management and safety components. PV systems are expected to be one of the most used power generation technologies in the upcoming decades, see more about this in section 2.1.7.

Figure 9. Illustration of a solar power plant[6]

2.1.4 Marine, tidal and wave power

Marine energy sources use the energy from waves and flowing water in seas and rivers to generate electricity. First, the marine current energy converter uses streaming water in rivers and oceans to run a turbine which is connected to a generator, see Figure 10. The principle is like the one of wind power but occurs under the water surface. The targeted marine currents can be located in rivers with a significant water flow speed or large oceanic streams that occur naturally due to differences in water temperature. Furthermore, the tidal power plant has a very similar function as the marine current energy converters, but with the major difference that the direction of the water flow changes depending on the direction of the tide. The tide is a result of the gravitational interaction between the Earth and the moon, and is much easier to predict than e.g., wind, waves or incoming radiation from the sun that actually reach the surface of the Earth. Finally, wave energy converters (WEC) aim at converting energy from propagating waves in oceans or large lakes to useful electricity. The WEC design can be done in several ways, e.g., as point absorber buoys, surface attenuators or overtopping devices among many more. Two WECs are illustrated in Figure 11. The oceanic energy sources have one major advantage

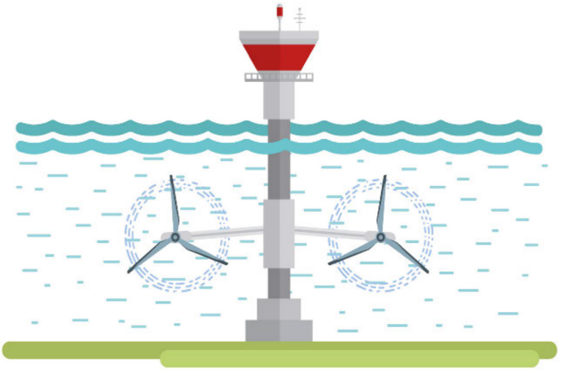


Figure 10. Illustration of a marine current power plant.[7]

[6] Credits: designed by *petovarga*, published in Adobe Stock, used according to terms for standard license.
[7] Credits: designed by *Oleksandr*, published in Adobe Stock,used according to terms for standard license.

compared to other renewables: the ocean and the rivers are available for energy conversion during a much longer period over the year. If an efficient energy conversion can be accomplished using these devices, the potential is extensive [6]–[8].

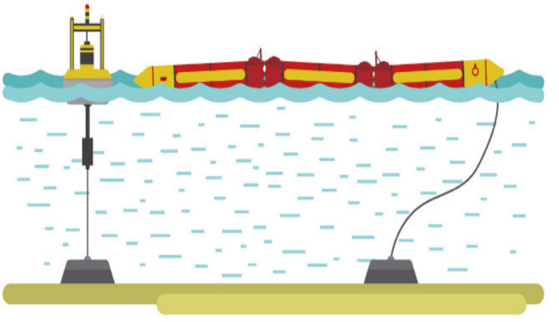


Figure 11. Illustration of two wave energy converters.[8]

2.1.5 Thermal power

One of the most common ways to generate electricity is to use heat in thermal power stations, illustrated in Figure 12. Heat is released when burning e.g., coal, oil, gas, biofuels, or waste which is used to boil a liquid e.g., water. The hot high-pressure steam is then used to run a steam turbine connected to a generator which generates electricity. The hot steam is then cooled in a separate tank or container, in larger power plants even in separate towers, before the low-pressure condensate is cycled back to the high-pressure vessel to begin another cycle. In general, all large-scale thermal power plants operate according to this well-known *Rankine cycle* with the condensate step at the end. There are several branches of thermal power plants, one of the most common is the combined cycle-gas-turbine which has several heat engines working in tandem using the same heat source. When burning e.g., natural gas directly in the turbine, the efficiency can be improved by using the released heat to boil water and run through another heat engine. Another common branch within thermal power is to use the waste heat as useful energy for e.g., district heating. These power plants are more commonly known as combined heat and power plants (CHP), since they provide both electricity and heat as useful energy.

Figure 12. Illustration of a thermal power plant.[9]

[8] Credits: designed by *Oleksandr*, published in Adobe Stock, used according to terms for standard license.
[9] Credits: designed by *petovarga*, published in Adobe Stock,used according to terms for standard license.

Also, a nuclear power plant is a type of thermal power plant that operates according to a similar thermal principle, but with a completely different boiling procedure.

2.1.6 Nuclear power

Since the 1950s there have been nuclear power plants operating globally, with Russia being the first nation to run a commercial power plant supplying a power grid, see illustration in Figure 13. The principle is built upon atomic fission, where a larger nucleus is subjected to striking neutrons and eventually splits into smaller nuclei. The fission reaction also results in large amounts of heat, which is used to boil water that is sent to a heat exchanger. The secondary medium is heated by the hot water and vaporizes, and the steam is used to run a turbine which is connected to a generator. It is well-known that this process comes at a high price: namely the risk of release of radioactive material. Therefore, the fission takes place in a large reactor which seals all possible radioactive material. The nuclear power plants have been a popular choice for baseline electricity generation in countries where coal/gas/oil are last-alternatives, and the other baseline generation capacity (e.g., from hydropower or wind power) is not sufficient to cover for the total electricity demand.

Figure 13. Illustration of a nuclear power plant.[10]

2.1.7 Forecasts of global electricity generation

Once every year the International Energy Agency (IEA) publishes a forecast of installed capacity and estimated electricity generation for the available energy sources, both from a global perspective but also per continent and country [1]. A global summary from year 2019 is presented in Table 1 (see page 17), and Figure 14 presents how the allocation between energy sources varies for continents and selected countries. Some of the most noteworthy highlights from Figure 14 are:

- China is expected to generate almost twice as much electricity by 2040 compared to 2018 and be the world's single largest producer of electricity with 10 000 – 12 000 TWh annually (more than three times the produced

[10] Credits: designed by *petovarga*, published in Adobe Stock, used according to terms for standard license.

electricity in the European Union in 2018). The main trend appears to be that wind, solar and nuclear are expected to replace fossil generation.

- United States, the European Union and Japan all remain at almost the same total generation levels but with a major re-allocation between energy sources. The common trend is that coal and natural gas is expected to be replaced by wind and solar energy, and to some extent by nuclear power in Japan.
- The remaining regions (India, Middle East, Africa, Central & South America, and Southeast Asia) are all expected to increase their amounts of generated electricity, and the generation mixes strongly depend on the chosen scenario. In the *stated policies scenario,* India, Middle East, and Southeast Asia will generate large amounts of electricity from coal and natural gas to meet the rapidly increased demand. In the *sustainable development scenario* though, a large share of the increased generation is allocated to wind and solar power instead.

Furthermore, if considering the European electricity mix in more detail it is worth pointing out the huge increase in electricity generated by wind power. By 2040 the energy from wind power is expected to cover for decommissioned generation from coal and natural gas, but also from nuclear to some extent. The increase in electricity generated from solar and biofuels is also important to account for but is much smaller than the expansion of wind power generation. Thus, with the information from Table 1 and Figure 14 it can be summarized that the European power system is expected to deal with very large amounts of variable RES, mainly from wind power generation.

Since the Nordic power system is not a part of the synchronous grid of continental Europe, it is interesting to compare the electricity mixes of the European Union and the Nordic countries. Figure 15 shows the expected development of the Nordic power system between 2020 and 2050. The forecast is an aggregation of the system development plans for the Nordic TSOs. From Figure 15 (a) it can be noted that the total electricity generation is expected to increase by at least 200 - 300 TWh the upcoming 20-30 years and it is expected to be covered mainly by wind power, solar and nuclear. Also, the installed capacity from renewables is illustrated for the period 2020 and 2040. One noteworthy aspect to consider from Figure 15 (b) is the development of offshore wind power, where the capacity is expected to increase from almost 0 GW to 35 GW producing around 100 TWh per year [9].

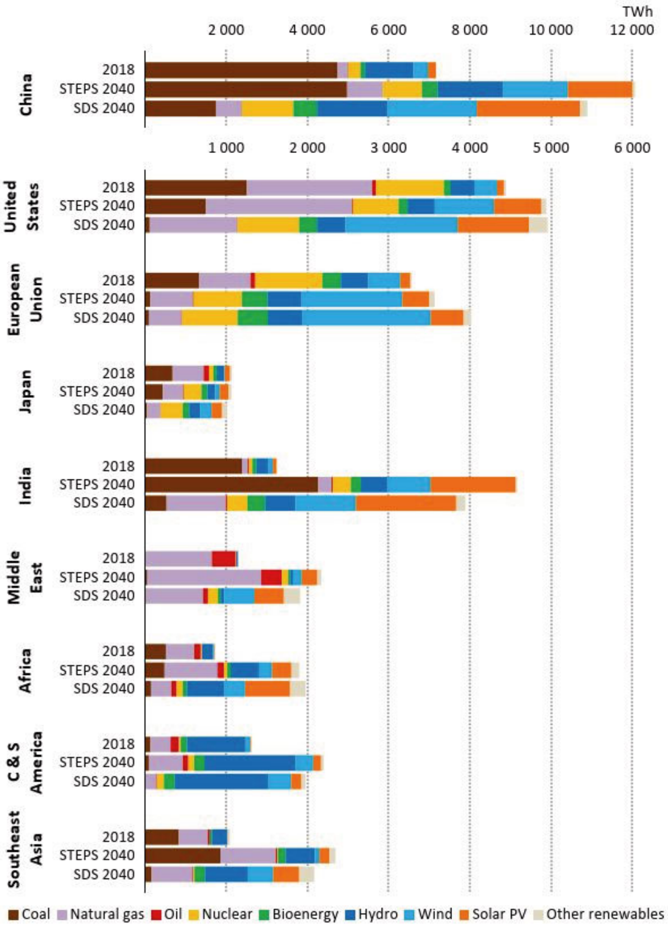


Figure 14. Global electricity generation per region (TWh) [1].

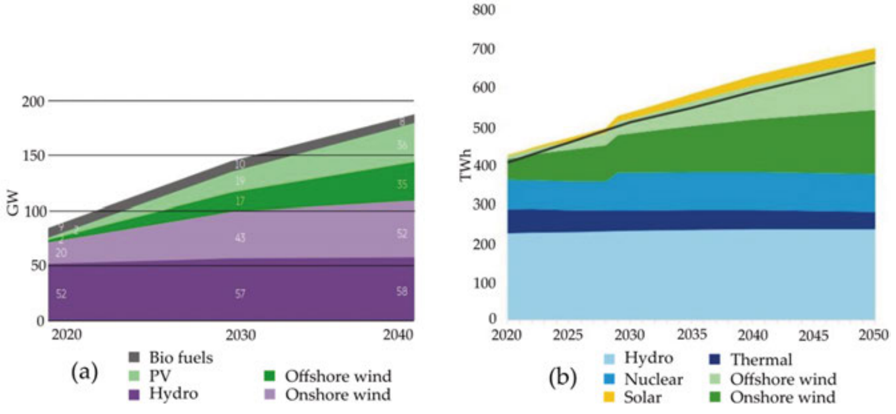


Figure 15. Installed RES power capacity and electricity generation in the Nordic power system [3], [9].

2.2 Transmission and distribution

Since electricity is not generated at the same location as the end users, infrastructure for transmitting the power is required. This infrastructure is usually divided in two major groups: high-voltage transmission grids and distribution grids. There are also sub-groups of each category, e.g., sub-transmission grids, primary and secondary distribution grids etc., but these are the two most common groups. They are defined and characterized according to their nominal voltage rating, visualized according to Nordic standards in Table 2. In this section, these grid structures and the projections of energy flows will be covered in more detail.

2.2.1 Transmission grids

The transmission grid is the part of the power system that deals with long-distance bulk energy transfer and connects the large power plants with the distribution system. The purpose of the transmission grid can be boiled down to three main aspects: (1) to transfer generated electricity from the generators to the rest of the power system, (2) enable energy interchange between utilities and markets, and (3) supplies the distribution system with enough power according to the downstream demand [10]. To enable high-efficient transport of electricity, the transmission grids are dimensioned for high, extra-high or ultra-high voltage levels up to or higher than 1000 kV. A handful of TSOs worldwide have already or plan to invest in power lines operating at 1000 kV and even 1100 kV (both DC and AC) to achieve even more efficient transmission across very long distances, e.g., in China, India, Russia, Brazil and the USA. Some of these ultra-high voltage power lines are already in place but are sometimes operated at lower voltage ratings (400-750 kV) since the electricity demand downstream is not high enough.

A typical transmission grid could be the Nordic transmission grid, which is visualized in Figure 16 [4]. In Figure 16, the largest generators, substations, and powerlines are marked and a few lines and cables under construction are also included, see the legend of Figure 16 for exact details. The Swedish transmission grid is coloured in green in Figure 16 and consists of around 16 000 km of power lines operating at 220 and 400 kV. To balance the power flow between regions, each country is divided into bidding areas and are visualized in Figure 17 [4]. From Figure 17 it can be seen that some countries e.g., Finland, Estonia, Latvia, and Lithuania have one bidding area only, while Norway and Sweden have 5 and 4 bidding areas respectively. As of today, the overall power flow has a south-going direction from the northern regions where most of the large power plants are located, to the larger cities and urban areas in the southern parts of the Nordic countries.

Table 2. Grid levels and their typical nominal voltages.

Grid level	Transmission						Subtransmission			Primary distribution				Secondary distribution
Swedish notation	*"Stamnät"*						*"Regionnät"*			*"Lokalnät"*				
Nominal voltage (kV)	1150	1000	800	400	220	132	66	45	33	22	11	6.6*	3.3*	0.4 / 0.23
Voltage notation	*Ultra-high & extra-high voltage*					*High voltage*								*Low voltage*

* Industry grids

The rapid plans for electrification of industry and transports in combination with increased shares of distributed generation in the southern parts of the Nordic region will affect the general power flow direction [3]. For some bidding areas it is expected to change significantly, and the expected changes of the annual energy flow in the Nordic power system are visualized in Figure 18. The vector arrows in Figure 18 show the annual energy flow between bidding areas (TWh/year), indicating both magnitude and direction. As illustrated in Figure 18, some of the major expected changes concern the following bidding areas:

- SE1 – Expected to go from large exporting to large importing area mainly due to expansion and electrification of industry.
- SE3 – A much more bidirectional flow is expected against NO1 and SE4 due to big changes of the internal energy balances. NO1 and SE3 are and are expected to become even more dependent on import capacity from neighbouring areas.
- SE4 – There are plans for extensive connection of offshore wind power in SE4, and large energy volumes are expected to be transferred to DK1 and possibly SE3.
- DK1 – Also expected to become a net-exporting bidding area due to extensive connection of wind power generation.

The Nordic power system is an alternating current (AC) system operating at an electrical frequency of 50 Hz. There is a number of active high-voltage direct current (HVDC) links that connect the Nordic power system to nearby synchronous areas, but also a few of the Nordic bidding areas, see Figure 16. Ultra-HVDC (UHVDC), traditional HVDC and HVDC light are the three most implemented DC technologies today and are becoming increasingly common in long distance transmission. There are several factors speaking for DC transmission as a more effective choice than AC transmission, and examples of these are:

Figure 16. The Nordic transmission grid and interconnections to neighbouring countries [4].

Figure 17. Bidding areas in the Nordic power system [4].

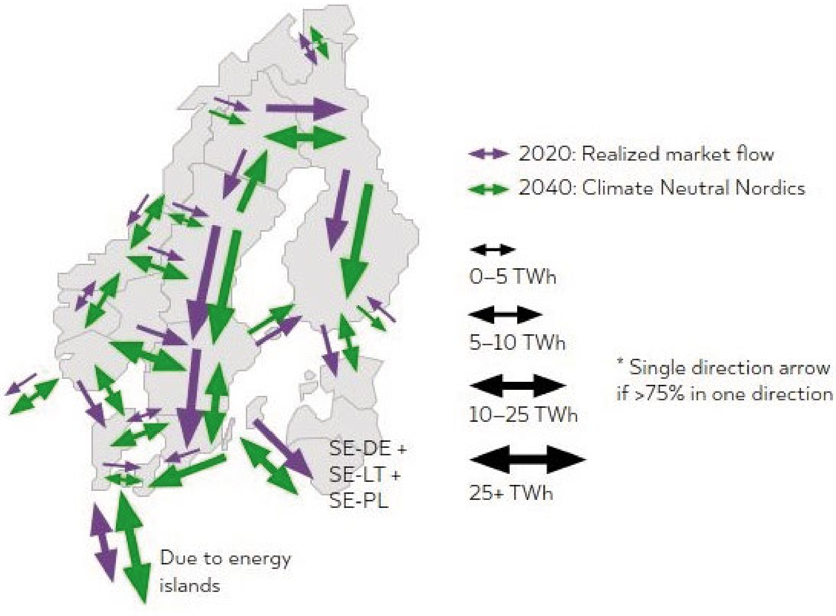


Figure 18. Annual energy flow in the Nordic power system in 2020 and 2040 [3].

- The right-of-way (ROW) for DC transmission is significantly less than for AC, i.e., the corridor space required for the towers and power lines. Reducing the land needed for transmission infrastructure is desired in highly populated areas, but also beneficial for the environment due to the reduced impact on the nature in the region.
- DC systems require fewer cables (two for DC compared to three for AC), reducing the transmission losses significantly. This aspect becomes important for long distance transmission.
- More efficient use of conductors: DC uses the entire section of the conductor while AC only use the peripheral section (due to the skin effect). This implies that DC can transmit 30-40 % more electricity in the same conductor.

Although, DC substations and converter technologies are still more expensive compared to conventional AC components. This results in higher investment costs for DC systems, but due to a more efficient transmission using DC there is a break-even point when comparing the costs for the two systems as a function of distance. The break-even distance is not fixed and changes as the markets and technologies for AC and DC transmission evolves but is around 500 km as of today, after which DC systems are more cost efficient [11].

2.2.2 Distribution grids

The distribution grids are the outermost part of the power system where the end users, industry and some distributed power plants are connected. Compared to the transmission grid, the operating voltage of distribution grids is significantly lower and thus the length of lines and cables are typically much shorter as well. The distribution grids are characterized by a large number of cables and lines, substations, components for power quality improvement and protection etc. In year 2022, the total length of the Swedish distribution grid (low and medium voltage grids) was estimated by Swedenergy (*sv: Energiföretagen*) to 540 000 km, including both ground cables and overhead lines[11]. They are also characterized by its geographically distributed units and the variety in scale: from large-scale power plants inside or on the outskirts of cities (typically CHP plants) to small-scale rooftop solar generation; from large industries with high power demand to small households and communities on the countryside; from urban city grids with underground cables to long-distance rural grids with overhead lines and island grids in the archipelago by the coast. These are just a few of many aspects that illustrate the large variety of scale, context, and environment within distribution grids. Figure 19 illustrates a typical electrical grid including the generation, transmission, and distribution grid.

Unlike the transmission grids, there is no single operator like the TSO who is responsible for all distribution of electricity in a country. Most commonly, every country (or state) is divided into network areas in which one DSOs are responsible for the distribution system i.e., has jurisdiction. This is known as *distribution concession* (also *concession agreements*, or just *concession*) i.e., the DSO has the sole right to implement, design and operate a distribution grid within the network area. It should be noted that the concession can be shared in a network area as well, if the concession owner sells (or leases, but maybe not as relevant in this context) shares of the contract or the entire contract to another DSO to operate a distribution grid in the same network area. This creates an opportunity for smaller local DSOs to emerge and is good for business and entrepreneurship to blossom. Furthermore, another major difference from the transmission grid is the level of digitalization. The distribution grids have traditionally been and are still much less digitalized and less monitored than the transmission grids, even though there is an on-going digitalization of distribution grids [12]. Thus, it is important to make sure that the equipment and infrastructure works and are operated safely when non-monitored.

Distribution grids may look very different depending on the size of the network area, the type of customers and the number of connected customers etc. Thus, every network area is unique, but they all have in common that there is

[11] Swedenergy, https://www.energiforetagen.se/ (Accessed 2023 09 26)

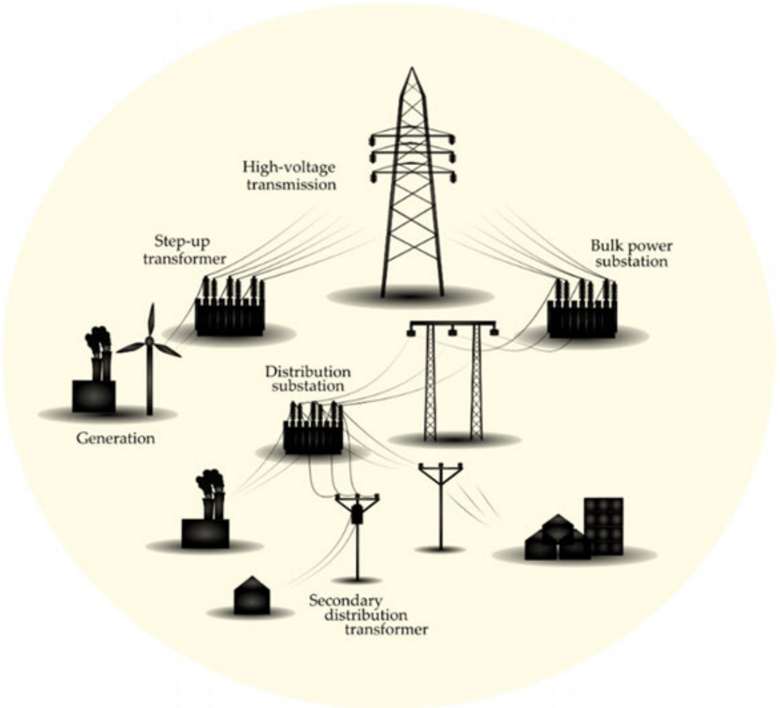
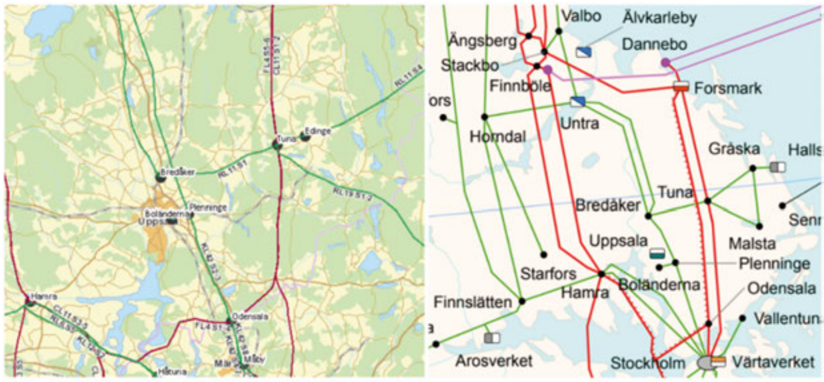


Figure 19. Illustration of a typical electrical grid with generation, transmission, and distribution.

a lot of equipment and infrastructure to keep track of. In a single network area, there are a large number of substations and transformers which step down the voltage from the high voltage to medium and low voltages like a ladder as the distance to the end users decreases. To ensure the safety and stability during operation and during fault events, extensive safety and protection systems are included throughout the distribution feeders. Also, there is a large catalogue of other devices which can be found in distribution grids for e.g., power quality issues (capacitor banks, voltage regulators, harmonic filters), electricity meters at end users and substations, distributed transformers, switching stations, lightning arresters, reclosers, network protectors and many others. According to Table 2 and Figure 19, the distribution is done in two main stages: first by *primary distribution* ranging from the primary substation which connects to the transmission grid, down to the secondary substation where the *secondary distribution* begins. It consists of the low voltage grid and reaches all the way to the end-users. Starting with the primary distribution, it starts with the step-down from high to medium voltage at the primary substation. Each of these distribution substations may supply several distribution feeders of varying size, depending on the civilization in the region. It could also be the opposite (which is also common), where one region has more than one primary substation. Taking Uppsala as an example, there are two large



(a) (b)

Figure 20. (a) Map of Uppsala with incoming power lines and substations marked, (b) one-line diagram of the grid in the region [13].

primary substations supplying the city with electricity, shown in Figure 20. The purpose of the primary distribution is to transmit the electricity from the primary substation to the secondary substations as efficiently as possible, but also connects some industry customers on the way down to the secondary substation. In this part of the grid, it is common to use both overhead lines and underground cables depending on the level of built environment. Overhead lines are more common in rural areas meanwhile underground cables are more frequently used in larger cities and urban areas. When reaching close to the end users, the secondary distribution takes over at the secondary substation and the voltage is stepped down even further. The low voltage grid is the final part of the distribution grid, and the European secondaries usually have voltage ratings of 380/220 V, 400/230 V (which is the Nordic standard), or 416/240 V (values expressed as line-to-line/line-to-neutral).

Another important aspect to keep in mind when comparing transmission and distribution grids is the location of infrastructure. Since transmission grids operate at very high voltage, it is important to minimize the risk of unauthorized human interaction with the infrastructure due to the danger of high-voltage equipment. Additionally, they cause strong electric and magnetic fields that affect the surrounding which demands increased safety and distance to humans and wildlife. Also, it is desired to build transmission grids as short as possible due to both electrical and economical aspects making it a win-win situation to build transmission grids far away from built environment. Distribution grids on the contrary are more or less required to be located in the same environment as civilization since this is where the power demand is located. The medium voltage grids are commonly seen on the outskirt of cities, and low voltage overhead lines can be seen close to roads and crossing fields on the countryside.

Traditionally, distribution grids have been designed mainly as radial feeders or by combining radial branches and loops - forming meshed network grids. Figure 21 illustrates the designs for two very small and simple grids of a radial and a meshed feeder. The classical radial tree is shown to the left and is a straight-forward design where every customer is connected directly to the main branch which is the only supplying feeder to all customers in that area. The level of complexity is low in this type of network regarding many aspects, e.g., power flow analysis, fault calculations, protection design etc. One major drawback with the radial design is the low reliability due to the single-feeder-supply. If a radial feeder is disconnected, all customers downstream the fault or the point of disconnection will be affected – which is very inefficient. A meshed design increases the reliability significantly since the power supply can be achieved from two or more feeders. In general, the meshed grid is a more complex structure and less intuitive to predict but comes with several benefits, mainly regarding increased reliability and reduced power losses and possibly reduced need for voltage regulation as well. It may also require a smaller number of cables and lines depending on the geographical location of the customers compared to a radial grid. The reliability aspect of different configurations further explained in chapter 2.3.4.

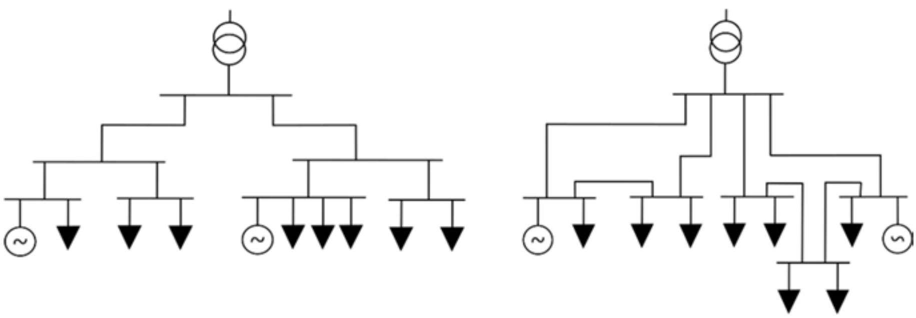


Figure 21. One-line diagram of two typical distribution feeders with a radial design (left) and mesh design (right) with a few loads (triangles) and distributed generators (circles with ~) connected.

More advanced grid designs have characteristics which origin from multiple designs and are typically implemented in active distribution networks (ADN), also known as smart distribution networks (SDN). A more complex distribution grid design is visualized in Figure 22. It illustrates a SDN with a selection of components and shows the distribution feeder from the primary substation down to the low voltage grid. These are complex networks with very high reliability and include radial, meshed and loop structures which are actively managed by the DSOs distribution management system (DMS) and live communication between components. The SDN may have a reconfiguration tool implemented, making it possible to reconfigure the operation of individual

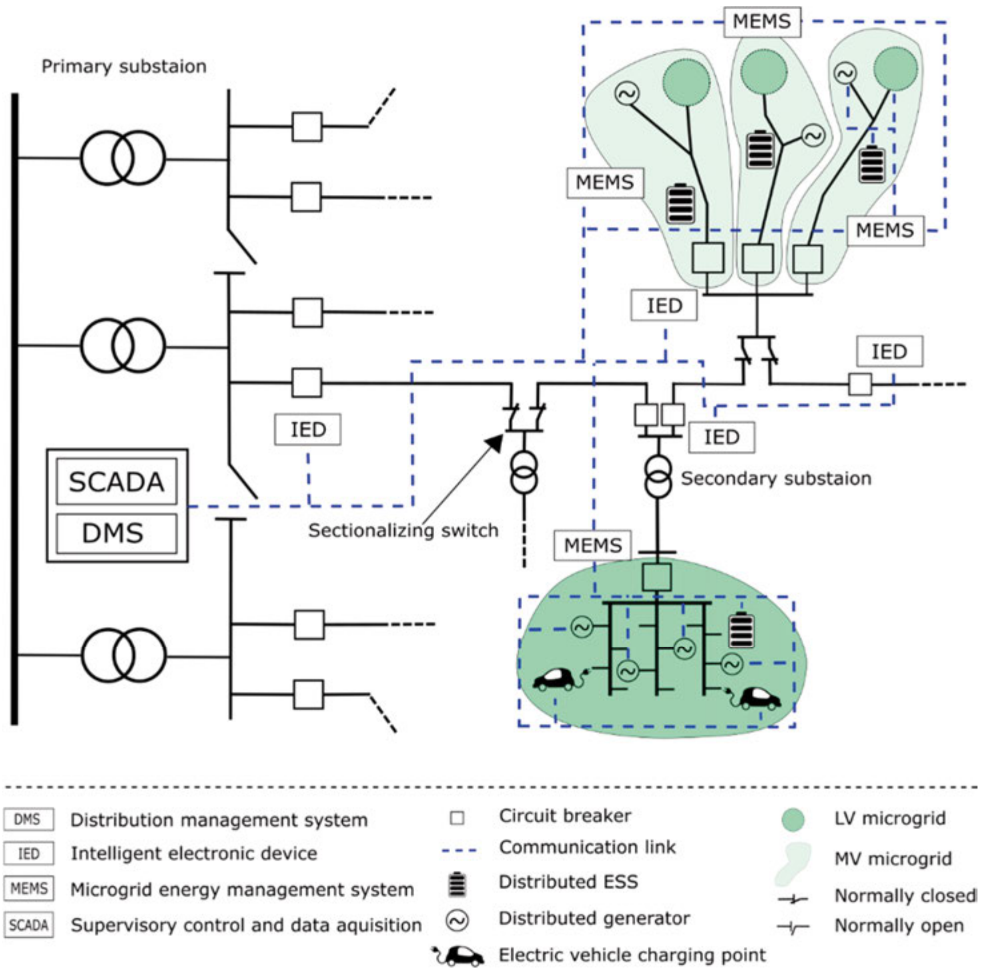


Figure 22. One-line diagram of a complex smart distribution network (SDN), re-worked with inspiration from [14].

branches within the feeder to improve the distribution quality. The grid reconfiguration tool requires automatization and proper communication throughout the grid, but if done frequently it may also lead to increased risk of failures. Therefore reconfiguration is most properly implemented together with other tools e.g., ESS and voltage control/reactive power control [14]. A few interesting things are illustrated in Figure 22: firstly, it can be seen that both low-voltage and medium voltage microgrids are present. They are connected to the feeder via sectionalizing switches, which usually operate in closed mode i.e., the connection to the main grid is established. When island-mode is desired in an area, the switches are opened and the local microgrid energy management system (MEMS) controls the local generators, ESS, protection devices and other components according to the new operation mode. When leaving island mode, the switches are flipped to closed mode again. The presence of microgrids in future distribution grids is expected by many [15]–[20], and the concept is explained further in section 2.5.4. Another important difference compared to the traditional distribution grid is the level of communication and flow of information throughout the system. In the SDN, management systems are present in different parts of the grid which communicate and interpret data continuously to optimize the local energy system. In Figure 22 there are a number of intelligent electronic devices (IED) which are linked to the regional distribution management system (DMS) and to the SCADA system (Supervisory Control and Data Acquisition). The SCADA and DMS are also linked to the MEMS to enable coordinated operation of all parts of the grid. The IED is the hardware attached to the component of interest which communicates with the central units of the SCADA and DMS systems. It usually consists of a signal transmitter and receiver, an analogue-to-digital-converter, and a microprocessor with digital signal processing.

The traditional distribution grid is designed for a one-way power flow from the primary substations all the way down to the end users, with few connections of local or regional power plants. Considering Figure 22, the landscape of distribution grids is changing with the increasing number of communication devices, EVs, solar PV systems and ESSs. Many conventional passive components are not designed for dynamic grids and bi-direction power flow which is an increasingly common phenomena when distributed generators during a period generate more electricity than the local demand. In these cases, distributed generation may become problematic and cause problems in MV/LV transformers, i.e., causing over voltages but also affecting the ability of voltage regulation. Most commonly, issues arise in long radial feeders or weak grids, which are characterized by high impedance and low short circuit power. Although, there are several available tools to prevent voltage variations from distributed generators, e.g., shunt capacitor banks (fixed or switched) and ESS. When evaluating distributed generation in distribution grids, five standard key performance indicators (KPI) are commonly used:

- *Voltage:* when distributed generators inject power to the grid they affect the grid voltage, and this may create distortions of the voltage level and also affect the voltage quality. Thus, regulating devices could be affected and flicker or harmonics may cause effects on the power quality. It is therefore important to evaluate how the voltage is affected by distributed generators.
- *Capacity:* during peak load hours it is desired to reduce stress on components, and if the distributed generation profile matches the load in time, the generators may supply some of the demand and reduce the need for power distribution from the primary substation. This could also be used strategically for investment and network upgrade deferral.
- *Energy:* by connecting local power generation, the need for distribution is reduced and thus the distribution losses are reduced as well. This depends

on mainly two things: firstly, due to the reduced distance between the generator and the load, and secondly due to the potentially increase in voltage level at the location of the generator, which decreases the current and thereby also the losses.
- *Reliability:* the reliability of distribution grids could be affected by connecting distributed generators, namely by supplying power to the local load(s) if there is a fault upstream. This probabilistic resilience is difficult to both quantify and evaluate due to the randomness of faults and variable generation from RES.
- *Protection:* one of the most important KPIs to evaluate is how the protection is affected and the ability to maintain a safe system. Large shares of distributed generation may affect the protection system and devices by e.g., increasing the short circuit current, causing maloperations of local protection equipment and possibly nuisance fuse blowing.

Finally, the distribution grids deal with one-phase connections and balancing these is a challenge for DSOs but is handled with high precision according to the standards defined by the Swedish Energy Markets Inspectorate (EI). The distribution grids are also very sensitive to local power quality issues and require a continuous proactive work to reduce the impact from e.g., charging infrastructure for electric vehicles, residential PV systems and other power electronic devices that may cause distortions in the local power quality. In this part of the grid, the power flow can vary significantly during periods as well and voltage regulation is essential. Thus, load tap changers on transformers and voltage regulators are useful tools which adjust the voltage level in the grid when the deviation from the nominal voltage is becoming large. Power quality and reliability aspects are further discussed in upcoming sections.

2.3 Stability and power quality

To ensure a high power quality and a stable operation within electrical transmission and distribution grids, carefully selected indicators and variables have been selected to be monitored and also been given acceptance limits. In this chapter, a selection of the most relevant stability, reliability and quality measures are covered. Power system stability can be divided into three main topics: *frequency stability*, *rotor angle stability* and *voltage stability*, and is illustrated in Figure 23. To ensure a stable power system operation, these three stability aspects have to be maintained at all times.

2.3.1 Frequency stability

In all electrical AC grids, there must be an instantaneous balance between generation and use of electricity. Imbalances result in changes of the electrical

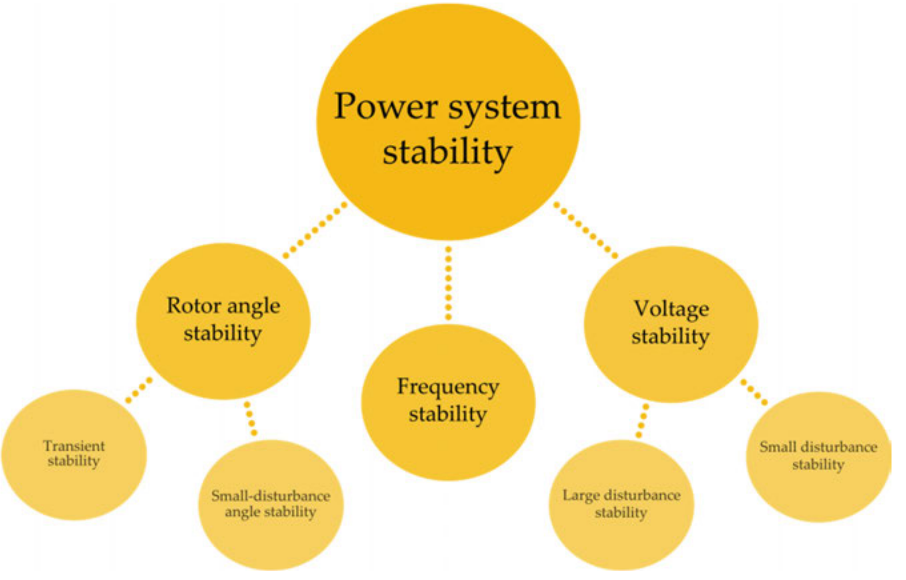


Figure 23. Power system stability aspects.

frequency of the grid, and too large deviations from the nominal value will result in large-scale blackouts. In the Nordic synchronous area and in the continental European grid, the nominal frequency is 50 Hz. Although, in USA and parts of Asia and South America the nominal frequency is 60 Hz. The relationship between power balance and electrical frequency is given by eq. (2.1), which is a paraphrase of Newton's 2nd law for rotating mass:

$$P_{prod} - P_{cons} = J_{eqv}\omega_{el}\frac{d\omega_{el}}{dt} \tag{2.1}$$

, where P_{prod} is the power generation (W), P_{cons} is the consumed power (W), J_{eqv} is the equivalent grid inertia (kgm^2), ω_{el} is the electrical angular velocity of the grid (rad/s) and $\frac{\omega_{el}}{dt}$ is the time derivative of the electrical angular velocity at the given time t. The relation between ω_{el} and the electrical frequency f_{el} is given by eq. (2.2) as

$$\omega_{el} = 2\pi f_{el} \tag{2.2}$$

The right-hand side of eq. (2.1) illustrates how the electrical frequency and it's time derivative depends on the power balance shown on the left-hand side. A decrease in generation or increase in consumption results in a negative balance and forces the time derivative term to be negative as well, and the frequency drops. The opposite happens when the power balance is positive. The right-hand side also includes the equivalent grid inertia term J_{eqv}, where the inertia counteracts the rate of frequency changes. Large power plants with heavy rotating machines contribute to the grid inertia with their rotating mass. It is desired to keep the rate of change of frequency (RoCoF) low to avoid fast changes of the grid frequency and to favor regulating mechanisms. Most RES are grid connected through power converter technology, and as of today most these devices do not contribute to the grid inertia due to the grid following control strategy. Thus, the inertia risks dropping low as the generation mix shifts towards increased shares of RES. Although, research is conducted on grid forming control strategies for these converters to increase the equivalent grid inertia from RES.

Breaking down frequency stability into subgroups, it depends on mainly the properties of the grid, the implemented frequency control and disturbances affecting the grid. Considering the properties of the grid, inertia and damping are both vital to preserve. The Swedish TSO Svenska Kraftnät (SvK) forecasts a reduction of inertia within the Nordic synchronous area, from about 300 GWs in 2020 to 150 GWs in 2040. The kinetic energy of the Nordic power system for the years 2020 to 2022 is shown in Figure 24. By observing the trend lines in Figure 24 it is clear that the inertia reaches its annual minimum during the summer when the large nuclear power plants have their maintenance period. Furthermore, the frequency control is managed by the TSO and consist of a bundle of services operating in different time scales. The fastest services are activated within one second and the slowest reserves are activated fully within 15 minutes to fully restore the frequency when needed.

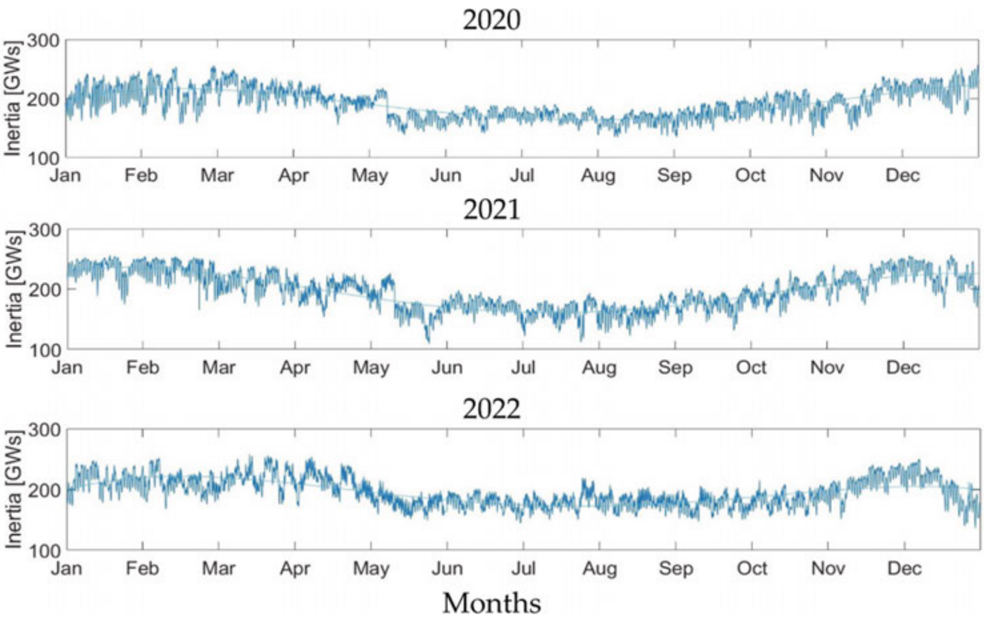


Figure 24. Variations of the inertia of the Nordic power system for the years 2020 – 2022. Data is publicly accessible at Fingrid open data database.

Finally, the magnitude and dynamics of grid disturbances are also crucial to consider. It is necessary that the power system remains stable when large generators, power lines or loads are disconnected. Thus, a common method is to design the system according to the largest dimensioning fault, i.e., the disconnection of the largest (highest rated) generator, transmission line or load. In the Nordic grid, the currently largest unit is the nuclear reactor Oskarshamn 3 rated at 1450 MW. Thus, the grid should remain stable when this reactor has to be disconnected or trips. Also, oscillating disturbances may occur and affect the grid frequency. Larger deviations can be avoided by ensuring sufficient damping properties of the grid.

Detailed market specifications for each service are discussed further in Chapter 4.2.

2.3.2 Rotor angle stability

In AC grids, rotating machines can be operated either synchronous or asynchronous compared to the grid. It is important that all synchronous machines remain synchronized even when disturbances occur, which more known as rotor angle stability. The rotor angle stability is usually split into transient stability and small disturbance angle stability, also illustrated in Figure 23. The transient stability is related to the larger disturbances within the power system, e.g., disconnection of large generators or loads or extensive faults. If such would occur, the power system should remain stable and the rotor angle dynamics is coupled to the electrochemical oscillations that arise [21]. Furthermore, the small-disturbance angle stability (also known as small-signal stability) describes a power systems ability to withstand oscillating disturbances. This is correlated to the inertia of the grid, where oscillation speed is reduced with increased inertia (i.e., the damping ability increases with increased inertia) [21].

2.3.3 Voltage stability

Each time a connected customer in a distribution grid changes its electricity use, there will be a small deviation in the local grid voltage. Since no one controls when these changes occur in time and how large they are, the electrical system must be robust enough to handle these deviations that happen continuously. Therefore, each DSO must guarantee that the defined voltage stability criteria are fulfilled, and the criteria are divided into several sub-groups. They specify allowed limits and regulations regarding short, long, and rapid voltage deviations, and also limits for harmonic content and asymmetries. From the Swedish context, the regulations are defined by the Swedish Energy Markets Inspectorate and the latest version was revised in 2013. There is an ongoing revision of the regulating document, and the updated regulations will be valid from January 2024. A selection of the most relevant regulations is presented in this section.

Short voltage changes: short-term voltage raise is defined as a temporary change of the effective value of the voltage (RMS) that exceeds 110 % of the nominal voltage. On the contrary, a short-term voltage reduction is defined as a temporary change of the RMS value of the voltage to a level less than 90 % of the nominal voltage. According to the Swedish regulation, there shall be no lasting effects after short voltage reductions according to those stated in [22]. This is valid for nominal voltage ratings up to 45 kV. Similarly, there shall be no lasting affects after short voltage raises, also according to [22], and is valid for nominal voltage ratings up to 1 kV.

Long voltage variations: voltage variations with longer lasting deviations are also regulated, and over a period corresponding to a week the 10-minute RMS values of the voltage should remain within 90 and 110 % of the nominal voltage rating.

Rapid voltage changes: rapid voltage changes are defined as a change of the RMS value of the voltage which is faster than 0.5 % per second, and where the RMS value is within 90 and 110 % of the nominal reference voltage before, during and after the deviation. Fast changes are determined by the stationary and maximum voltage changes, and the sum of rapid changes and short-term voltage reductions should not exceed the limits in [22]. Rapid voltage changes are also known as *flicker,* which can be observed by the human eye e.g., as fast changes in brightness in lamps.

Voltage asymmetry: in a three-phase AC system, voltage asymmetry is defined as the deviation between phases and includes deviations in both magnitude of the RMS values and phase angles. Over a period corresponding to a week, the 10-minute RMS values must be less or equal to 2 %.

Harmonics: in an electrical AC grid, the current and voltage are sinusoidal signals, and the main components alter according to the nominal frequency (also known as the fundamental frequency). There are also components of the current and voltage which are sinusoidal signals where the frequency is an integer multiple of the nominal frequency. These signals are grouped and known as harmonics, and if the harmonic content is high enough it will cause power quality issues resulting in e.g., heating in components and cables or distortions in motor and generator equipment. Most often, current harmonics arise due to the presence of non-linear loads (e.g., power electronic devices), which may draw current which is not perfectly sinusoidal (or not necessarily sinusoidal at all). The distortions of the current give rise to voltage harmonics due to source impedance of the voltage source. Most commonly, the harmonics are divided into groups of odd and even multiples of the fundamental frequency, and triplen harmonics are especially important to keep small (i.e., the 3rd, 9th, 15th harmonics etc.) among the odd ones. The allowed harmonic content in the grid voltage is regulated both by the level of each harmonic and by the total harmonic distortion (THD). The total harmonic distortion of the grid voltage is calculated according to Eq. (2.3)

$$THD_U = \frac{\sqrt{\sum_{i=2}^{n} U_i^2}}{U_1} \tag{2.3}$$

, where U_i is the magnitude of harmonic of order i, and U_1 is the nominal voltage. The harmonic content of the current is calculated in the same way by replacing the voltage values by the current values in Eq. (2.3). Over a period corresponding to a week, the 10-minute values of the THD_U should be less than 8 %, and during the same period the 10-mintue values for each individual harmonic U_i should be less than the limits presented in Table 3. It can be seen that the allowed harmonic content from even harmonics is significantly less than for odd harmonics since these are crucial to keep low. From Table 3 it is also clear that the allowed harmonic content from the triplen harmonics is much less than the other odd harmonics.

2.3.4 Reliability

For DSOs, ensuring a high reliability of the grid is of highest priority. Each minute when a connected customer is without electricity supply is costly and should be minimized. To achieve a distribution grid with high reliability and resilience, a number of parameters should be considered:

Table 3. Limits for harmonic distortions in distribution grids.

Odd harmonics				**Even harmonics**	
Non triplen harmonics		**Triplen harmonics**			
Harmonic order	Relative harmonic content (%)	Harmonic order	Relative harmonic content (%)	Harmonic order	Relative harmonic content (%)
5	6.0	3	5.0	2	2.0
7	5.0	9	1.5	4	1.0
11	3.5	15	0.5	6 - 24	0.5
13	3.0	21	0.5		
17	2.0				
19	1.5				
23	1.5				
25	1.5				

- Robustness of the grid infrastructure
- Time to locate, isolate and restore the grid during a fault event
- Accessibility of lines, cables, and substations
- Redundancy within a restricted area

The above-mentioned parameters describe some of the challenges that DSOs face when planning and operating their grids. Robustness is the property describing to what extent a grid is able to handle an unforeseen event without losing performance. There are several related concepts to robustness, mainly vulnerability and resilience. The vulnerability is the lack of robustness, i.e., the opposite concept. Resilience on the other hand describes how well a power grid is able to recover after an unexpected event with low probability but high impact. Ensuring robust feeders and substations is one of the main tasks for the DSO, and it is also desired to have a high resilience. By achieving both of these properties, the grid is robust against unexpected events and quickly recovers to its nominal operation [23].

Furthermore, the time aspect is very important in this matter. In passive and analogue distribution grids it can take long before a fault is located, and the restoration process can begin. In grids with more digitalized monitoring, it is easier to locate the fault thus saving important time. But the time required for repairing the grid is also dependent on the level of accessibility of lines, cables, and substations – e.g., it will be more demanding to repair underground cables than overhead lines, and substations in rural areas will be more time demanding to reach than those in urban areas due to longer distances. To evaluate the performance of the grid reliability, a few well-known reliability indices are considered annually and compared to previous years and between DSOs. A selection of the most common indices is presented in Table 4.

Table 4. Common reliability indices.

Metric	**Explanation**	**Formula**
SAIFI	System Average Interruption Frequency Index	$\frac{\sum \lambda_i N_i}{N_T}$
SAIDI	System Average Interruption Duration Index	$\frac{\sum U_i N_i}{N_T}$
CAIDI	Customer Average Interruption Duration Index	$\frac{\sum U_i N_i}{\sum \lambda_i N_i}$
ASAI	Average Service Availability Index	$\frac{\sum N_i \times 8760 - \sum U_i N_i}{\sum N_i \times 8760}$

N_i – Number of customers at location i

N_T – Total number of customers

U_i – Annual outage time for location i

λ_i – Failure rate

Finally, the DSO can also increase the redundancy of a feeder by adjusting the grid configuration. There are a number of common feeder configurations based on the conventional design principles. A selection of such is presented in Figure 25, and shows five different configurations for distribution feeders:

- *Radial network:* All customers are connected to the same main feeder, which is the only feeder available. The customers have no interconnections on neither MV nor LV side.
- *Primary loop:* All customers are connected to the same local main feeder which creates a loop back to the main distribution feeder. The loop configuration is equipped with switches between all branches to ensure the reliability if the loop has to be broken, but the grid is commonly operated as radial.
- *Primary selective network:* All customers are connected to the same main feeder, but also to a second main which can be used if the main feeder has to be disconnected.
- *Secondary selective network:* All customers are connected to individual distribution transformers but are also connected to a secondary feeder on the low voltage side in case one of the main feeders has to be disconnected. In this case, the transformers have to be dimensioned according to the total possible load downstream. These are common in areas with high load density, e.g., large cities.
- *Spot network:* All customers are connected to the same LV bus, which is a common design in e.g., shopping malls, where several stores and enterprise are located in the same facility. The LV bus is fed by multiple feeders in parallel and the number of required feeders can change depending on load demand, required reliability etc.

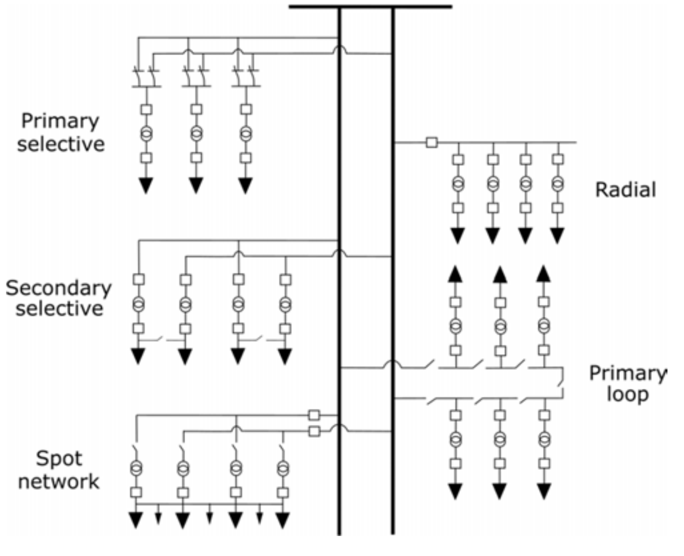


Figure 25. Primary distribution feeder configurations.

During the last decade, the Nordic DSOs have turned in the dilemma of using overhead lines or underground cables in MV grids towards using almost solely underground cables. Even though the challenge to master the highly capacitive cables persists, the benefit of placing the cables underground outweighs the downs by creating a much more resilient distribution system with reduced risk for faults and accidents, more available space in the environment and hopefully reduced need for maintenance.

2.4 Hosting capacity

In a dream scenario, it would be possible for the DSO to allow connection of all PV systems, EV chargers, wind power farms and other distributed energy resources (DER) to the grid. Unfortunately, there exists an upper boundary for the installed capacity of these and is commonly referred to as the *hosting capacity*. A general definition is proposed by [10]:

"The amount of DER a feeder can support under its existing topology, configuration, and physical response characteristics. When this hosting capacity is reached, any further additions will result in a deterioration of service if remedial actions are not taken".

Also, similar definitions can be found in [24] and [25]. According to this definition, after a certain amount of installed capacity the grid infrastructure will experience too large stress and the power quality will be insufficient. When determining the hosting capacity of a certain DER or a bundle of DERs for a feeder, all relevant performance indices should be examined to fully evaluate the hosting capacity. For each performance index there exist an upper boundary when the limit is reached. Thus, the hosting capacity for the given DER or bundle of DERs is reached when the first performance index reaches its limit. Figure 26 illustrates how performance indices may change as the connected DER capacity increases in a feeder. The upper graph shows a performance index which ideally should remain low, and the red curve indicates that the performance is worsen as the DER capacity increases. When the performance index reaches its limit, the hosting capacity is found. On the contrary, the middle graph presents the case for a performance index which ideally should be high. As more DER is connected, the performance reduces, and the hosting capacity is found where the blue curve crosses the lower limit. Finally, the green curve in the bottom graph of Figure 26 shows how the performance first improves with increased DER connections, but after a certain threshold the performance starts to decrease until the index limit is reached. There are several possible methods to increase the hosting capacity of DER, e.g., ESS, flexible loads, load tap changers on transformers or generation curtailment [24].

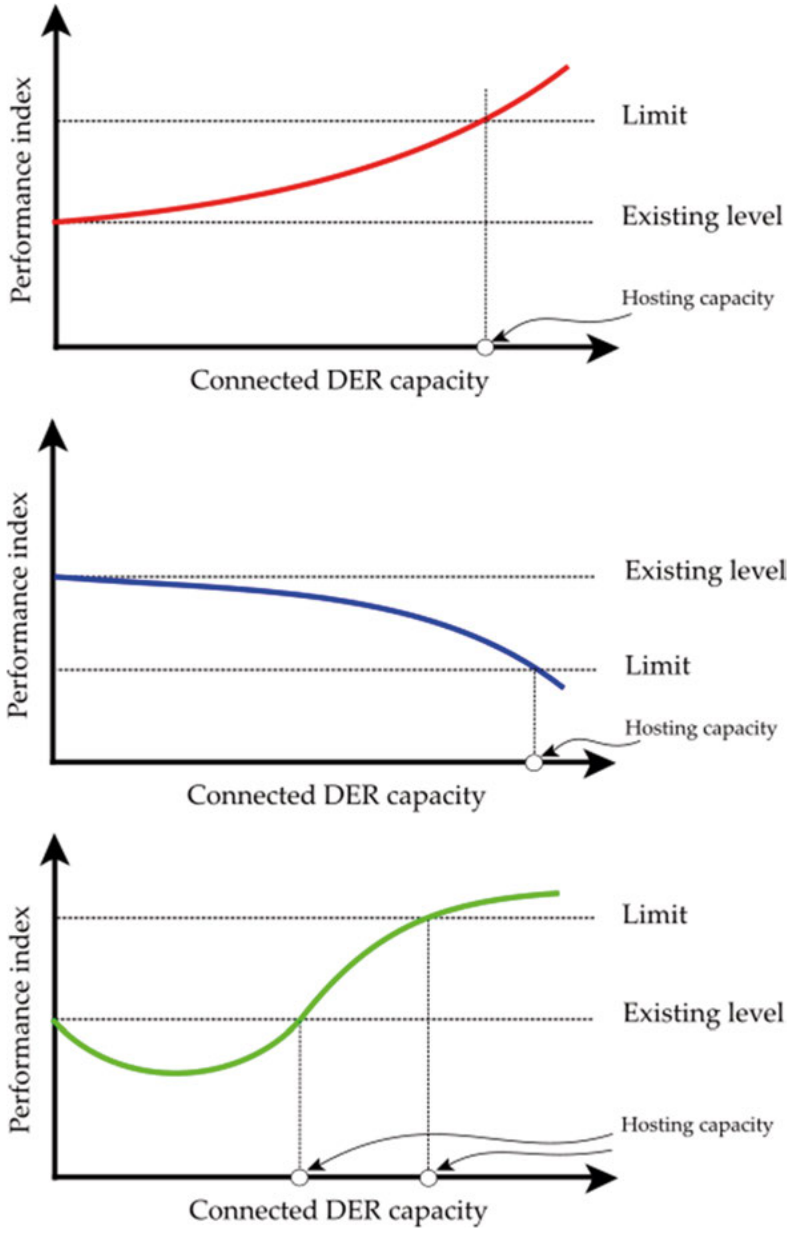


Figure 26. Illustration of hosting capacity, with performance index as function of connected DER capacity for three different cases. Reworked with inspiration from [24].

2.5 Trends

There are several trends emerging which will affect the power system and the distribution grids in upcoming years. Some trends increase the electricity demand significantly, e.g., electrification of industry and transports, while some trends affect structural aspects of the grid, e.g., the increasing number of prosumers, development of smart grids & microgrids. The Nordic TSOs have complied a joint forecast for some major evolving trends which concern the power system and is presented in Table 5 [3]. Considering the electricity consumption, the *general c*onsumption is expected to reduce by 5 TWh every ten years. Although, the *total* electricity use is expected to increase with about 130 TWh every ten years mainly due to electrification of industry, transports, and the introduction of large-scale hydrogen production. Also, a large number of data centers are expected to emerge and be grid connected before 2030 and account for an increased demand of 20 TWh.

Table 5. Consumption, RES and thermal capacity forecast of the Nordic countries [3]

	Type	**2020**	**2030**	**2040**
Electricity consumption (TWh)	General consumption	231	226	224
	Industry	131	185	179
	Data centers	2	25	25
	Hydrogen/P2X	0	26	108
	Transport	3	22	51
	Heat pumps	9	17	23
	Other consumption	21	26	34
	Total	**399**	**527**	**655**
RES capacity (GW)	Hydro	52	57	58
	Onshore wind	20	43	52
	Offshore wind	2	17	35
	PV	2	19	36
	Bio fuels	9	10	8
	Total	**85**	**145**	**189**
Thermal capacity (GW)	Nuclear	11	11	10
	Waste	12	0.8	0.8
	Fossil	6	5	2
	Total	**17**	**17**	**14**

2.5.1 Prosumers

On the customer side, the number of grid-connected users with local electricity generation is increasing - mainly due to the popular rooftop-mounted PV systems. In 2016, the number of grid-connected PV systems in Sweden was about 10 000, of which almost 8 500 had an installed capacity less than 20 kW. By 2021, the amount of PV systems had increased to 92 300 and 80 200 of these were smaller than 20 kW[12]. Thus, the share of customers which both generate and use electricity increases rapidly and are commonly known as *prosumers* (a portmanteau of *producer* and *consumer*). The local DSOs together with the electricity trading company usually offer a net metering service to facilitate and promote customers to invest in local generation. The trading company buys eventual excess generation, and the electricity is fed back to the grid. This way, all customers with local generation gets compensated for excess generation. The number of prosumers is expected to increase as the market price for PV systems keeps falling, and as the electricity price remains high (or even increases further) local generation is highly attractive. Prosumers may also invest in ESSs to store excess electricity for later use by using e.g., a battery pack mounted on the facility or possibly by using parked EVs. Prosumers could also use ESSs for other services, further discussed in Chapter 3.

2.5.2 Electrification of transports and industry

Another global trend is the electrification of transports in all segments: from bikes and scooters to passenger cars, buses, and trucks. Also, during the last years, boats and electric aircrafts have become an on-the-table topic in the business. The general development is strongly connected to climate action and abandonment of fossil fuels. Since the transport sector accounts for almost 30 % of the final energy use globally [1], it is crucial to ensure sustainable and efficient transports. In 2018 the global electricity demand for transports was 57 TWh, and is expected to increase at least tenfold by 2030 depending on policies scenario [1], [26]. From a distribution grid point-of-view, this will result in a lot of cars being parked and charged at homes, workplaces, shopping malls, sport facilities, highway rest areas, etc. Also, fast charging of cars, buses and trucks for goods distribution will put new demands on power capacity in previously low power density areas. These are major challenges for DSOs, both to estimate the consequences for the grid regarding reinforcements, power quality and safety aspects, but also how to ensure enough public charging points to promote the shift to e-mobility.

Secondly, as the industry also aim to shift partially or fully to electric, the expected increase in demand will put the entire power system on its edge due

[12] Swedish Energy Agency, Statistics for grid connected PV systems, https://energimyndigheten.se/ (Accessed 2022-08-26)

to the large amounts of electricity. In Sweden only, the electricity consumption of the industry is expected to increase by 75 TWh from 45 – 117 TWh between the years 2020 and 2030 [27]. The industry branches which expect to increase their demand the most are *steel & metal, chemistry,* and *mining* industries together with the *technology sector* (e.g., battery industry).

2.5.3 Smart grids

One of the trends in the development of distribution grids is implementation of the *smart grid* concept, a topic which was touched upon in chapter 2.2.2 already. The included features form an umbrella of tools that can be implemented to increase the performance and efficiency of distribution grids and are compiled in Figure 27. The smart grid can be described as a modern grid where communication between components and between components and operators is used to a large extent, and where distributed components play a large role. By implementing tools, components and operating strategies highlighted in Figure 27, the goal is to achieve a grid with higher reliability, efficiency, and sustainability than otherwise. More comprehensive information about smart grids is published in [15], [17], [18].

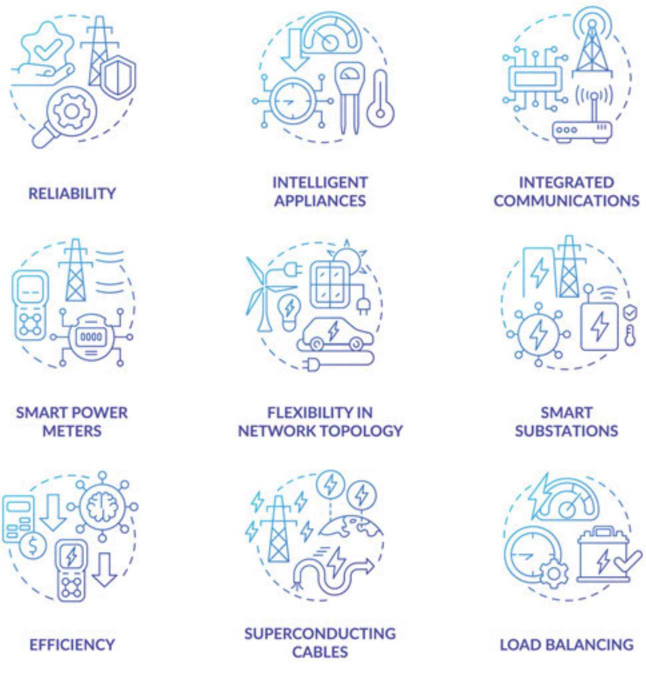


Figure 27. Overview of the smart grid concept.[13]

[13] Credits: designed by *BSD Studio*, published in Adobe Stock, used according to terms for standard license.

2.5.4 Microgrids

As the demand for high reliability and resilience of distribution grids increases globally, the idea of creating power system islands within the electrical grid has grown and technical solutions are starting to reach the market. Designing electrical grids for islands have been done for many years, but decoupling and running sections of larger distribution grids stand-alone have not been done as frequently. A typical microgrid could be visualized as in Figure 28, where one or several loads are supplied with electricity through a combination of DER including local generation and storage. If a fault or disturbance would occur upstream the grid, it would be possible to maintain the supply of electricity to the loads within the microgrid area. A microgrid heavily relies on the functions included in the smart grid, with the ability to maintain local power system stability features when disconnected from the main grid. Thorough reviews of development, control method and future challenges of microgrids are compiled in [16], [20], [28].

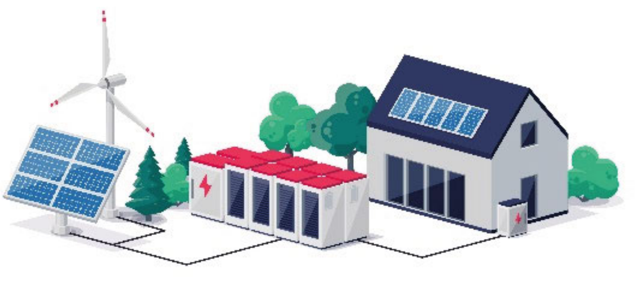


Figure 28. Visualization of a microgrid.[14]

2.5.5 Energy communities

Another evolving trend within distribution grids are *energy communities,* which can be described as groups of citizens that team up for the climate who invests in energy equipment and components for their own use. Energy communities are citizen-driven and contribute to increasing the public awareness and acceptance of projects within the clean energy transition. All forms of

[14] Credits: designed by *petovarga*, published in Adobe Stock, used according to terms for standard license.

energy used and required within the energy community are accounted for, including e.g., electricity, gas, and heat. An energy community is not restricted to a certain legal entity, and could for instance be a non-profit organization, a cooperative, or an association. Some of the benefits are lowered energy costs and increased energy efficiency, and it also creates local job opportunities. Actors and citizens within the EU can find useful information regarding energy communities on the European Commission website if interested in starting a new community.[15]

2.5.6 Smart integration of EVs: V2X, V2H and V2G

Finally, a frequently discussed topic recent years has been the smart integration of EVs where synergies between the EVs and e.g., households, workplaces and the distribution grid are promoted. It is known that most passenger cars are parked either at home or at work during a large majority of the time each day. Therefore, there is a great potential to schedule charging of EVs with respect to the expected daily fluctuations in the grid load or to enable charging infrastructure without enforcing reinforcements in already existing nodes [29]. It has also been discussed and investigated whether it is possible for EVs to also feed electricity back to the coupling point, e.g., the household, workplace, or public charging station. This way, EVs could be considered as mobile energy storages and not only as loads, see Figure 29.

There are well-established concepts in this field which are frequently used depending on the context. The most general concept is the *Vehicle-to-everything* (V2X), which includes the communication between the vehicle and any object or entity that can be affected by the vehicle. Subgroups of V2X focus on interactions with both smart grids and households but also pedestrians, other vehicles, devices, and cloud services. In the context of distribution grids, the two perhaps most relevant concepts are:

Vehicle-to-home (V2H): the EV is plugged into the charging point of the household and the battery of the car can be used both for charging and discharging to meet requirements of the overall electricity use in the building (typically a stand-alone house).

Vehicle-to-grid (V2G): the EV is plugged into a charging point at home or in public and the battery of the car is used to favour the distribution grid for e.g., grid congestion management, voltage control or RES integration. Aggregated V2G capacity could potentially be used to provide ancillary services or more extensive balancing in a region.

The smart integration of EVs is further discussed in **Papers VII – VIII**.

[15] European Commission – Energy communities, https://energy.ec.europa.eu (Accessed 2023-08-08)

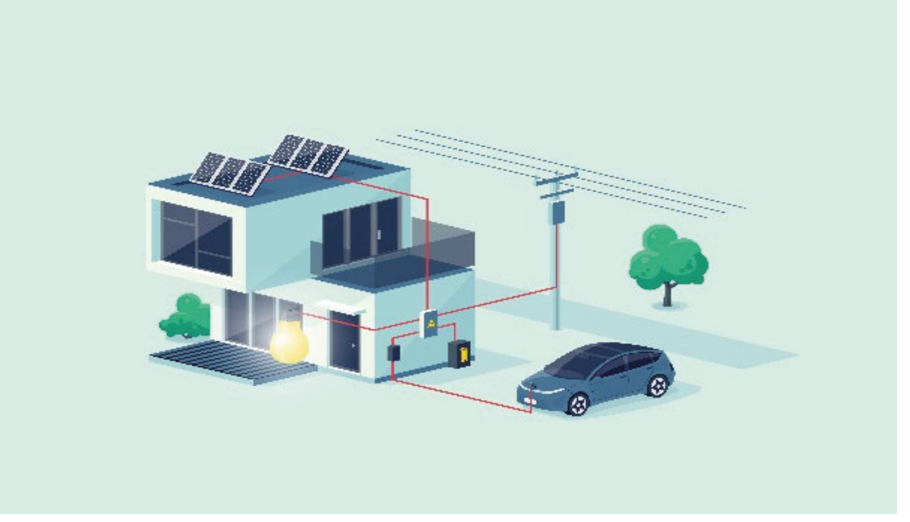


Figure 29. Visualization of V2X.[16]

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3. Energy storage systems for grid applications

The power system has a growing need for power and energy flexibility and is required in all parts of the system. In this chapter the need for flexibility in distribution grids will be covered together with a brief discussion of energy storage technologies, available grid applications and services. Finally, the distribution of installed capacity for the storage technologies is presented by their main use case together with projections of the ESS market and cost development.

3.1 Need for flexibility in distribution grids

As touched upon in chapter 2.2.2 already, the distribution grid is the outermost part of the electrical grid where the customers (or *end-users*) are connected. As the clean energy transition continues, large amounts of DER are expected to be connected to the distribution grids. The stochastic behavior of both loads and local generation in combination with large seasonal variations creates an increased demand for flexibility. An illustration of a distribution grid with highly stochastic components is shown in Figure 30. A few examples of why and where flexibility is needed are the following:

- During periods with high wind speeds and sunny weather there is a possibility of excess generation i.e., the generation is larger than the downstream demand. If too much generated electricity is fed back to the grid reverse power flows might arise, which can be problematic from a power quality and protection point of view. Since the original grid was not designed for bi-directional flows through primary and secondary distribution substations, the situation can quickly become problematic.
- In parts of the world with large variations between winter and summer climate, there are usually high demand periods during which the peak load occurs. This could for instance be during an extremely hot day when a lot of electricity must be used for cooling, or during a very cold day when extensive heating is required. One of the risks of fast-growing cities is that distribution grid reinforcements lack behind and bottlenecks arise. Ending up in this situation as a DSO can be challenging, since it most often is desired from a municipality level to let cities grow and industry expand.

- Every grid connected customer is free to use electricity whenever they want within the frames of their contracted fuse size. This naturally creates large variations within minutes, hours, days, and seasons and has to be dealt with in order to maintain a sufficient power quality both in the substations but also at all customers. This it usually taken into consideration during the business-as-usual (BAU) network planning stages, where large margins and/or flexible components can be considered.
- Another evolving trend is the rapid connection of charging infrastructure of EVs, ranging from slow home-chargers to public fast charging stations using hundreds of kW [30]. The increased power demand can partially be covered by local tools e.g., load balancing and smart charging which both may reduce the impact on the grid load, but traditional grid reinforcement has to cover for the largest connection points and in areas where the capacity margin is tight already.

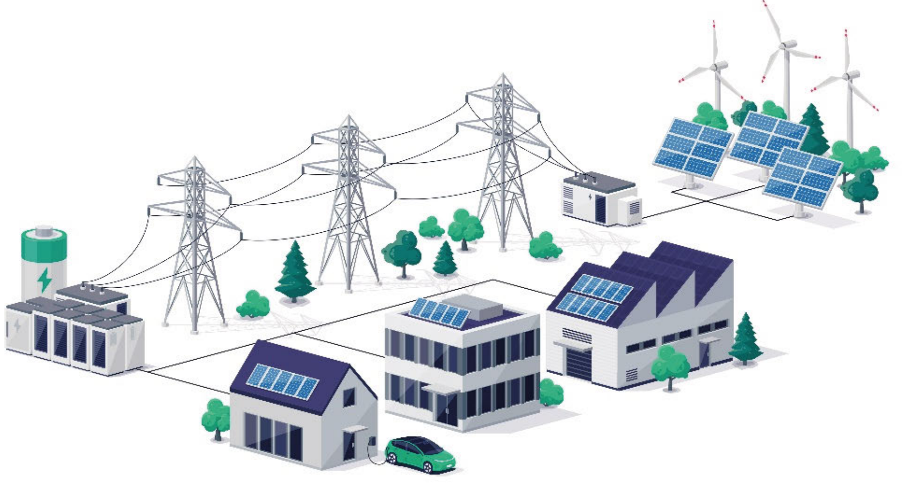

Figure 30. Illustration of a highly stochastic distribution grid.[17]

Some of the above-mentioned challenges can be solved effectively by e.g., tap changers of transformers and distributed capacitor banks for voltage control, while some challenges require additional capacity for flexibility. The two most common tools to consider then are *demand side response* (DSR) (also *demand side flexibility*) and ESSs. This thesis covers the technical potential of ESS only, but it is of importance to include aspects of DSR when evaluating the full potential of flexibility sources within the power system.

[17] Credits: designed by *petovarga*, published in Adobe Stock, used according to terms for standard license.

3.2 Energy storage systems

Ever since the power grids started to expand in the late 19th century, but mainly in the beginning of the 20th century, there has been a need for energy storage. At first, the implementations were of small scale, and energy was stored as primary fuel before generation and balance was maintained by regulating the momentaneous generation at all times. In the beginning of the 20th century a paradigm shift occurred were previously small and distributed power plants were replaced by larger power stations, and the first hydropower dams were built. This was a natural step in the development of the electrical grids: the more generation capacity and number of end-users connected to the same grid, the larger became the need for flexibility in generation. In North America, the hydropower station at Niagara Falls was one of the first large-scale power stations with dam structures and has been operating since late 19th century. In Sweden, The Royal Waterfall Board (sv: *Kungliga Vattenfallsstyrelsen*, later *Vattenfall*) was founded in year 1909 and since then hydropower has played and still plays a key role in power system regulation and balancing with large amounts of energy stored in the many dams.

The ability to store energy is crucial when operating power systems, and most energy is stored as primary energy in large reserves. For example, water dams are built to store potential energy of water at high altitudes, biomass is piled or compressed into pellets which are stored until later use, and nuclear fuel is also a high-energy density reservoir which can be released on demand. It is also possible to store energy after the primary generation step by turning electricity into other forms of energy and storing it until needed. Doing this in an energy efficient way enables many possibilities for power system applications. Energy storage could thus be defined as [31]:

"The act of deferring an amount of the energy that was generated to the moment of use, either as final energy or converted into another energy carrier."

The energy storage focus in this thesis will be on systems and technologies that can convert electricity into other forms of energy and store it until a later moment in time.

3.2.1 Energy storage technologies

One of the most common ways of categorizing energy storage technologies is by the form of which the energy is stored, with the major groups: *chemical, electrical, mechanical* and *thermal* storage technologies with corresponding subgroups [32]–[34]. The categories are illustrated in Figure 31. In the following section of this chapter, each ESS group will be explained briefly, and the content is partially included in **Paper I.**

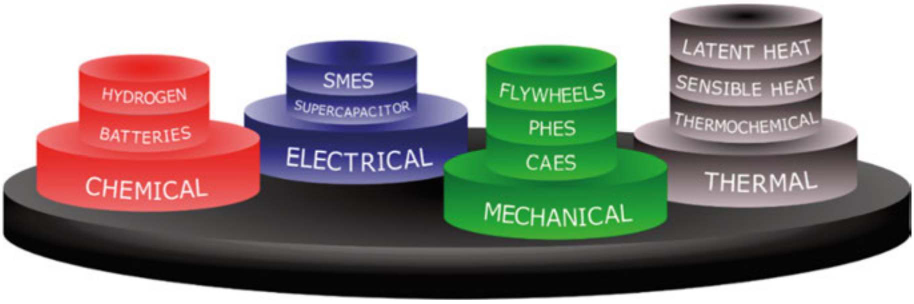

Figure 31. Overview of ESS technologies. **Paper I.**

3.2.1.1 Chemical storage technologies

Batteries

The battery energy storage system (BESS) is one of the most common ESS technologies, and batteries are found in many of our everyday life applications e.g., mobile phones, computers, headphones, cars, remote control for TVs etc. It is an electrochemical cell with solid, liquid or paste electrolyte between the positive and negative electrode. The BESS consists of a storage unit, power conversion and energy management systems together with complementary components like protection equipment, cooling systems and measurement units [35]. During operation (discharge), electrochemical reactions occur at the electrodes and the electric potential between the electrodes give rise to a current flowing through the external circuit. Some of the most well-known battery types are *lead acid*, *lithium ion*, *molten salt,* and *flow* batteries. BESSs are becoming increasingly popular for power system applications due to the fast response time, high efficiency and practical advantages concerning mobility, fast construction time on site and modularity.

Hydrogen

During the last decade, hydrogen energy storage systems (HESS) have been widely investigated for power system applications due to the intense discussions regarding long term storage within and across seasons. One common way of designing a HESS is by combining an electrolyzer with a storage tank and a fuel cell to produce, store and use the hydrogen [36]. Since hydrogen is a flammable gas the safety aspect is of high priority, and to store the hydrogen in an efficient way high pressure tanks can be used but increases the costs significantly. The discussions regarding gas grids have also gained a lot of interest as many sectors reckon hydrogen as a future energy carrier, which would favor storage and transport aspects. According to the *European hydrogen roadmap*, hydrogen could play a key role in future power system aspects regarding improved integration of RES [37].

3.2.1.2 Electrical storage technologies

Capacitors & Supercapacitors

Conventional capacitors store energy as static charge between two metal plates with a non-conducting layer in between with a resulting electric field between the plates [38]. The distance between the two plates is typically very short and the area of the plates large in comparison to achieve a high efficiency [39]. In general, capacitors have a high-power output compared to the energy capacity making them suitable for applications that require bursts of energy during short periods. More advanced models of the traditional capacitor go under the name *supercapacitors* (SC). Instead of the dielectric layer, it uses an aqueous or organic electrolyte together with porous separators. Several manufacturers aim for utility and transport applications but still face market challenges [40].

Superconducting magnetic energy storage

The superconducting magnetic energy storage (SMES) is one of the most recently emerged energy storage technologies and is used in a few large-scale research projects. A SMES consists of three core components: a coil of superconducting material, power conversion and refrigeration systems. At very low temperatures, superconducting materials can be used for efficient energy storage but requires extensive cooling [38], [41], [42]. Some of the main barriers are the costs for superconducting wires and the cooling system, and strong magnetic fields may limit the placement possibilities of the SMES.

3.2.1.3 Mechanical storage technologies

Flywheels

The idea of storing kinetic energy using a spinning object is realized using the flywheel technology. A typical flywheel energy storage (FES) is built using five main components: a flywheel, a vacuum chamber, magnetic bearings, a generator/motor and a power conversion system. By adjusting the rotational speed of the flywheel, energy can be stored or dispatched i.e., the motor is used to accelerate the flywheel when charging, and the generator is used to generate electricity during discharge. The energy capacity is determined by the inertia of the flywheel and the rated rotational speed. A common classification of flywheel types is done based on the rotational speed: either *high* or *low*. The low-speed FESs are built with a heavy flywheel (commonly made of steel) and rotate up to a few thousand revolutions per minute (rpm), while the high-speed FESs uses a flywheel of lightweight composite material that allows RPM ratings up to almost a million [40], [43]. Due to the high efficiency and specific energy in combination with fast response time, the interest in power system applications is large.

Pumped hydroelectric storage

The conventional pumped hydroelectric storage (PHES) design requires two reservoirs at different elevation, a turbine and a generator, a pump and interconnecting waterways. When electricity is needed, water from the upper reservoir is tapped through the turbine that drives the generator. During charging of the PHES, water is pumped from the lower to the upper reservoir. One of the main benefits of the PHES is the possibility of long-term storage of very large energy volumes, especially if co-located with existing hydropower plants with large dams [40], [44]. Naturally, the potential of PHES is dependent on sufficient supply and access to large water volumes and a topography with large differences in elevation.

Compressed air

Compressed air energy storage (CAES) systems have similar storage functionalities as the PHES, where large energy volumes can be stored for a long time. The CAES consists of a large storage camber, a set of compressors, a turbine, generator and a motor [45]. When filling the storage, electricity is used to run the compressors and the pressure increases in the storage chamber. During discharge, the compressed air is expanded by running the turbine that drives the generator and electricity is generated. The CAES strongly rely on the existence of a large and solid storage chambers, e.g., old mine caverns, since the construction of such a large chamber would be economically unfeasible.

3.2.1.4 Thermal storage technologies

The thermal energy storage (TES) stores energy as heat by heating and cooling a medium in an enclosed environment [41], [42]. To generate electricity a heat engine is used, and it is common to locate a TES in connection to a thermal power plant or an industry where a lot of heat is released. TES types can be separated by either the operating temperature (high or low) or by the state of the storage medium (sensible, latent or thermochemical). The low efficiency and long response time reduces the suitability for power system applications with fast dynamics, but the low storage losses make it more suitable for seasonal storage.

3.2.1.5 Summary of storage technologies

Figure 32 shows an overview of the typical power and energy capacities of the presented ESS technologies. From Figure 32 it can be noted that the chemical ESS technologies cover a wide range of the power spectrum: from a few kW up to hundreds of MW. The typical discharge time is one up to several hours for BESSs, while HESs can store much larger volumes. Furthermore, considering the electrical ESSs they have a much higher power-to-energy ratio and are suitable for application where short but powerful bursts of energy are required. The mechanical ESSs have the potential to store large amounts of

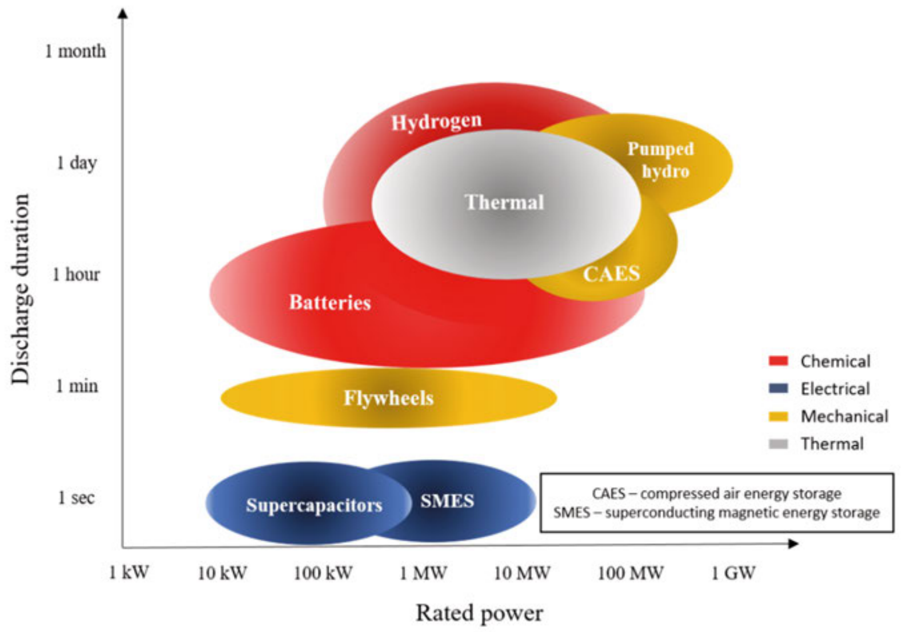

Figure 32. Comparison of power and energy characteristics of ESS technologies. **Paper I.**

energy (mainly CAES and PHES) while the FES operates in the intra-hour timeframe. Finally, TES have properties similar to the larger mechanical storage technologies and hydrogen and can reach discharge durations of several hours in the MW power rating range.

3.3 Grid applications and services

In the Nordic countries, the TSO has the system responsibility and is the main responsible for the functionality of the power system including balancing, stability, safety, expansions, interconnections, etc. To ensure that transmission and distribution grids are operated with high performance regarding balance, stability, reliability, and power quality it is crucial to ensure enough regulating capacity and flexibility in all parts of the grid. Since power systems are sensitive to larger disturbances, e.g., sudden stops of generators, faults or broken power lines, or disconnection of large loads, it is important to be well prepared with flexible components and reserve capacity. Figure 33 provides an overview of common ancillary services managed by the TSOs that target various functions and aspects of the power system. Most of the services shown in Figure 33 are contracted with the TSO directly, but the capacity for *frequency* *control* is purchased using market-based mechanisms. Considering the balancing aspect, the Nordic electricity market was deregulated in year 1996 and as of today, almost all electricity is traded in the *Nord Pool* market. Electricity suppliers or third-party actors can enter balance responsibility agreements with the TSO to participate in the balancing of the power system. Most of the energy is traded on the day-ahead market and the final corrections are handled by the intraday market, ensuring the balance in and between all bidding areas for each market time unit. To improve the performance of balancing, the imbalance settlement period changed from 1 hour to 15min in 2023 (also referred to as *market time unit, MTU)*.

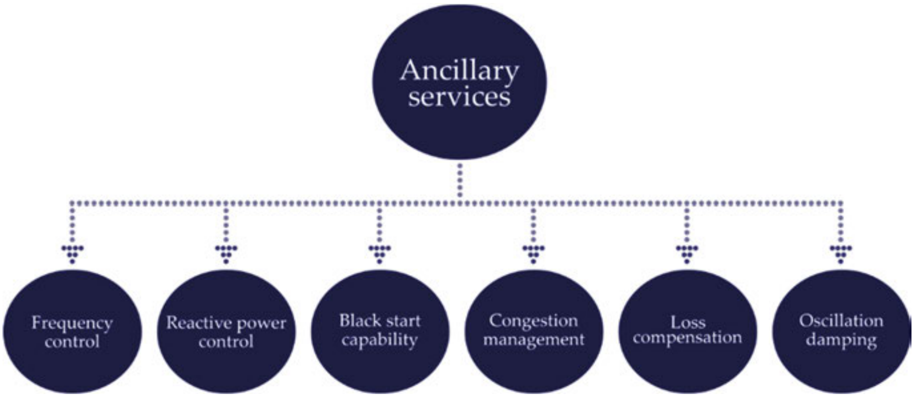

Figure 33. Overview of ancillary services.

On the medium and low voltage levels the DSOs manage other types of tools and services that target the local grid rather than the stability of the power system. Challenges that DSOs face concern e.g., congestion management of distribution feeders, avoidance of bidirectional power flows, harmonic pollution reduction from DER, management of voltage variations and power quality measures, improvement of reliability KPIs, to name a few. DSOs have the possibility to enter agreements with third parties to purchase certain products or services, and traditionally there has not been any markets operated by the DSOs besides from local flexibility market pilot projects. It can therefore be concluded that the placement of ESSs will affect the potential to provide ancillary services and/or providing local services, where possible placements of grid connected ESS are illustrated in Figure 34. To distinguish between a service and an application, the following separation is done [46]:

Service: "*an operation that is fulfilled by the ESS including its power conversion system*"

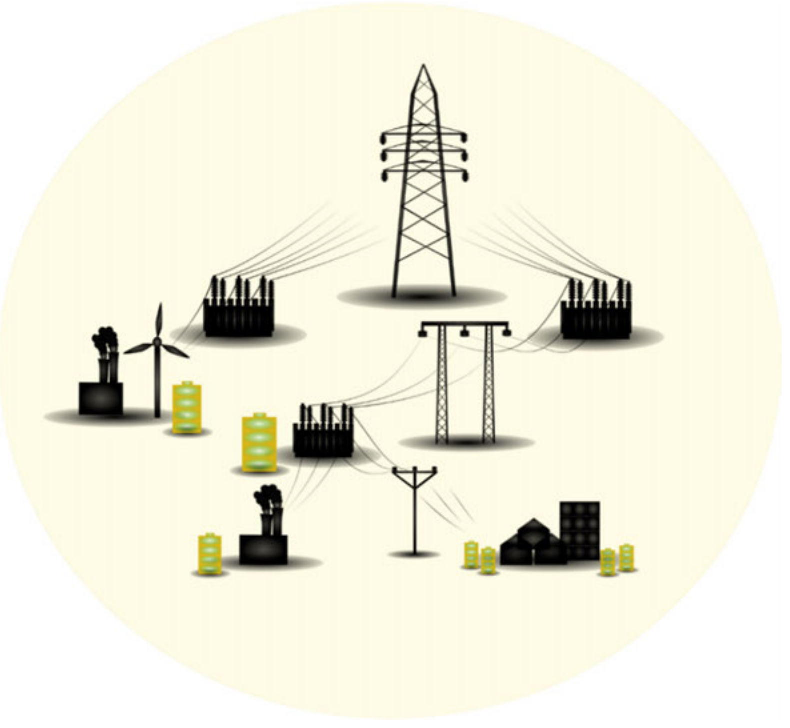

Figure 34. Placement possibilities of energy storage units. **Paper I.**

Application: *"a location within the grid and the connection and functionality of the ESS in relation to its surrounding infrastructure as well as its technical characteristics"*

According to these definitions there is a clear difference between a service and an application but are still widely mixed in the literature. To give a few examples, possible categorizations of grid applications and services are done in the following ways:

- Generation, transmission & distribution (T&D) and end user side [47]
- Bulk energy, ancillary services, customer energy management and RES integration [46]
- Power generation, Transmission system, and distribution system [48]

Clearly, the separation can be done either by considering which part of the grid that is targeted or by the character of the application where power and energy are separated. Regardless of categorization of applications, the possible services are many and can be compiled to the ones presented in Table 6, where both services and groups of services are included. In the literature the number of different services varies between 10 and 30 depending on categorization and level of detail in the service separation [40], [46], [47], [49]–[55]. To create a more hands-on overview of the available services, those who are similar have been grouped and placed in the same service group. For example, congestion relief or congestion management is closely related to transmission or distribution investment deferral, and therefore referred to as a single group named *T&D investment deferral*. The same goes for *Frequency restoration services* (or *frequency regulation*), *RES integration* and *Spin-/Non-spin reserves* which are also bundles of several services. The services and service groups presented in Table 6 and Figure 33 are designed with strict specifications and requirements regarding e.g., minimum bid sizes, activation times and duration times. Since the ESS technologies have varying characteristics, it is interesting to see how the timescales of services match with the considered technologies and is illustrated in Figure 35. From Figure 35 it can be seen that the mechanical, chemical, and thermal ESSs are suitable for energy specific services e.g., energy time shift, balancing, arbitrage, and load following. The electrical ESSs are more suitable for services that require very fast activation times but with short endurance e.g., fast frequency regulations and fast voltage variations. Although, some of the BESS technologies with very fast response and activation times have been considered for frequency regulation in both literature and real-world examples due to the good technical match between the technical properties of the BESSs and the service requirements, and also due to the lucrative business case. In the Nordic power system, the frequency regulation is split into three main groups: *Frequency Restoration Reserves (FRR)*, *Frequency Containment Reserves (FCR)* and *Remedial action.* The FRR services aim to restore the frequency to its nominal value after a larger disturbance, while the FCR services and remedial actions try to counteract further deviation in the electrical grid frequency during a disturbance. There are two FRR services, one automatic (aFRR) and one which is activated manually (mFRR) and are typically activated several minutes after a larger disturbance. Furthermore, there are three FCR services purchased by the TSO: one for normal disturbances (FCR-N) and two services which are activated during larger disturbances (FCR-D), one for upward and one for downward regulation.

Finally, the remedial actions for frequency regulation are purchased today by a single product called *Fast Frequency Reserve (FFR)* and is activated in about 1 second in case of a larger disturbance. Figure 36 illustrates how the frequency reserves get activated during a fictive event during which the grid frequency drops enough to activate them all i.e., below 49.7 Hz. As shown in Figure 36, the FFR capacity is activated very quickly after the disturbance is registered, while the FCR capacity takes slightly longer before fully activated, approx. 30 seconds. After a few minutes, the FRR capacity is fully activated as well, and the grid frequency starts to approach 50 Hz again. A summary of the technical details regarding the services managed by the Swedish TSO Svenska Kraftnät (SvK) is compiled in Table 7 together with the terms for economic remuneration.

Table 6. Services (S) and service groups (SG). **Paper I.**

Service	Description
Black start capability (S)	• Assisting re-energization after a major grid failure [38], [46], [56] • Supporting other generator units with initial power [38], [40], [46], [51], [56]
Energy arbitrage (S)	• Generating revenue from the price difference of electricity in the spot market, selling electricity during peak hours and buying during off peak hours [57], [58]
Frequency restoration services (SG)	• Fast balancing of deviations between generation and demand [46], [59] • Various products in different markets. Usually, one or more proportional services to prevent further deviation and one or more integrating services to restore the grid frequency [46], [59]
Peak shaving (S)	• An ESS is connected to the grid at a chosen location to discharge during a specific time to reduce the peak demand [46], [60]
Power outage mitigation (S)	• The ESS is connected to cover for outage of power supply from one or more generators [61] • May also be connected as a more traditional back up unit downstream the grid [62], [63]
RES integration (SG)	• An ESS is connected to support the integration of renewable energy sources [34], [40], [46] • May be used for e.g., capacity firming, ramp rate control or time-of-use shifting of energy [40], [46]
Spinning/non-spin reserves (SG)	• Reserve capacity provided by the ESS which is excluded from the normal operating capacity [49], [64]–[66] • Rotating machines are synchronized to the grid without injecting any power to the grid [65], [67] • Capacity bids are usually cleared by the TSO a few times per year [65]
T&D investment deferral (SG)	• By installing an ESS in a congested grid, it is possible to reduce the loading of the infrastructure during peak load, postponing otherwise required investments. Can also be connected to store generated electricity at power plants (e.g., wind or solar farm) to avoid downstream bottlenecks [46], [51], [64], [68]
Voltage support (S)	• The ESS provides active and reactive power control to improve the local voltage quality [49], [69]

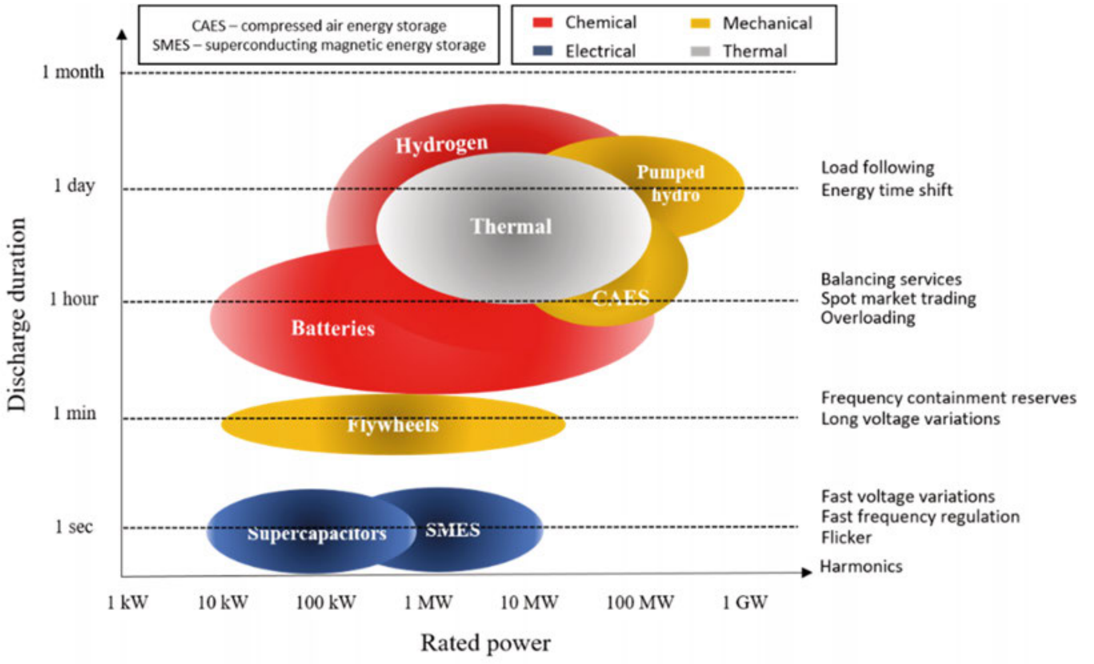

Figure 35. Storage characteristics in relation to grid applications and services. **Paper I.**

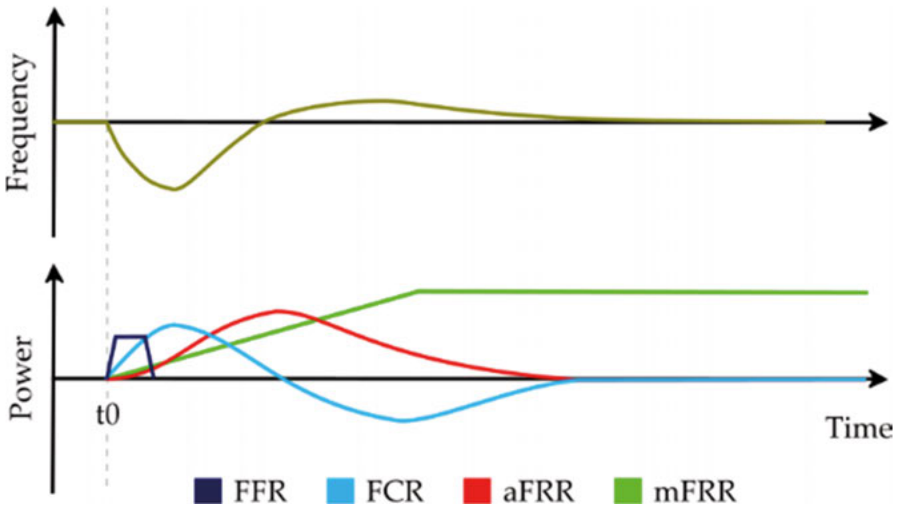

Figure 36. Activation of frequency reserves during a larger disturbance.

Table 7. Requirements for frequency reserves specified by the Swedish TSO SvK.

Remedial action	**Frequency Containment Reserves**			**Frequency Restoration Reserves**	
FFR	**FCR-D up**	**FCR-D down**	**FCR-N**	**aFRR**	**mFRR**
Upward regulation	Upward regulation	Downward regulation	Symmetrical	Upward and/or downward regulation	Upward and/or downward regulation
Min. bid size 0.1 MW	**Min. bid size** 0.1 MW	**Min. bid size** 0.1 MW	**Min. bid size** 0.1 MW	**Min. bid size** 1 MW	**Min. bid size** 5 MW
Activation Automatic activation for changes in frequency when there are low levels of rotational energy in the system	**Activation** Automatic linear activation within the frequency interval 49.90 – 49.50 Hz	**Activation** Automatic linear activation within the frequency interval 50.10 – 50.50 Hz	**Activation** Automatic linear activation within the frequency interval 49.90 – 50.10 Hz	**Activation** Automatic activation for frequency deviations from 50.00 Hz	**Activation** Manual activation when requested by Svenska Kraftnät
Activation time Three alternatives for 100%: - 0.7 s at 49.50 Hz - 1.0 s at 49.60 Hz - 1.3 s at 49.70 Hz	**Activation time** According to document with technical requirements	**Activation time** According to document with technical requirements[18]	**Activation time** According to document with technical requirements	**Activation time** 100 % within 5 minutes	**Activation time** 100 % within 15 minutes

[18] FCR technical requirements, SvK, https://www.svk.se/

Volume requirements for Sweden	**Volume requirements for Sweden**	**Volume requirements for Sweden**	**Volume requirements for Sweden**	**Volume requirements for Sweden**	**Volume requirements for Sweden**
Up to 100 MW	Up to 558 MW	Up to 538 MW	231 MW	Up to 111 MW	No requirements
Endurance	**Endurance**	**Endurance**	**Endurance**	**Endurance**	**Endurance**
5 or 30 seconds	At least 20 min	At least 20 min	1 hour	1 hour	1 hour
Procurement	**Procurement**	**Procurement**	**Procurement**	**Procurement**	**Procurement**
Bids on capacity market	Bids on capacity market	Bids on capacity market	Bids on capacity market	Bids on capacity market	Bids on energy activation market
Capacity remuneration	**Capacity remuneration**	**Capacity remuneration**	**Capacity remuneration**	**Capacity remuneration**	**Capacity remuneration**
Pay as cleared	Pay as bid	Pay as bid	Pay as bid	Pay as cleared	N.A
Energy remuneration	**Energy remuneration**	**Energy remuneration**	**Energy remuneration**	**Energy remuneration**	**Energy remuneration**
N.A	N.A	N.A	According to regulating prices	According to regulating prices	Pay as cleared, regulating prices

3.4 Installed capacity worldwide

In 2017, the International Renewable Energy Agency (IRENA) published a report on *Electricity Storage Costs* together with a comprehensive overview of grid connected ESS capacity sorted by primary use case and by storage technology and is presented in Table 8 [70]. From Table 8 it can be noted that the total installed capacity was estimated to 176 GW, and the ESS technology with the single largest installed capacity was PHES followed by TES, chemical and other mechanical technologies (CAES and FES). The main use case that accounted for the largest share of the total installed capacity was doubtless *Electric Energy Time Shift* with 150 GW, followed by *Electric Supply Capacity* with 7 GW and *Black Start Capability* with 6 GW. Considering the service allocation among the TESs, *RES Capacity Firming* accounted for the majority of the capacity followed by *On-site Renewable Generation Shifting*. Furthermore, the electro-chemical ESSs were mainly used for *Frequency regulation*, *Spinning reserves* and *Electric Bill Management* while the other mechanical ESSs were used for *On-site power, Black Start Capability* and *Electric Supply Capacity.* It is also interesting to see how the capacity was allocated between different storage technology types within each storage group, and the statistics show that *molten salt* technologies accounted for 75 % of the total TES capacity, while *Lithium-ion* batteries dominated in the electro-chemical group with 59 % of the shares. Finally, FESs accounted for 59 % of the other mechanical ESSs [70].

3.5 Projections of the global BESS market

The International Energy Agency (IEA) put special emphasis on the development of grid connected BESS due to the suitability for many grid applications at all grid levels in combination with the fast-growing market and practical advantages regarding installation times etc. In the World Energy Outlook from year 2022 a projection is presented regarding the expected global development of connected BESS as function of shares of wind and solar and is shown in Figure 37 [71]. From Figure 37 it can be seen that India and the United States are the two continents with the largest forecasted shares of BESS in both Announced Pledges Scenario and Stated Policies Scenario. The forecasted BESS capacity in the European Union is expected to end up about half of the ones in the US and India, while the development in China is expected to be less extensive.

Two other projections of the global market development of BESS were made by BloombergNEF[19] in 2022 and the U.S. Department of Energy in 2020 [72], where the accumulated capacity of grid connected BESS was forecasted to

[19] BloombergNEF, https://about.bnef.com/ (2023-09-26)

Table 8. Installed energy storage power capacity globally, sorted by primary use case and technology [70].

Main use case	**Installed capacity (GW)**				
	PHES	**TES**	**Electro-chemical**	**Mechan-ical**	**Grand total (GW)**
Electric Energy Time Shift	149.94	0.14	0.15	0.11	150.34
Electric Supply Capacity	6.91	0.00	0.07	0.20	7.18
Black Start	5.92		0.04	0.32	6.29
Renewables Capacity Firming	3.20	2.39	0.10		5.68
Electric Supply Reserve Capacity – Spinning	2.00		0.18	0.01	2.18
Frequency Regulation		0.00	0.95	0.04	1.00
On-site Power	0.14	0.00	0.00	0.86	1.00
Electric Bill Management	0.38	0.10	0.16		0.64
Renewables Energy Time Shift		0.48	0.05		0.54
Demand Response	0.42		0.01		0.43
Voltage Support	0.30		0.00		0.31
On-site Renewable Generation Shifting		0.21	0.02		0.23
Resiliency			0.03	0.01	0.04
Transport Services			0.04		0.04
Grid-Connected Commercial (Reliability & Quality)			0.02		0.02
Microgrid Capability		0.00	0.01		0.02
Electric Bill Management with Renewables			0.02		0.02
Ramping			0.02		0.02
Distribution Upgrade Due to Solar			0.01		0.01
Stationary Transmission/Distribution Upgrade Deferral			0.01		0.01
Distribution Upgrade Due to Wind			0.00	0.01	0.01
Load Following (Tertiary Balancing)			0.00		0.00
Transmission Congestion Relief			0.00		0.00
Electric Supply Reserve Capacity – Non-Spinning			0.00		0.00
Transportable Transmission/Distribution Upgrade Deferral			0.00		0.00
Grid-Connected Residential (Reliability)			0.00		0.00
Transmission Support			0.00		0.00
Grand total (GW)	**169.21**	**3.32**	**1.91**	**1.57**	**176.01**

approx. 400 GW in year 2030 and 1095 GW in year 2040. As any forecast, the further into the future it reaches the more uncertain it is. Considering the projected development until 2030 only, it is expected that the annual deployment of grid related BESSs will increase globally from approx. 20 GWh in year 2020 to 140 GWh in year 2030 [72]. The use cases which are expected to be the most common for BESSs are *Energy Time Shifting, Peak Shaving* and *Commercial & Industrial PV+BESS* applications and account for about 70 % of the total capacity. Finally, the National Renewable Energy Laboratory (NREL) presented an updated cost projection for utility-scale BESS in June 2023 which is illustrated in Figure 38 [73]. From Figure 38 it can be seen that the largest changes in the market prices are expected within the upcoming five to ten years, both regarding power and energy components. Thereafter, the market price development rate is expected to slow down.

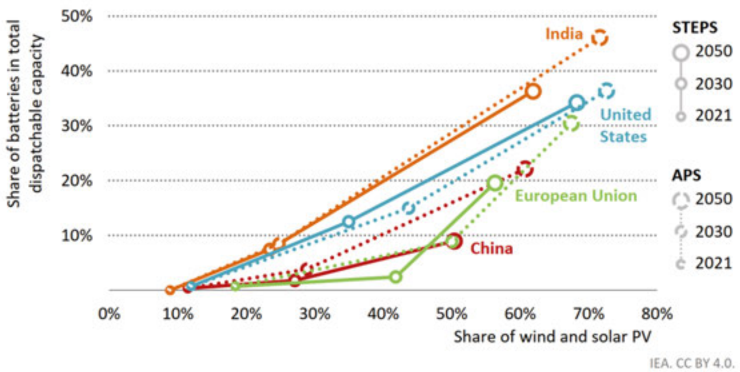

Figure 37. Projections for development of BESS installations [71].

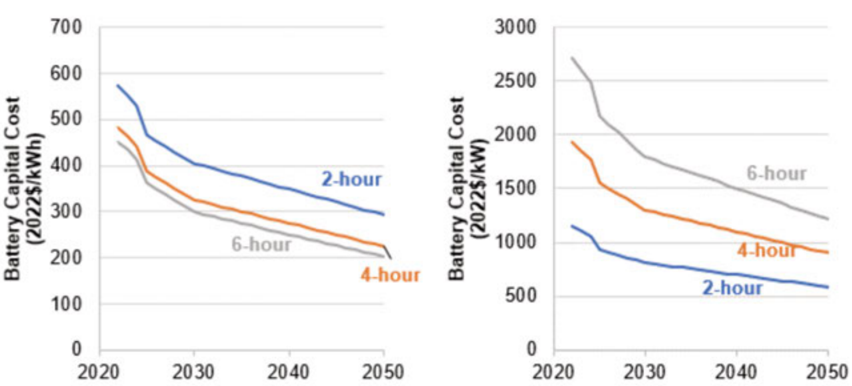

Figure 38. Projections for cost development of BESS [73], used with permission.

4. Service stacking using energy storage systems for grid applications

Finding use cases where the technical potential of ESSs is used to a higher extent is highly valuable for the power system, and the method of bundling services a single portfolio is commonly known as *service stacking* (also *value stacking* and *revenue stacking*). This chapter begins with an explanation of the fundamental principles and ideas of service stacking followed a brief background on optimization theory. Thereafter, challenges with solving the optimization problem and obtaining an in fact optimal solution are discussed. Finally, the main results and key discussion points from the literature review on the topic are presented - which are included in **Paper I.**

4.1 Formulating the service stacking problem

Service stacking is very similar to a classic scheduling optimization problem, where the ESS power and energy capacity should be allocated for each time unit according to a given objective function subject to (s.t.) a set of active constraints for the time horizon T. The fundamental problem is illustrated in Figure 39. The scheduling can be done for any time horizon, but since the trading in most energy and capacity markets is done on daily basis with a settlement period (market time unit) of one hour or quarter of an hour, these could be suitable alternatives. In the case for seasonal storage the planning has to be done differently by considering which time of the year it is. Seasonal storage has not been considered in the appended papers of this thesis but is an interesting topic for future research, see chapter 8. The *Smart Electric Power Alliance (SEPA)* has suggested that service stacking could be formulated as[20]:

"Value stacking is defined as the bundling of grid applications, creating multiple value streams, which can improve the economics for distributed energy resources".

There are several aspects and parameters that affect the potential of service stacking, e.g., storage placement, sizing, technology characteristics, service availability etc. Therefore, the evaluation of service stacking should be con-

[20] SEPA, *Maximizing value from DERs though value stacking,* https://sepapower.org/ (2023-09-26)

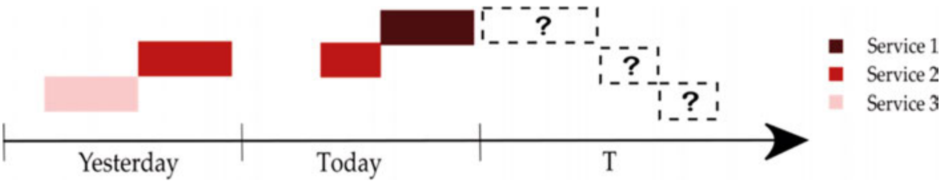

Figure 39. Fundamental problem of service stacking. **Paper I.**

sidered case-by-case. The simplest way to implement service stacking is to consider an ESS where different services are provided during separate time periods. This will increase the degree of utilization of the ESS and creates an additional revenue stream but is not an optimization in any way. By implementing advanced algorithms and scheduling tools including forecasting models while considering multiple services in parallel, it is possible to create more complex but also more valuable portfolios.

A general optimization problem with minimization of a selected property can be formulated as:

$$\begin{aligned} &\min f(X) \\ &s.t.\, g(X) \geq 0 \\ &s.t.\, h(X) = 0 \end{aligned} \tag{4.1}$$

In Eq. (4.1), f is the objective function, X is a set of variables x_1 to x_n bound by the inequality constraints $g(X)$ and the equality constraints $h(X)$. The objective function should be an explicit mathematical formula for calculating e.g., the profit of service provision, self-sufficiency, or net load demand, while the constraint functions g(X) and h(X) represent the outer and specific boundaries of the problem, e.g., state-of-charge, energy and power limits. The objective function and/or the constraints could also contain functions for estimating and limiting ESS degradation and promote or limit certain services during specific periods or hours.

4.2 Optimization theory and implemented methods

4.2.1 Background

Optimization problems exist almost everywhere in our lives, both in small and large scale. The general problem can be formulated as: *"to select or determine the best choice among all available alternatives for a given domain, sometimes subject to a set of active constraints"*. Additionally, from a mathematical point of view, it can be described as: *"the search for a maximum or minimum value of the objective function by iteratively testing available values of the* *input variables within the feasible space of the problem, bound by the active constraints, until no better solution can be found"*. These problems range from simple character like finding the shortest or fastest route between the supermarket and home, to more complex problems with many variables, large uncertainties and randomness that appear in e.g., engineering or biology.

In the search for the optimal solution to a given problem it is important to consider that the set of feasible solutions might include several local optima, also called *extreme points*. Therefore, it is not guaranteed that an obtained optimal solution is in fact a global optimum - and for many solvers this is a difficult task to work around. One exception is the case for *convex optimization* where convex functions are minimized over convex sets, which also works for maximization of concave functions over convex sets. In this case, a local optimum is indeed a global optimum and thus it is valid that the optimal set also is convex. Local and global minima are illustrated in Figure 40 (a), and two examples of convex sets are shown in Figure 40 (b). Convex sets can be visually explained as in Figure 40 (b), where the requirement is that the line between two points within the feasible region has to stay within the region as well and never cross the outer boundaries. For a convex function, the requirement is that the line segment between two points should always be above the function.

Depending on the characteristics of the optimization problem, some of the traditional optimization methods might not be able to find a feasible solution within reasonable time - or not at all. Therefore, possible methods for solving optimization problems diverge into two main groups: classic mathematical methods based on calculus, and heuristic methods where the search is guided

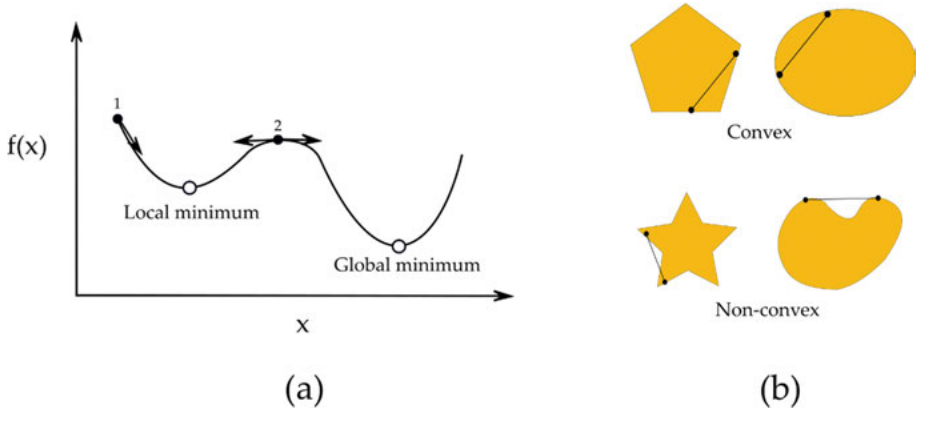

Figure 40. Conceptual illustrations of (a) local and global minimum, (b) convexity.

by rules, randomness, or empirical intelligence. Several of the heuristic methods are strongly inspired by complex processes that occur in nature. There are pros and cons with all optimization methods, but some of the general trade-offs that come with the two pathways are *optimality*, *execution time*, *accuracy & precision,* and *completeness.* The classic methods have clearly stated necessary and sufficient conditions for optimality to be guaranteed, while heuristic methods do in general not guarantee that the best obtained solution is a global optimum. Although, some of the classical methods may struggle with computational performance for complex problems of large scale. Heuristic methods are designed to deal with this kind of problems which is valuable when a solution that is close-to optimal is good enough. Finally, if an optimization problem has many solutions which are optimal it is not sure that heuristic methods are able to find all possible solutions. In the following part of this chapter, classical and heuristic methods will be explained more in detail. It should be noted that there exists more types of optimization methods based on e.g., machine learning or artificial intelligence too, but no such methods have been implemented in the work proposed by the author and have thus been excluded from this thesis.

4.2.2 Classical methods

On the first side of the coin one finds the methods which are based on classical calculus optimization theory. Depending on whether the problem is of *discrete* or *continuous* character the method for solving the problem will vary as derivative methods can be applied to continuous problems only. Some of the major branches of the tree of classical methods consist of *integer*, *linear*, *quadratic*, *nonlinear* and *stochastic optimization*. They all have in common that the solution is a single point which is sequentially improved until an extreme point is found (i.e., local minimum or maximum) and the convergence rate is normally fast, especially for convex problems. Linear programming (LP) is one of the cases included in convex optimization where the objective function and all active constraints are formulated as linear functions. Integer programming (IP) is a variation of linear programming where one, several or all variables are constrained to integer values only. This causes the problem to no longer be convex and is significantly more difficult to solve compared to LP. Furthermore, quadratic programming (QP) and nonlinear programming (NLP) allow the objective function and sometimes the constraints to take higher order terms. These methods try to solve non-convex problems as efficiently as possible and it is common to implement special formulations of LP to reduce the complexity by achieving convex subsets of the problem. Finally, stochastic programming (SP) includes one or several aspects of randomness where parts of the constraints or the objective function (or both) depend on one or more random variables. In **Papers III - IV**, a *Mixed-Integer Linear Program* (MILP) was formulated and solved in order to determine the optimal scheduling of a large-scale BESS. The complete problem formulations are found in Chapter 5.1.

4.2.3 Heuristic methods

On the second side of the coin one finds the heuristic methods which have been developed as classical optimization methods have been insufficient or being too computational heavy to implement. Heuristics can be explained as problem solving methods that iteratively try different sets of solutions for a large number of iterations (also called *generations*), and for each generation proceed with the best alternatives until convergence has been achieved. The general solving approach is to guide the search through the set of feasible points by implementing intelligent or random guiding during the iterations. Thus, optimality is not guaranteed but the approximation of the exact solution might be sufficient for the given purpose. Some examples of classic informal heuristics which are used in applied problem solving are *trial and error*, *rule of thumb*, *common sense*, *affect heuristic* and *educated guesses*. In mathematics and computer science there are several well-known and established algorithms and methods based on heuristics, e.g., *tabu search, simulated annealing, ant colony optimization*, *particle swarm optimization* and *genetic algorithm*. Tabu Search (TS) is based on a local search procedure where neighboring potential solutions are evaluated, and by using memory structures poor solutions are sorted as "tabu" and thus avoided in future iterations. Another type of heuristic method is Simulated Annealing (SA) which is based on a probabilistic approach where the goal is to minimize the internal energy of a given system by considering the temperature of the neighboring states. Finally, evolutionary algorithms (EA) are part of the larger topic *Evolutionary computation* and are designed to mimic evolutionary processes and mechanics. Some of the most well-known EA methods are the Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO) and the Genetic Algorithm (GA). In **Paper V,** a GA was implemented to find the optimal scheduling strategy for a BESS located at a sports facility to provide several services during a limited period. The complete problem formulation is found in Chapter 5.2.

4.3 Challenges in finding an optimal solution

Considering the complexity of service stacking, there are several significant challenges when it comes to making accurate models and strategies for ESS scheduling. In this chapter, a selection of such challenges is presented. The full analysis is included in **Paper I.**

4.3.1 Forecast modelling

Recall the fundamental problem of service stacking illustrated in Figure 39. The idea is to create an operational strategy where the energy and power capacities are allocated for multiple services during the upcoming period *T*, based on some historical analysis of market prices and volumes of the included services together with other relevant dynamics e.g., grid load, load demand of single customers, ambient temperature, local generation profiles, etc. This creates a high demand for accurate and reliable prediction and forecasting models in order to ensure the efficiency and precision of the ESS scheduling. Since predictions and forecasts come with errors and risks it is desired to keep these small. There are several well-recognized methods for implementing forecasting, where two common alternatives are illustrated in Figure 41. The first method, indicated by (1) in Figure 41, is based on access to historical data of the considered signals (market prices and volumes, load profiles, etc.) *M* days before the day of delivery, *D,* which are used for training a forecasting model based on e.g., grey box, black box, machine learning or AI theory. In general, access to large amounts of training data will improve the chances of tuning a well-performing forecast model. The second alternative, indicated by (2) in Figure 41, relies on a statistical approach where a distribution is generated for each signal and used as decision variable in the model. Distributions can be created for as many aspects as possible, e.g., weekdays, weekends, cold or warm days, holidays, etc., in order to provide as relevant statistics as possible. The output from the two methods is typically either a time series with values of the predicted outcome, or a distribution of the possible outcome with corresponding probabilities. To isolate the effects of service stacking, no forecasting models have been implemented in **Papers III – VI** but is certainly an interesting topic for future research. To minimize such errors, historical data was used as perfect predictions in **Papers III - VI**.

4.3.2 Bid strategies

In real-world implementations where ESS operators participate in markets for various services, it is possible to place a bundle of bids as an alternative to placing single bids for each MTU. Thus, the operator carefully has to evaluate the risk of bids not being cleared, which is not always an easy task. Bids with higher clearing price could potentially yield higher profit but come with a higher risk of not being cleared, and vice versa for lower clearing prices. Another parameter to consider within the risk assessment is the probability of activation of some services e.g., FCR-D which is activated only if there is a disturbance large enough to activate the regulating objects contracted for the particular hour. In **Papers III – VI** only single bids have been considered due to the simplified forecasting method implemented as previously described. Also, to evaluate the probability of FCR-D activation a probabilistic approach

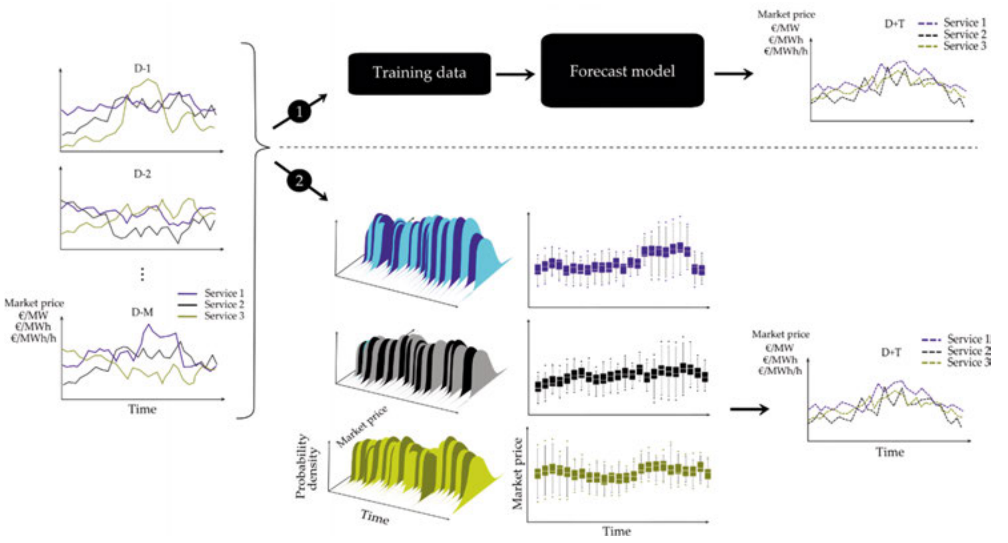

Figure 41. Illustration of two possible methods for forecasting market and system dynamics. **Paper I.**

was implemented instead of activation by frequency measurement data to create a more generic study.

4.3.3 Multi-objective optimization

When implementing complex service stacked portfolios it is a natural instinct to request a portfolio which optimizes not only e.g., profit or self-sufficiency of locally generated electricity, but rather a scheduling tool that accounts for multiple objectives within the same optimization problem. *Multi-objective optimization* (MOO, also *multi-criterion,* or *Pareto optimization*) is a more advanced formulation of the service stacking problem, where the objective function is formulated as a set of functions, $F(X)$ and the optimization problem is formulated by Eq. (4.2):

$$\begin{aligned} &\min F(X) \\ &s.t.\, g(X) \geq 0 \\ &s.t.\, h(X) = 0 \end{aligned} \tag{4.2}$$

When considering the MOO approach formulated in Eq. (2), there will be many solutions X that minimizes F due to fact that the different objectives of F are in conflict to some extent. Therefore, it is more convenient to first obtain the *Pareto front* which is the compilation of all mathematically equal optima, and thereafter a single optimum can be selected based on the formulation of the problem. Further reading regarding MOO can be done in [74]–[76].

4.3.4 Scheduling over several timescales

The services and applications described in Chapter 3 do not necessarily target phenomena that occur in the same time scale. For example, *Energy Time Shift* and other energy specific services operate in time perspectives over several hours, days or seasons, while e.g., voltage regulation and other power quality services operate within the time frame of seconds. It is also a significant difference between scheduling ESSs for services which are purchased or contracted day-ahead compared to intraday trading, and it becomes even more difficult when combining these. This adds another dimension to the service stacking problem: is it worth to keep some hours free for intraday trading, with the risk of doing nothing? Or should all hours be scheduled for day-ahead trading with possibly reduced profit?

4.4 Literature review results

The main results of the literature review (**Paper I)** are summarized in Figures 42 to 44. First, Figure 42 shows the distribution of services which the reviewed articles included, and it can be seen that a large number of studies did include energy arbitrage and services for frequency regulation in their portfolios, followed by services for RES integration and T&D investment deferral. This can partially be explained by the fact that energy volumes and power capacities for energy arbitrage and several services for frequency support are purchased via mature markets, are not placement-specific and are contracted on a day-ahead markets. Together, these aspects combined make them fairly easy to include in portfolios if the technical requirements of the services are fulfilled by the ESS. Furthermore, Figure 43 shows the distribution of the most common service combinations where it can be seen that the combination of energy arbitrage and frequency regulation was the most common. Other frequently considered combinations included RES integration, e.g., RES integration together with frequency regulation or energy arbitrage, but also peak shaving. Co-scheduling of RES integration with additional services is a natural approach to aim for since e.g., wind and solar generation come with large periodic fluctuations. Together with good forecasting of RES generation it possible to stack services efficiently, and the service range will depend on the placement and size of the ESS.

Moreover, Figure 44 shows the distribution of ESS power and energy capacities, and it can be seen that a majority of the considered ESS were between 0.1 – 10 MW and MWh, and only a few studies considered ESS larger than 100 MW and MWh. The average power-to-energy ratio (C-rating) was 0.75,

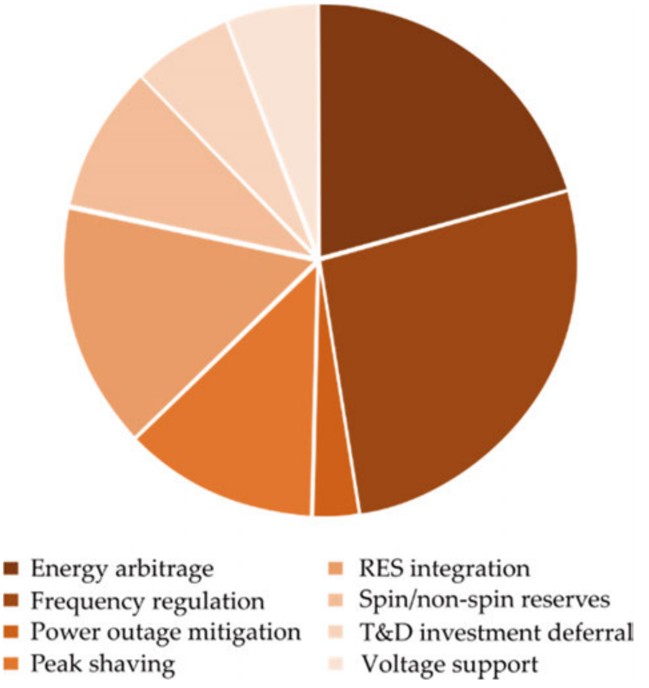

Figure 42. Distribution of services. **Paper I.**

where the highest was 4 and the lowest 0.1. This indicates that among the reviewed articles, it was more common to consider ESSs with C-ratings lower than but not too far away from 1. Finally, a few real-world examples of where service stacking has been implemented for large-scale ESSs are compiled in Table 9. From Table 9 it can be seen that the concept has been implemented for ESSs of varying capacity and technology spread over a large geographical area. This further illustrates the width of the potential of service stacking.

4.5 Summary

To briefly summarize the content presented in Chapter 4, service stacking has been investigated for a wide range of ESS technologies, power and energy capacities and service combinations in portfolios. It is a promising method that increases the availability of the storage capacity towards the power system, which is valuable on both local and system level. There are several challenges that arise with implementation of service stacking, where a few examples are sizing, placement, planning/control/communication, and the trade-off between revenue and storage degradation. Since the prerequisites and the context varies for each ESS installation it is important to remember that this is a

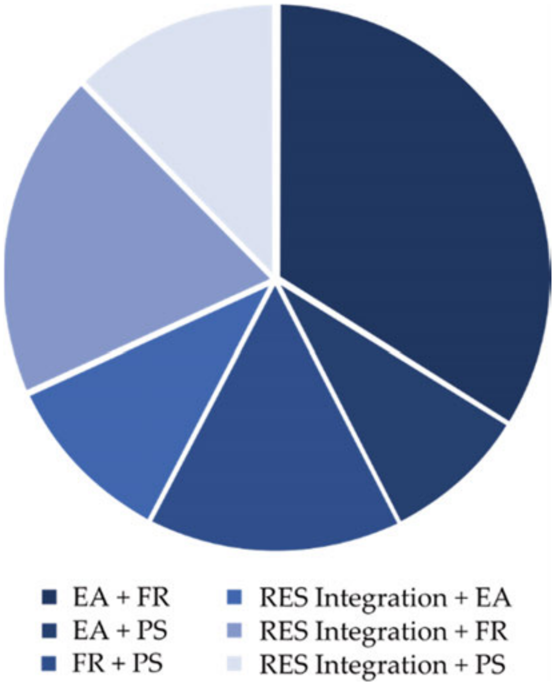

Figure 43. Distribution of most common service combinations. **Paper I.**

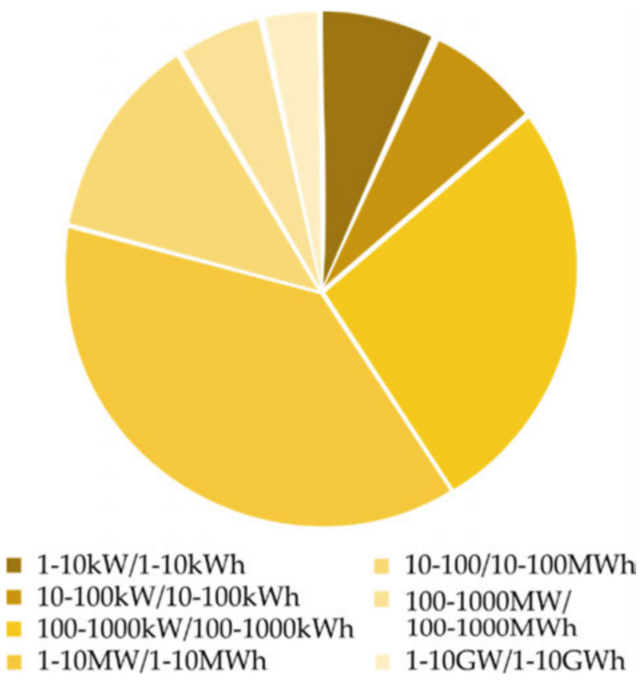

Figure 44. Distribution of ESS sizes. **Paper I.**

case-by-case evaluation, but the trends that are recognized in the results of the review are highly valuable for operators and investors when considering implementation of service stacking. Lastly, a common attitude among the authors of the reviewed articles is that use cases where multiple services are bundled has to become more common and more promoted in order to create a competitive baseline for ESS implementations.

Table 9. A selection of real-world examples where ESSs have implemented service stacking. **Paper I.**

Location	Storage technology	Rated capacity [MW/MWh]	Services
Dinorwig, Wales	PHES	1728/9100	Energy time shift Frequency regulation Spinning reserve
Abingdon, England	FES	400/1.44	On-site power supply Frequency regulation
Huntorf, Germany	CAES	290/480	Minute reserve Spinning reserve
Alabama, USA	CAES	110/2700	Energy time shift Frequency regulation Spinning reserve
Hornsdale, Australia	BESS	100/129	Energy arbitrage Non-spin reserve
Leighton buzzard, England	BESS	6/10	Congestion relief Energy time shift Frequency regulation Non-spin reserve
Uppsala, Sweden	BESS	5/20	Congestion relief Frequency regulation
Vermont, USA	BESS	4/3.4	Backup power Microgrid Peak shaving
Darlington, England	BESS	2.5/5	Congestion relief Energy time shift Voltage support

5. Implementations of service stacking for energy storage systems in congested distribution grids

Chapter 5 covers the content of the appended **Papers II – VI** where service stacking has been implemented for both large and small-scale ESSs. First, the large-scale storage implementations will be presented (**Papers II – IV)** followed by a case study that concerns distributed ESS capacity at sports facilities (**Paper V)**. Finally, **Paper VI** evaluates the effects on congested distribution grids for high shares of distributed ESSs with service stacked portfolios which are compared to the effects in the case with centralized ESSs. Since **Papers II – VI** follow the same topic and were written partially based on the results from previous work, the aim, method, and main results of each paper will be presented in chronological order before proceeding to the next paper.

5.1 Large-scale energy storage systems for congestion management and additional services in Uppsala, Sweden

Uppsala is one of the cities in Sweden which has experienced grid congestion challenges, mainly due to the fast expansion rate of the city with a growing population and requests for industry establishment – but also in combination with the decommissioning of the local CHP electricity generation[21, 22]. The regional peak demand typically occurs during the winter and the distribution of the 250 highest load hours per year for the years 2018 – 2022 are compiled in Figure 45. From Figure 45 it can be noted that the peak load typically occurs in the evening when people arrive at home after work during the months December to February. Furthermore, Figure 46 shows a scatter plot of the regional peak load as a function of the ambient temperature for the same period and a clear trend can be seen where the load demand increases as the temperature decreases for temperatures below 15 °C. In **Papers II – VI**, ESSs are proposed to assist with the congestion management by providing flexibility-as-a-service, and the targeted grid load is market by the ellipse in Figure 46.

[21] Region Uppsala, *Forecast of population size*, https://regionuppsala.se/ (Accessed 2023 09 25)
[22] Uppsala Municipality, *How we work with: trade and industry,* https://uppsala.se/ (Accessed 2023 09 28)

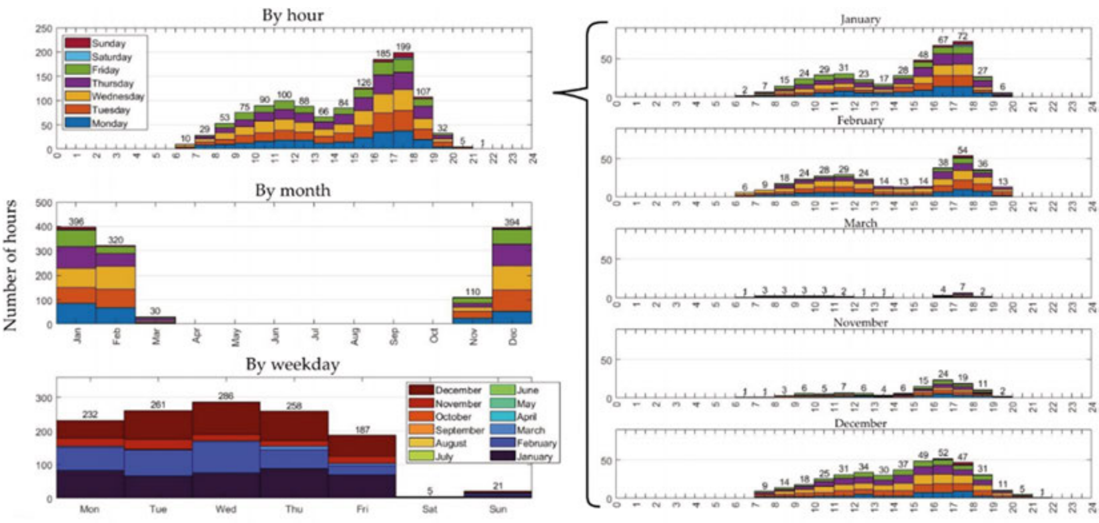

Figure 45. Grid load peaks in network area UPP for the years 2018 - 2022. **Paper IV.**

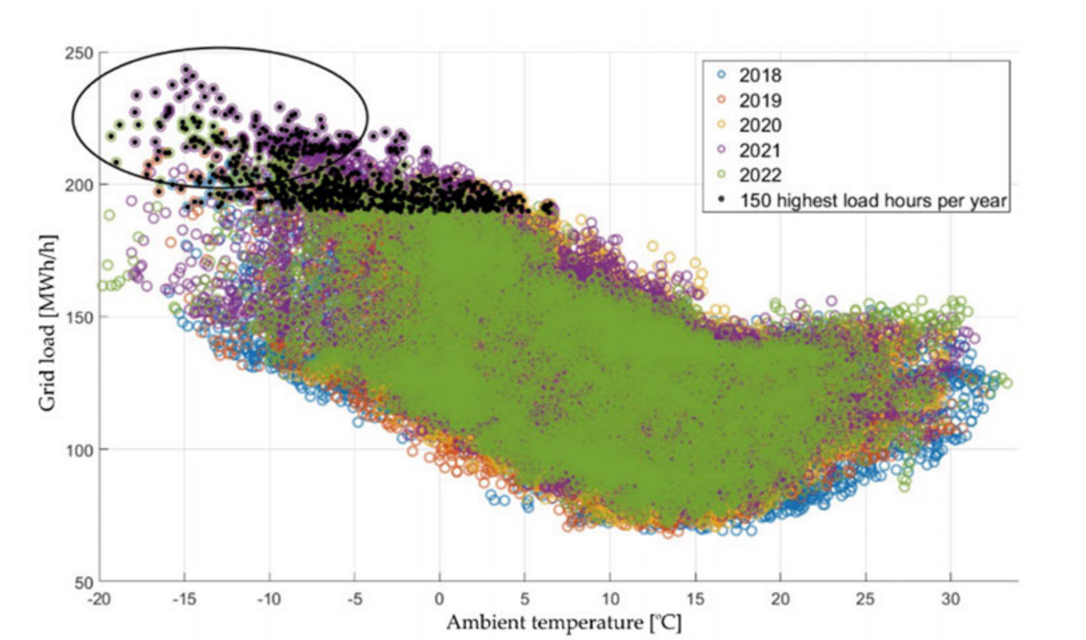

Figure 46. Scatter plot of grid load as a function of ambient temperature for the years 2018 - 2022. The ellipse shows the targeted peak load. **Paper IV.**

In December 2020, a 5 MW/20 MWh BESS was connected to the grid in the outskirts of Uppsala, Sweden, as part of a research and development (R&D) project within Vattenfall AB. It is owned and operated by Vattenfall Network Solutions and a photo from the site is shown in Figure 47. There were several aims with the BESS installation, where one was to study how the BESS could assist the grid during the peak load periods and how it could be used to provide other services during less stressful periods.

Papers II - VI focused on the same regional context and considered cases for centralized (**Papers II – IV** and **VI)** and distributed (**Papers V – VI)** ESSs where service stacking was implemented to increase the degree of utilization of the ESS. The additional availability for power system applications could generate value for both DSOs and the TSO, and also for the end-users if connected behind-the-meter for local purposes while creating important revenue streams.

Figure 47. Photography of BESS installation site in Uppsala, Sweden. **Paper II.**

Paper II

The aim of **Paper II** was to identify possible effects in the grid voltage when operating the BESS for grid services and to promote possible solutions for service stacking implementations. A test cycle was designed to fulfil the requirements for both flexibility and FCR-D services and is shown in Figure 48.[23] The cycle started with activation from idling to discharge at full rated

[23] The requirements which applied during the time of the study were 50% activation within 5 seconds, and full activation within 30 seconds. The most recent requirements are presented in Chapter 3.

power within 30 seconds, followed by a mode switch from 5 MW discharge to 1 MW charging before finally returning to idling.

The main results from the measurements are shown in Figures 49 and 50, where power flow and grid voltage are shown for the three events and also for a longer period during the same day. First, from Figure 49 the subfigures for event (a) shows the ramping from idle to discharge mode and it can be seen that the activation was done within the timeframe of the requirements. The 5 MW discharge of the BESS caused no remarkable deviations in the grid voltage during this period. Furthermore, in event (b) the jump from 5 MW discharge to 1 MW charge was done – also accomplished within the activation requirements and with no large effects on the grid voltage. Finally, in stage (c) the BESS was set to idle mode again. The grid line-to-line voltages were measured for a few hours before and after the performed test and are shown in Figure 50, from which it can be noted that the voltage was kept at a stable level during the entire period. Finally, it was proposed in **Paper II** that the BESS have a great potential to provide multiple services to increase the availability of the BESS capacity for power system applications while creating important revenue streams for the BESS operator at the same time. This was the first step in the process of implementing service stacking for a large BESS in a congested distribution grid which has been further evaluated in **Papers III, IV** and **VI**.

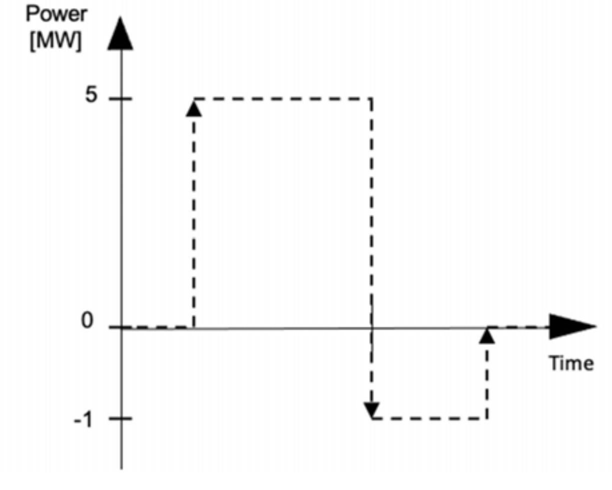

Figure 48. Test cycle of the BESS, with power flow according to the generator sign convention. **Paper II.**

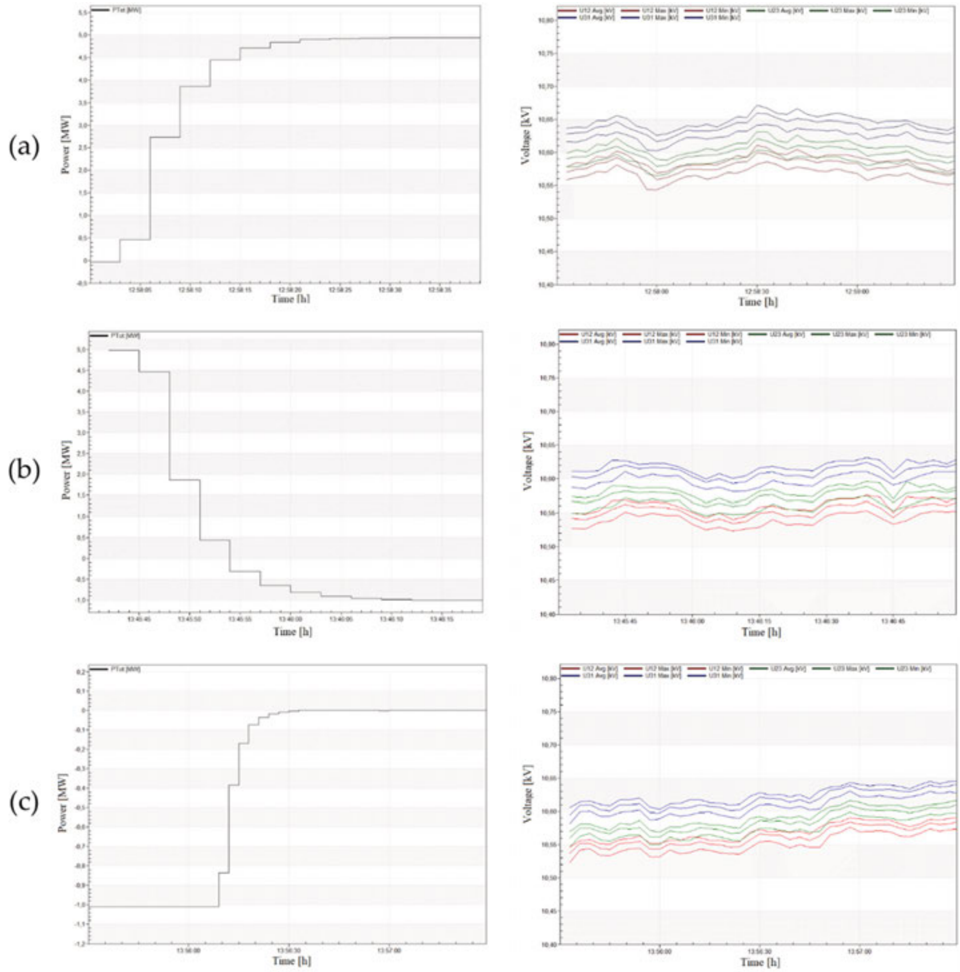

Figure 49. Power flow and voltage fluctuations during the events of the test cycle. (a) Ramp up from idle to discharge mode, (b) jump from discharge to charge mode, (c) Ramp down from charge to idle mode. **Paper II.**

Paper III

Provided the background and previous analysis from **Papers I – II**, the aim of **Paper III** was to implement the ideas of service stacking for a large BESS in a congested grid. The aim was further to illustrate how service stacking potentially could enhance the value of a grid connected ESS in a congested distribution grid and included the implementation of an ESS service scheduling optimization tool. Additionally, the aim of **Paper III** was also to include tools for estimating the cycle aging of the BESS for the considered cases and was part of the technical KPIs. It was desired to design a service portfolio complex

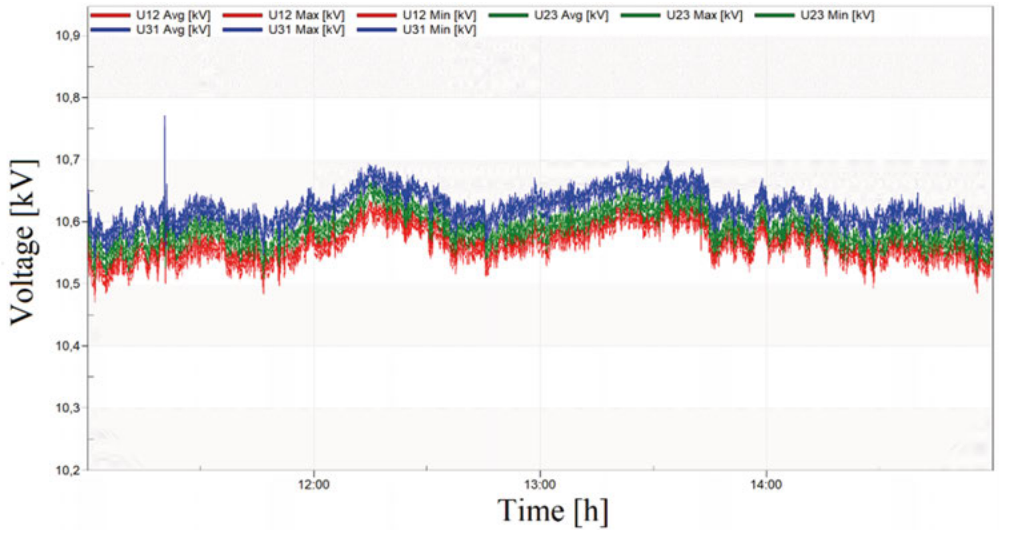

Figure 50. Measurement data for phase voltages. **Paper II.**

enough to require an optimization solver for determining the scheduling strategy. This was accomplished by including flexibility-as-a-service, energy arbitrage and FCR-D up in the portfolio, which are three services of different character and technical requirements. An overview of the market trading windows for the included services are shown in Figure 51 together with a few other markets and services to put the selected ones into a broader perspective. From Figure 51 it can be seen that the capacity for all considered services are purchased or contracted within two days before the day of delivery, D.

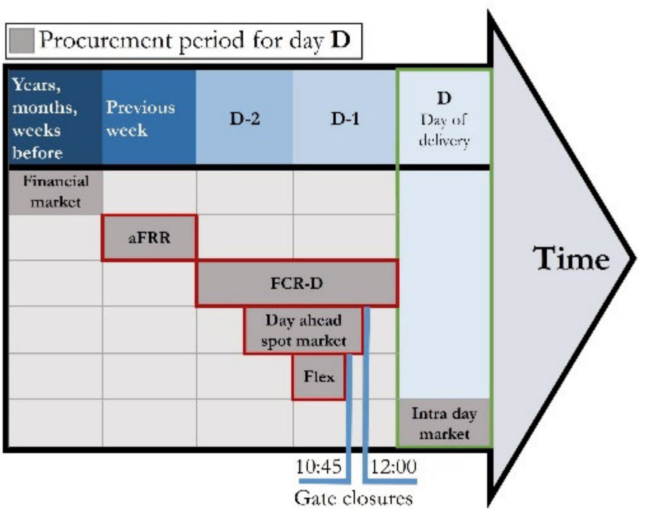

Figure 51. Market trading windows for the included services. **Paper III.**

Furthermore, an overview of the created and implemented scheduling tool is shown in Figure 52 where the flow chart starts with the inputs on the left-hand side and ends with the output KPIs on the right-hand side. The scheduling tool consisted of three major blocks: *predictions, schedule optimization* and *bid clearing & activation*, followed by the considered technical and economic KPIs. In **Paper III**, only the technical KPIs were included in the study. The first step included obtaining predictions of the hourly clearing price for all included markets and services in the portfolio and were necessary since they determined the economic value of each service. Forecasting and time series prediction come with errors and uncertainties, and if the implemented prediction model would yield estimations with poor accuracy there would be a risk of bids not being cleared. Thus, to minimize the impact from forecasting errors and to maintain focus on the potential of service stacking, historical data was used to create perfect predictions for all markets, load demands and local generation profiles in **Papers III – VI**. Uncertainties and risks that arise by implementing forecasting models and different bid strategies are further discussed in Chapter 7.

Furthermore, the second step covered the scheduling optimization block and used the obtained time series predictions as input. The scheduling problem was formulated as a profit maximization problem using a rolling-horizon approach where one day (24 hours) was scheduled at the time for the full period. It was formulated as a LP with equality and inequality constraints and was solved with MathWorks: MATLAB. Since most solvers deal with minimization, the problem was reformulated as a minimization problem. In **Paper III** the general optimization problem was formulated according to Eq. (5.1):

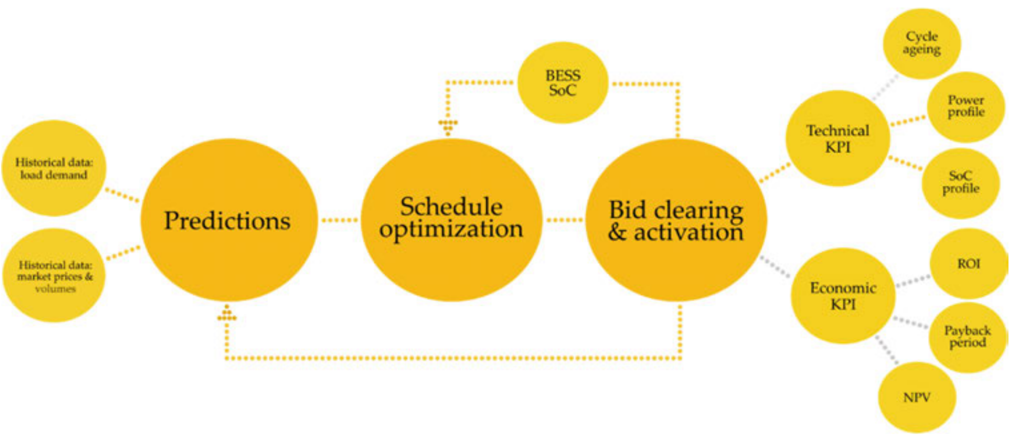

Figure 52. Flow chart of the implemented scheduling tool. **Papers III-VI.**

$$
\begin{aligned}
\min & -f(x) \\
s.t.\ & g(x) \geq 0 \\
& h(x) = 0
\end{aligned} \tag{5.1}
$$

In Eq. (5.1), $f(x)$ is the objective function, $g(x)$ is the set of active inequality constraints and $h(x)$ is the set of active equality constraints. The objective function was formulated according to Eq. (5.2) as:

$$
f(x) = \sum_{i=1}^{24} \sum_{j=1}^{3} \left(P_{i,j}\pi_{i,j}^{e}t_{i,j} + P_{i,j}\pi_{i,j}^{c} - \frac{P_i^{charge}\pi_i^{charge}t_i}{\eta} \right) \tag{5.2}
$$

Where i is the hour index, j is the service index, $P_{i,j}$ is the BESS active power (MW), $\pi_{i,j}^{e}$ is the energy remuneration (€/MWh), $\pi_{i,j}^{c}$ is the capacity remuneration (€/MW), $t_{i,j}$ is the duration time during activation (endurance), and η is the efficiency. Recall from Chapter 3 that the type of remuneration will vary for each service. Furthermore, the BESS operation was constrained by its technical boundaries regarding power and energy (state of charge, SoC), formulated in Equations (5.3 – 5.5). Additionally, the BESS was limited by a maximum cycle intensity of 2 full cycles per day, formulated in Eq. (5.6).

$$
0 \leq P_{i,j} \leq 5 \text{ [MW]} \tag{5.3}
$$

$$
\sum_{j=1}^{3} \left(P_{i,j}\right) + P_i^{charge} \leq 5 \text{ [MW]} \tag{5.4}
$$

$$
\mathrm{SoC}_{min} \leq \mathrm{SoC}_{\mathrm{ini}} + \sum_{i=1}^{24} \sum_{j=1}^{3} \left(\frac{P_i^{charge}t_i\eta - P_{i,j}t_{i,j}}{E^{tot}} \right) \leq \mathrm{SoC}_{max} \tag{5.5}
$$

$$
\sum_{i=1}^{24} \sum_{j=1}^{4} P_{i,j}t_j \leq kE^{tot}(\mathrm{SoC}_{max} - \mathrm{SoC}_{min}) \tag{5.6}
$$

Finally, the BESS was also limited to be scheduled for either charging or provision of one service in each hour only. This was accomplished by introducing a binary optimization variable $\alpha \in [0,1]$ and related to the active power by the constraints given by Equations (5.7) and (5.8):

$$
\frac{P_{i,j}}{P_{max}^{BESS}} \leq \alpha_{i,j} \leq P_{i,j} \tag{5.7}
$$

$$
\sum_{j=1}^{3} \alpha_{i,j} + \alpha_{i,charge} \leq 1 \tag{5.8}
$$

The estimation of the cycle aging was done based on the method and results obtained in [77], where empirical testing of Li-ion cells was performed, and a capacity life loss model was obtained. The estimated degradation from cycling could then be estimated by Equations (5.9) and (5.10):

$$Q_{loss} = 30.330 \exp\left(\frac{-31500}{8.314T}\right) A_h^{0.552} \tag{5.9}$$

$$A_h = Cycle\ number\ \cdot DoD\ \cdot Cell\ capacity \tag{5.10}$$

The main results of the study are compiled in Figure 53, where typical winter and summer profiles are shown for the fully stacked portfolios. The empty bars are cleared bids (C) and the filled bars correspond to the final activation of the ESS. As can be seen from Figure 53, the scheduling optimization tool managed to schedule the BESS for multiple services during the year, where flexibility was provided during the peak load in the winter period and the remaining capacity was allocated for FCR-D up. It was also possible to estimate the cycle aging as result of the operational strategies at varying operating cell temperatures, and the results are compiled in Table 10, where the reference case corresponds to when the BESS provides flexibility service only. The main contribution of **Paper III** is the proposed method where several services could be scheduled successfully during both winter and summer seasons using LP. The presented results are slightly up-scaled regarding cleared flexibility capacity, activation of FCR-D up capacity and the energy dispatched during FCR-D up activation since the study was presented as work in-progress. More accurate and fine-tuned results are presented in **Paper IV.**

Table 10. Summary of estimated capacity life loss. **Paper III.**

Case	**Capacity life loss [%]**		
		T [°C]	
	15	45	60
Reference	0.69	2.41	4.12
Service stacking	1.72	5.93	10.14

Paper IV

The aim of **Paper IV** was to further investigate the potential of the previously described BESS in **Papers II** and **III**. The work in-progress results shown in Figure 53 indicated that it was more convenient to aim for providing ancillary services rather than energy arbitrage, thus the service portfolio was extended with another important ancillary service managed by the TSO, namely fast frequency reserve (FFR). This service is included in the portfolio of *remedial actions* managed by the Swedish TSO, where the contracted capacity is activated very fast when a larger disturbance in the grid occurs – see Table 7 in

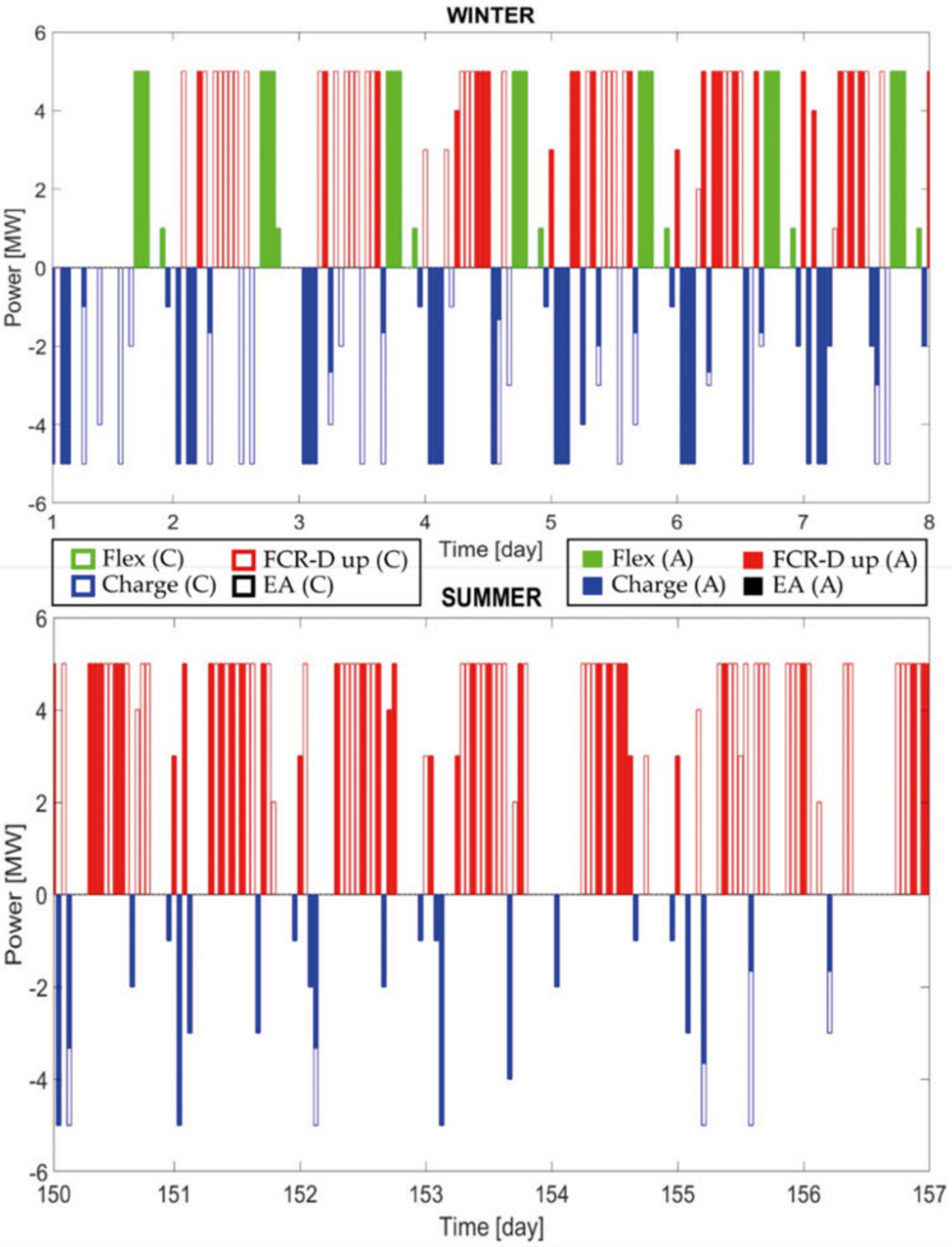

Figure 53. Typical winter and summer profiles for the fully stacked portfolio. Letters C and A correspond to “cleared” and “activated” profiles of the BESS. **Paper III.**

Chapter 3 for more details. The need for FFR capacity is mainly during the summer period when the large and heavy rotating machines of the nuclear power plants are disconnected during maintenance i.e., when the total amount of inertia in the power system is lower than during normal operation. Thus, including FFR and flexibility-as-a-service in the same portfolio could be a good match since the market periods do not interfere with each other. Furthermore, it is also of importance to clarify how the electricity spot price affects the tendency of allocating capacity for energy arbitrage. Therefore, the scheduling optimization tool was used to schedule the BESS for two separate years during which the spot price was significantly different. The bid clearing prices for all considered markets are shown in Figure 54 for the years 2021 and 2022.

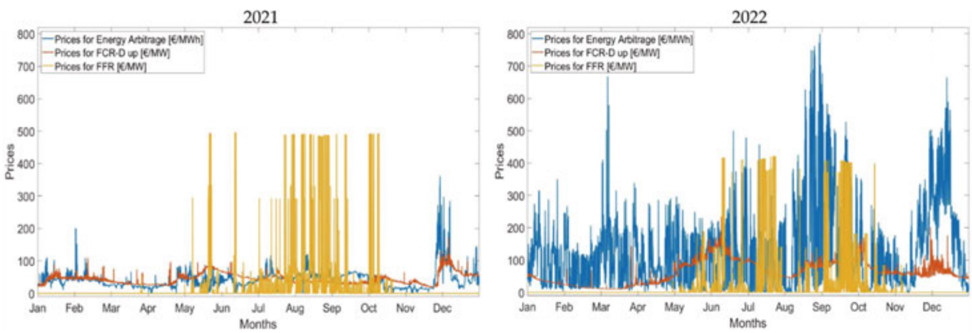

Figure 54. Historical data for the electricity spot prices (€/MWh), hourly average FCR-D up clearing price (€/MW) and FFR (€/MW) for the years 2021 and 2022. **Paper IV.**

Finally, the last part of **Paper IV** covered two sensitivity analyses: first, the cycle intensity constraint where the constant k was varied between 1 and 2.5 to illustrate the effects on available energy on daily basis; and second, the energy amount dispatched during FCR-D activation was varied between 0.5 and 20 minutes, thus effects on the service allocation for different values of reserved energy were evaluated. For the main simulations where the portfolios were compared, this value was chosen to 2 minutes.

The methodology presented in Equations (5.1 – 5.10) were updated for provision of one additional service, and in **Paper IV** the economic analysis was included as well i.e., all circles in the flow chart shown in Figure 52 were considered. To estimate the net present value (NPV), return on investment (ROI) and payback period (PP), the generated profit after one year of operation was calculated for each portfolio by Eq. (5.11). In Eq. (5.11), k is the day index, $R_{j,k}$ is the generated revenue and $C_{j,k}^{e}$ is the costs of energy for each day (€/day), and $C^{O\&M}$ is the cost for operation and maintenance (OPEX, €/year). R and C were calculated by Equations (5.12) and (5.13):

$$Profit = \sum_{j=1}^{4}\sum_{k=1}^{365}\left(R_{j,k} - C_{j,k}^{e}\right) - C^{O\&M} \tag{5.11}$$

$$R_{j,k} = \sum_{i=1}^{24} P_{i,j}\pi_{i,j}^{c} + \sum_{i=1}^{24} P_{i,j}\pi_{i,j}^{e}t_j \tag{5.12}$$

$$C_{j,k} = \sum_{i=1}^{24} P_i^{charge}\pi_i^{charge}t_j \tag{5.13}$$

By estimating the NPV for each year during the investment period for all scenarios it was possible to calculate the ROI, and the PP could be determined by finding the break point when the NPV turned positive. The NPV and ROI were calculated using Equations (5.14) and (5.15), and the values for the residual value (RV), investment horizon (*m*), interest rate (*r*), OPEX and investment costs (CAPEX) are summarized in Table 11.

$$NPV = \frac{RV}{(1+r)^m} - CAPEX + \sum_{i=1}^{m}\frac{Profit}{(1-r)^l} \tag{5.14}$$

$$ROI = \frac{NPV_m}{CAPEX} \tag{5.15}$$

Table 11. Parameters for economic evaluation.

Parameter	**Value**
CAPEX	300 €/kWh (341 $/kWh) [78]
Interest rate	5 %
Investment horizon	15 years
OPEX	2.5 % of CAPEX annually [79]
Residual value	33 % of CAPEX

The main results of **Paper IV** are compiled in Figures 55 and 56. Figures 55 and 56 show typical winter and summer profiles for the considered BESS, and similar to Figure 53 the empty and filled bars correspond to cleared bids and ESS activation correspondingly. In Figures 55 and 56 for Scenarios 2 and 4 it can be noted that the BESS was scheduled for a large majority of the time due to the possibility of placing a large number of bids for FCR-D up – which agreed with the preliminary results from **Paper III**. Furthermore, the tendency of allocating capacity for energy arbitrage was small, especially during year 2021 when the electricity price was lower. Although, from Figure 56 it can be noted that energy arbitrage was scheduled for a few hours during both the winter and summer periods in Scenario 4 due to the high electricity spot prices, but the majority of the service provision targeted FCR-D up. Another effect of the varying spot price can be seen when considering Scenario 1 in both Figures 55 and 56, where the number of daily cycles is significantly more during year 2022 which was expected. Finally, the provision of FFR was successfully scheduled during the summer period when the prices were higher than the ones for FCR-D up and can be seen in Scenario 4 for both years.

Furthermore, the simulation results showed that the outcome for the two considered years varied for almost all scenarios. The results for Scenario 1 were clearly affected by the higher electricity prices in year 2022 and a larger number of cycles was registered – which affected the total cycle aging i.e., the degradation of the BESS. The high spot prices resulted in a PP of 7 years, but in the case of more regular price fluctuations in year 2021 the investment was not financially motivated. In Scenarios 2 and 3, the provision of FCR-D up and FFR did not affect the cycle aging remarkably due to the small energy throughput compared to energy arbitrage in Scenario 1, and the economic KPIs also showed better results where the PP was estimated to between 3 and 7 years with ROI between 1.90 and 8.25. Finally, the results for the fully stacked portfolios in Scenario 4 were also affected by the varying electricity spot price where the increased capacity allocated for energy arbitrage is reflected by the increased cycle aging. The economic KPIs were mainly affected by the differences in clearing prices of the FCR-D up and electricity spot day ahead markets, which resulted in a shorter PP and higher ROI if the conditions were extrapolated according to the prices during year 2022.

Regarding the sensitivity analysis of allowed cycle intensity for the fully stacked portfolios, the results indicated that the most sensitive region was between 1 and 1.5 cycles per day since the majority of the capacity was allocated for ancillary services with small energy throughput. Although, it can be noted that the differences were larger for year 2022 when the electricity prices were higher, and more capacity was allocated for energy arbitrage. Finally, the sensitivity analysis regarding the reserved energy for FCR-D up activation showed that by allocating less energy for each bid of FCR-D up the number of hours increases significantly, which is logic.

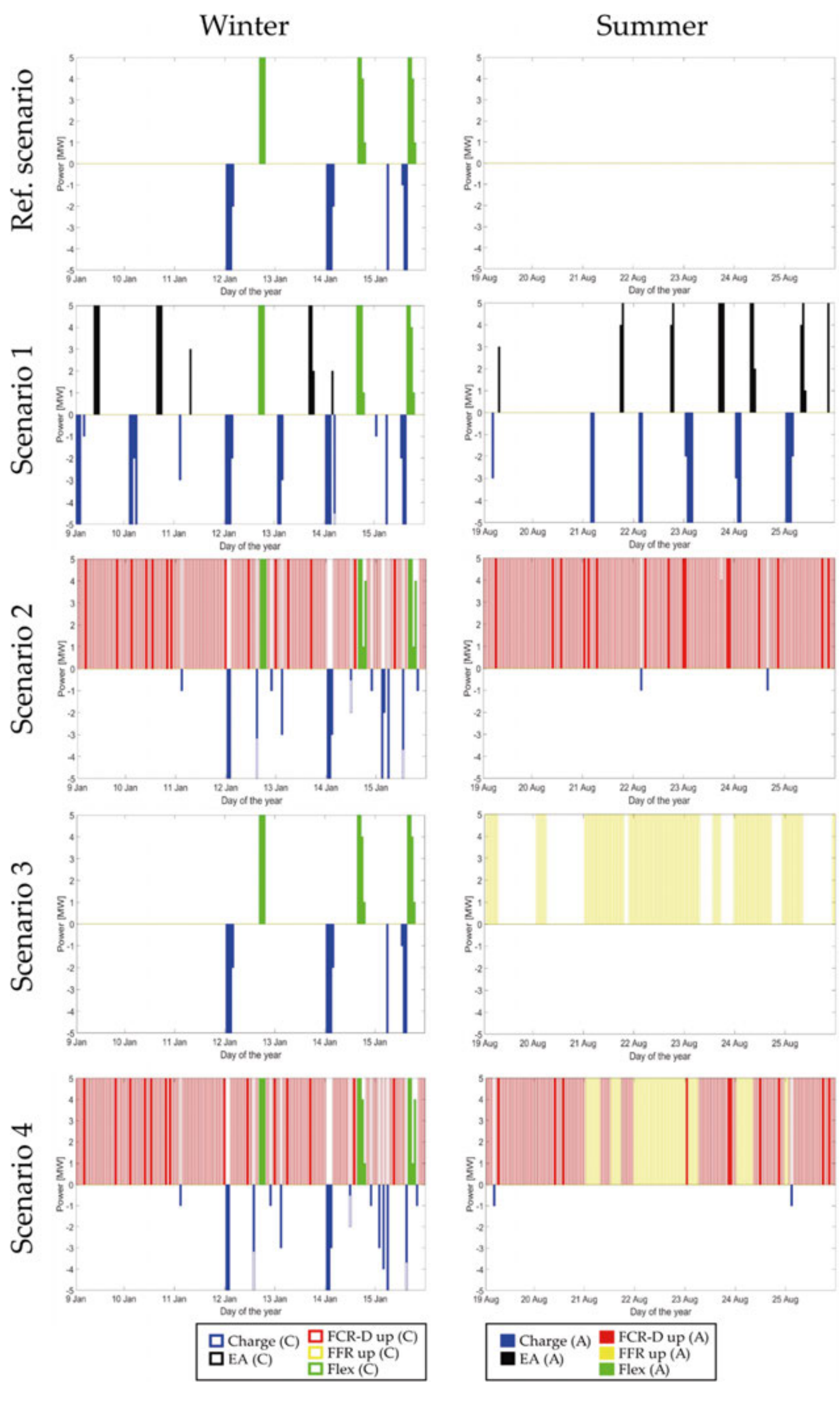

Figure 55. Winter and summer profiles for the reference case and the four evaluated scenarios for year 2021. Empty boxes show cleared bids (C) and filled boxed show the final activation (A) of the BESS. **Paper IV.**

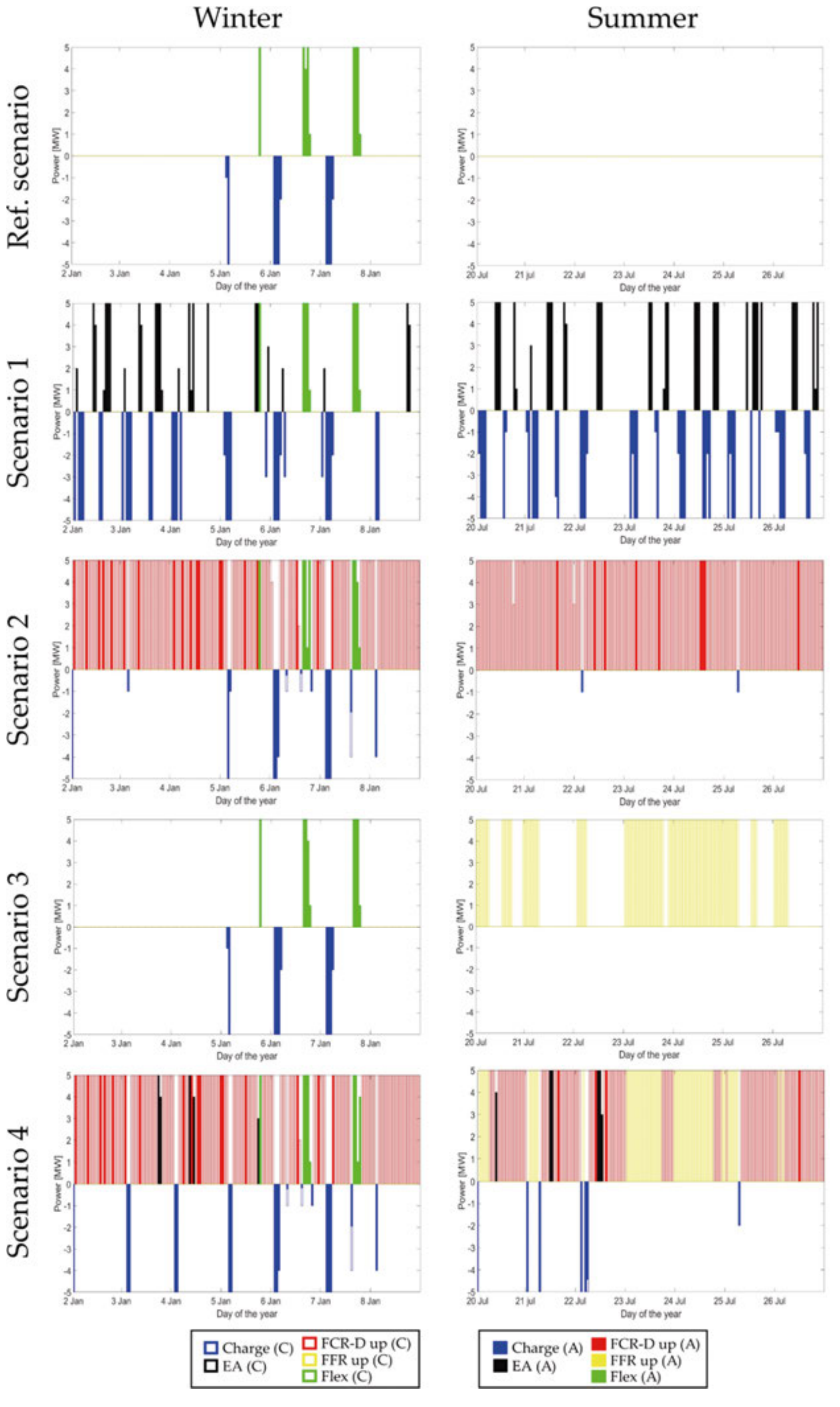

Figure 56. Winter and summer profiles for the reference case and the four evaluated scenarios for year 2022. Empty boxes show cleared bids (C) and filled boxed show the final activation (A) of the BESS. **Paper IV.**

5.2 Energy storage systems at sports facilities for congestion management and additional services

Paper V

The aim of **Paper V** was to implement service stacking for a customer-sited ESS for provision of congestion management (flexibility) and additional services. More specifically, the services included in the portfolio were chosen to local tariff optimization, flexibility service and FCR-D up and was simulated for two separate years, namely 2021 and 2022. For this study, *Uppsala Municipality: arenas and real estate* was considered due to the large electricity demand during the period when the regional grid experience its peak load. Additionally, there are plans for connection of a rooftop-mounted PV system on one of the recently built stadiums in Uppsala, Studenternas IP – and was therefore chosen as the considered load for this analysis. The capacity of the considered BESS was chosen to 150 kW and 300 kWh, and the rated energy capacity was also evaluated in a sensitivity analysis - see **Paper V** for all details regarding ESS sizing. An overview of the soccer stadium and the neighboring bandy stadium is shown in Figure 57, and the aggregated electricity demand of the two stadiums is shown in Figure 58 for the years 2020 to 2022. From Figure 58 it can be seen that the electricity use in year 2020 was significantly lower during the first months of the year due to the opening of the new soccer stadium, but during the remaining time of the considered period the annual profile looks similar for all years. The ice rinks of the bandy stadium have to be formed and maintained from October until the middle of March, thus the electricity demand is much higher during this period.

Due to the large electricity consumption, the facility requires a high-voltage electricity contract which includes a cost component based on the peak load – making the optimization problem more complex compared the one considered in **Papers III – IV**. Therefore, the scheduling optimization solver was chosen based on a metaheuristic approach, more specifically the GA which has the ability to solve more complex problems than the previously implemented method based on LP. Choosing an appropriate method for this problem required a decision where one among several available methods had to be selected. This is further debated in the general discussion in Chapter 7. The complete composition of the high-voltage tariff is presented in Figure 59.

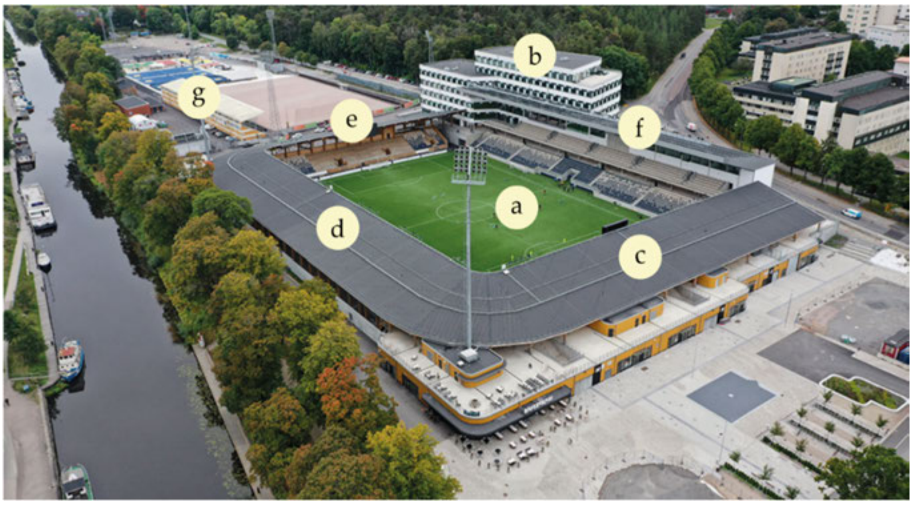

Figure 57. Overview of Studenternas IP. (a) Soccer stadium, (b) gym and offices, (c) north stand, (d) east stand, (e) south stand, (f) west stand, (g) bandy and ice rink. **Paper V.**

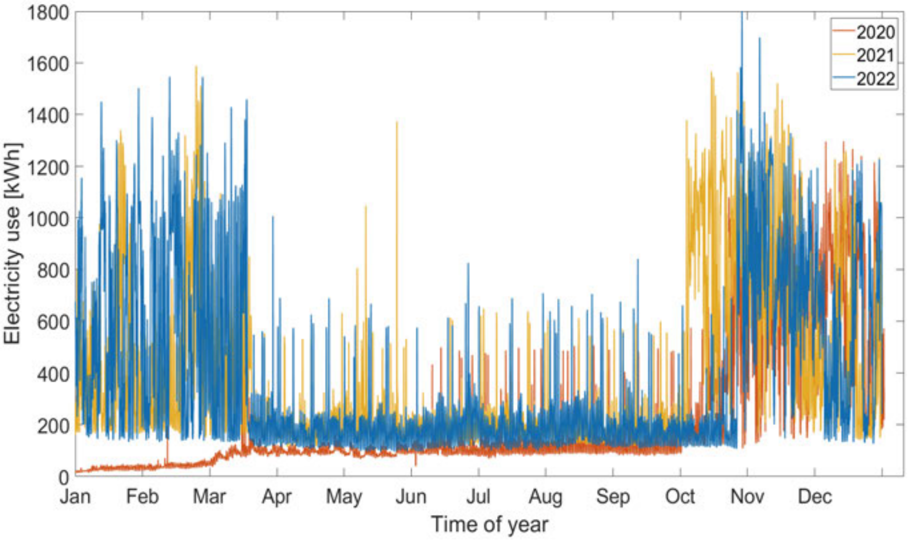

Figure 58. Electricity use of Studenternas IP during years 2020 to 2022. **Paper V.**

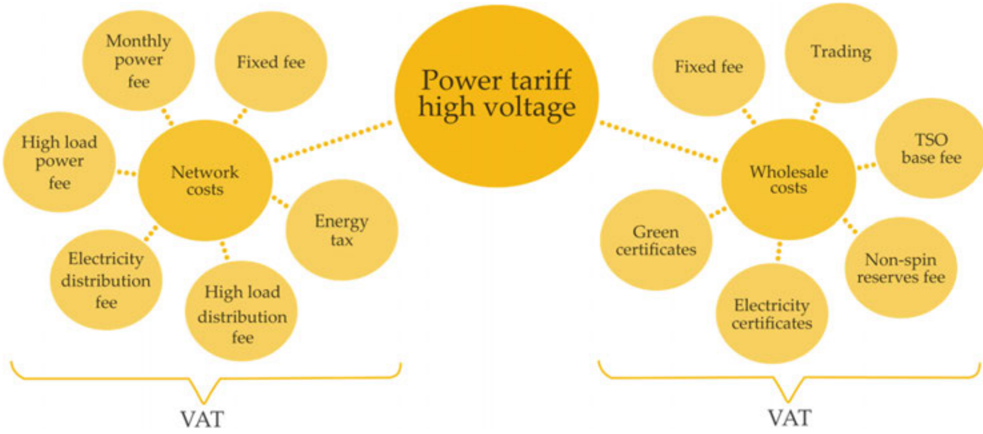

Figure 59. Overview of the tariff components. **Paper V.**

The iterative process used by the GA in the search for an optimal solution is illustrated in Figure 60. The initial population (i.e., the starting guess) is evaluated where all individuals of the population are scored, and the best fitting solutions are saved for the next iteration. The remaining solutions are then stochastically changed either through mutation or crossover, and new solution to evaluate are obtained (also called *children*) and saved for the next iteration that then replace the bad solutions in the current population. The population is updated iteratively until one of the defined stopping criteria is met, e.g., tolerance in the change of the fitness function value, number of generations to evaluate, or the total simulation time.

The first main difference in the formulation of the optimization problem compared to previous work concerns the definition of fitness function (i.e., the objective function), and was formulated according to Eq. (5.16) as:

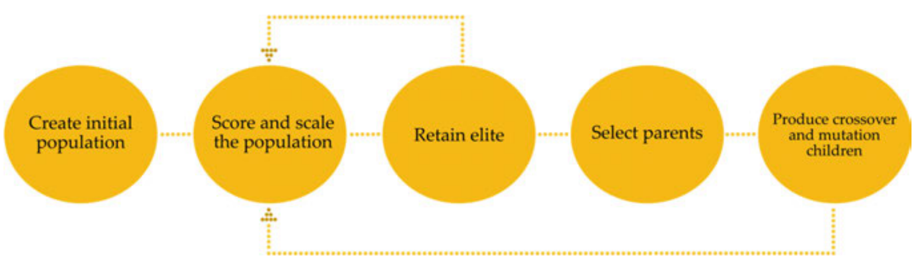

Figure 60. Flow chart of the genetic algorithm working principles. **Paper V**.

$$
\begin{aligned}
f(x) = W\pi_{peak}\max(P_{net}) + \sum_{i=1}^{24}\pi_e P_{net,i} - \sum_{i=1}^{24}\alpha_{3,i}\pi_{flex,i}P_{flex,i}t_{flex,i} \\
- \sum_{i=1}^{24}\alpha_{4,i}\pi_{FCR_D,i}P_{FCR,i}t_{FCR} + Penalty \qquad (5.16)
\end{aligned}
$$

Where *i* is the hourly index, π_{peak} is the monthly power fee (€/kW), π_e is the cost for electricity (€/kWh), π_{flex} is the flexibility clearing price (€/kWh) and π_{FCR_D} is the hourly average price for FCR-D up (€/kW). Furthermore, P is the active power allocated for each service (kW), t is the duration time for each service (hours), and P_{net} is the net power of the stadium (kW) which was calculated by Eq. (5.17):

$$
\begin{aligned}
P^{net} = P^{load} - P^{PV} + \alpha_{charge}P^{charge} - \alpha_2 P^{Tariff_{opt}} - \alpha_3 P^{Flex} \\
- \alpha_4 P^{FCR_D} \qquad (5.17)
\end{aligned}
$$

In Equations (5.16) and (5.17), α_j are binary optimization variables with the same characteristics as in **Papers III – IV** and limits the BESS from providing multiple services during the same hour. Similarly, the constraints regarding active power, energy, SoC, cycle intensity and ESS degradation were implemented in the same way in **Paper V** as in **Papers III - IV** but with updated power and energy capacities (see Equations 5.3 – 5.6 and 5.9 – 5.10). Furthermore, the second difference concern the *Penalty* term in Eq. (5.16) which was implemented to guide the algorithm in its search for the optimal value, and calculated by Eq. (5.17):

$$
Penalty = \sum_{i=1}^{24}\sum_{j=1}^{3} w_{i,j}\alpha_{i,j} \qquad (5.17)
$$

The penalty $w_{i,j}$ was allocated for suggesting undesired service provision and would in this case be if the algorithm suggested provision of FCR-D or local peak shaving when the DSO requested flexibility service. The value of $w_{i,j}$ was set to 10^5 for all services and hours. Finally, the term *W* in Eq. (5.16) was used to scale the impact of tariff optimization in the fitness function, and a sensitivity analysis was conducted for the value of *W* for the values 1, 10, 10^2, 10^3, 10^4 and 10^5.

Moreover, the same economic KPIs were evaluated as in previous work, namely NPV, PP and ROI (see Equations 5.14 and 5.15) with the same investment assumptions (see Table 11). To estimate the profit after one year of operation, the revenue, costs, and monthly savings were calculated according to Equations 5.18 – 5.22b, where $\Delta C_{e,l}$ is the monthly saving in the cost for electricity and R is the revenue for corresponding service. In Equations 5.19 –

5.20, the parameters *C* are all components included in the high-voltage tariff (see Figure 59 with matching index).

$$Profit = \sum_{l=1}^{12} \Delta C_{e,l} + \sum_{k=1}^{365} \left(R_{Flex,k} + R_{FCR_D,k}\right) - C^{O\&M} \quad (5.18)$$

$$C_{net,l} = \Big(C_{fix} + P_{max}\left(C_{P,BAU} + C_{P,HL}\right) + E_{BAU,l}C_{E,BAU} + E_{HL,l}C_{E,HL} + C_{tax}\left(E_{BAU,l} + E_{HL,l}\right)\Big) \times VAT \quad (5.19)$$

$$C_{trade,l} = \left(C_{fix} + E_{use,l}(C_T + C_{TSO} + C_{NSR} + C_{Ecert} + C_{GEcert})\right) \times VAT \quad 5.20)$$

$$C_{e,l} = C_{net,l} + C_{trade,l} \quad (5.21)$$

$$R_{Flex,k} = \sum_{i=1}^{24} P_{flex,i} t_{flex} \pi_{flex} \quad (5.22a)$$

$$R_{FCR_D,k} = \sum_{i=1}^{24} P_{FCR_D,i} \pi_{FCR_D,i} \quad (5.22b)$$

The main results of **Paper V** are summarized in Figures 61 and 62. The typical winter and summer profiles have the same layout as previous profiles shown in Figures 53, 55 and 56 showing cleared bids (empty bars) and ESS activation (filled bars). From Figures 61 and 62 it can be seen that the BESS was successfully scheduled for all three services, and in line with previous results from **Papers III – IV** the service allocation of fully stacked portfolio seems to favor FCR-D up. Considering the summer and winter profiles in Scenario 1, it can be noticed that the BESS was used more frequently for tariff optimization during the winter period compared to during the summer. This can be visually explained by looking at the seasonal variations in the load demand presented in Figure 58 where it can be seen that the electricity consumption is many times higher during the winter. In combination with the effects caused by the tariff it was thus more convenient aiming for tariff optimization during this period and this pattern was valid for both considered years. Furthermore, the results from Scenario 2 indicate that peak shaving and flexibility service could be co-scheduled successfully, and during some hours the demand for flexibility matches perfectly with the demand for local tariff optimization. This is a win-win situation for the BESS operator, since the peak load is reduced while providing an additional service.

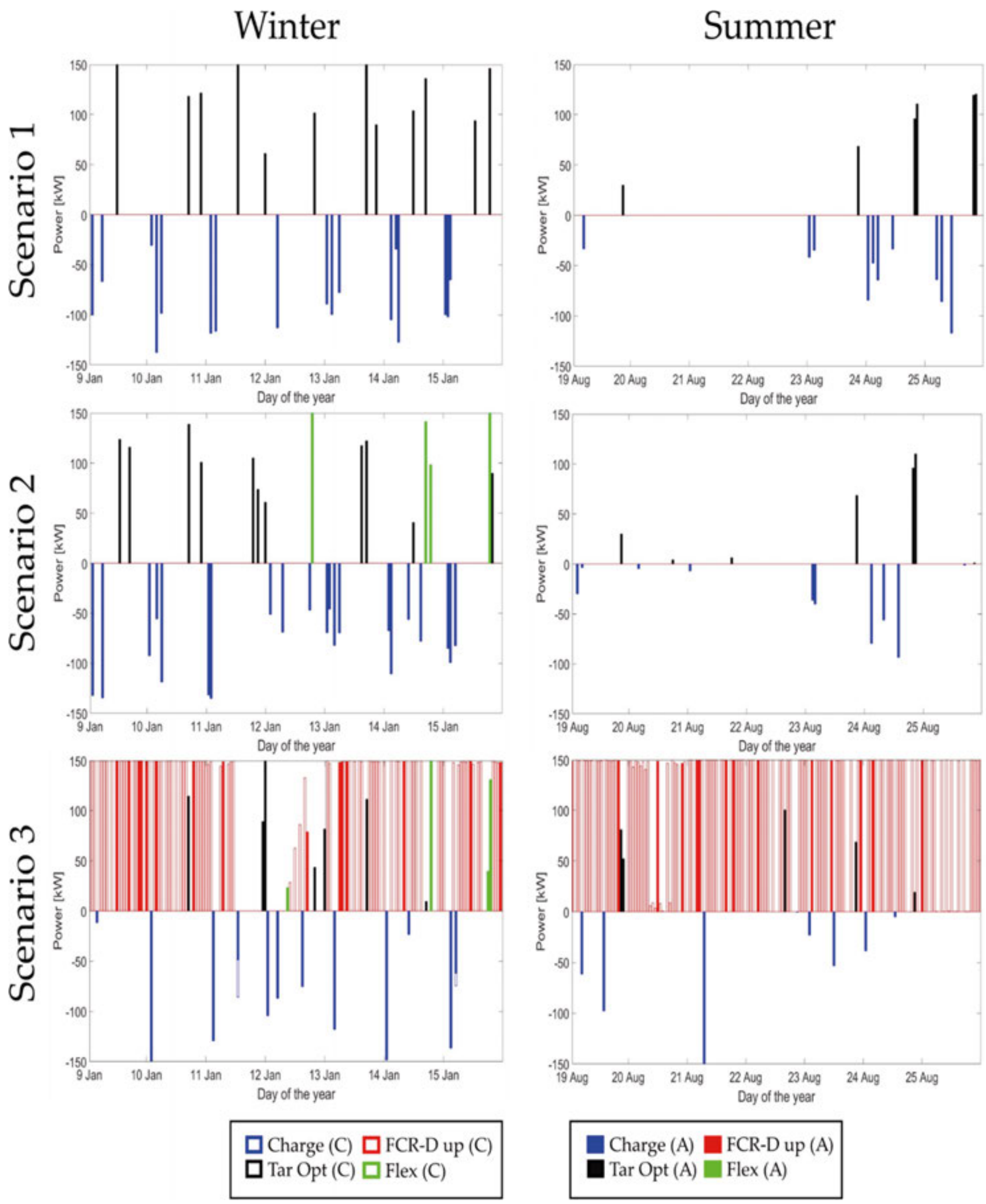

Figure 61. Scheduled service profiles for winter and summer periods for year 2021. Empty boxes represent cleared bids (C) and filled boxes represent BESS activation (A). **Paper V.**

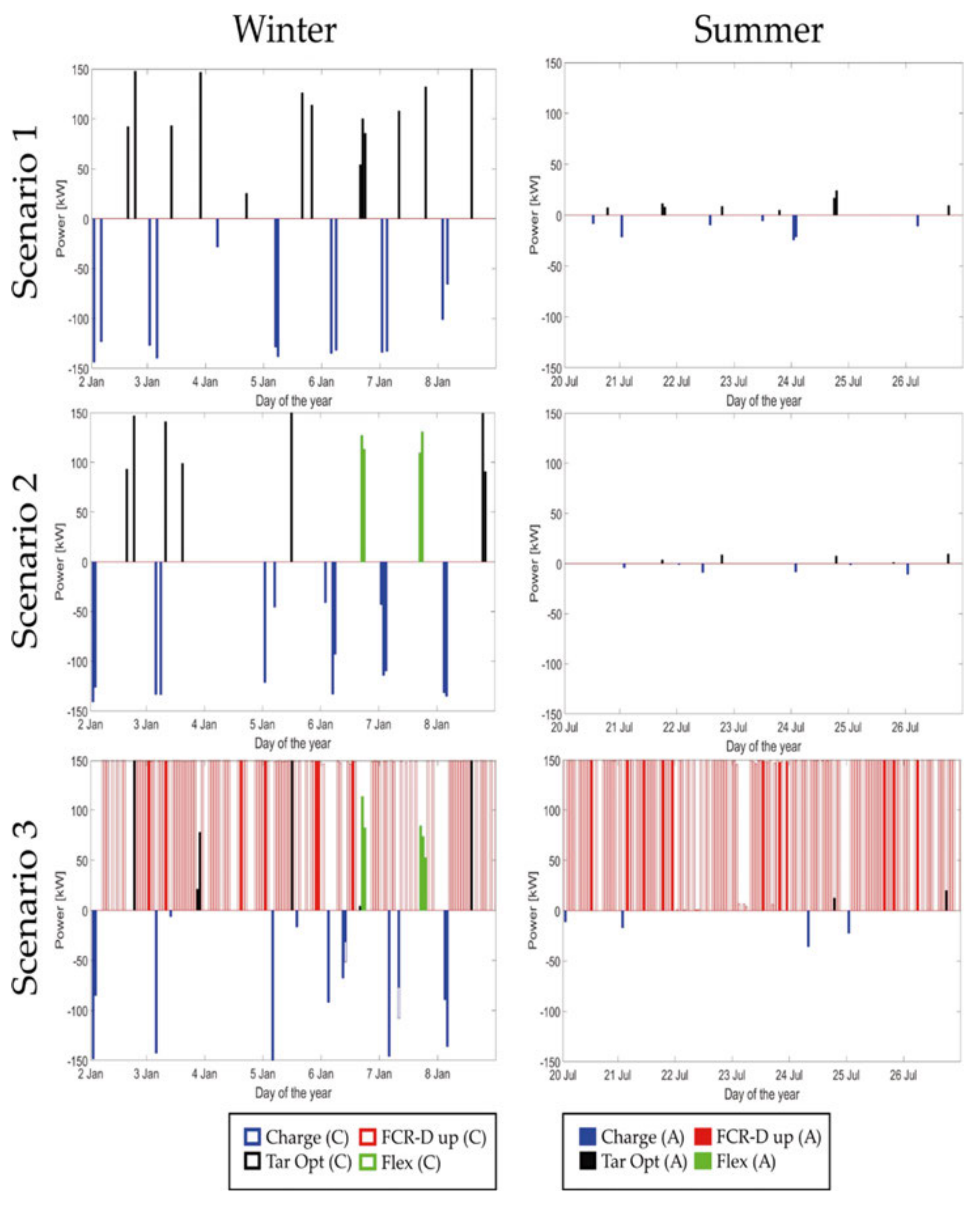

Figure 62. Scheduled service profiles for winter and summer periods for year 2022. Empty boxes represent cleared bids (C) and filled boxes represent BESS activation (A). **Paper V.**

Moreover, regarding the sensitivity analysis of the BESS rated energy capacity, the results indicated that the increased storage capacity enabled the BESS to increase the peak shaving slightly up to a C-rating of 0.5, and further increase resulted in minor changes only. The increased storage capacity did not result in any significant changes in the total cost of electricity; thus, the ROI gets lower as the storage capacity increases. Finally, regarding the sensitivity analysis of the scaling factor W in the fitness function the results showed that it was possible to shift the priority balance between services of the portfolio. By focusing on local services, the tariff optimization could be done more efficiently, and changes in the total cost of electricity could be observed as the value of W increased. Although, this was accomplished at the cost of less revenue from FCR-D and the possible revenue from FCR-D is much larger than the cost reduction of the peak load – resulting in reduced ROI for higher values of W.

5.3 Evaluation of effects on congested distribution grids using centralized and distributed energy storage systems with service stacked portfolios

Paper VI

The aim of **Paper VI** was to investigate and compare possible effects in a congested distribution feeder as a result of high shares of ESSs with service stacked portfolios for the two cases with centralized and distributed storage capacities. To accomplish this, the developed scheduling tool from **Paper V** was co-run with the publicly available IEEE European LV test feeder to capture the grid dynamics based on load flow calculations in OpenDSS. The default version of the test feeder was configured to stage a situation with high loading of the substation, which was achieved by down-sizing the rated power of the substation transformer in combination with up-scaling of the 55 connected loads. The original and scaled load demands are shown in Figure 63 for both minute and hourly resolutions.

Furthermore, the distributed storage units were modelled as 5 kW/5 kVA/13.5 kWh BESSs with characteristics similar to the ones of the commercially available Tesla Powerwall 2, while the centralized ESS were modelled as a single BESS unit connected to the LV side of the substation with a capacity equal to the aggregated capacity of the DERs. Figure 64 shows the one-line diagram of the (a) original and (b) configured versions of the considered test feeder, and the two ESS cases were simulated separately. The objective of the scheduling tool was to co-schedule the distributed ESSs for local tariff optimization

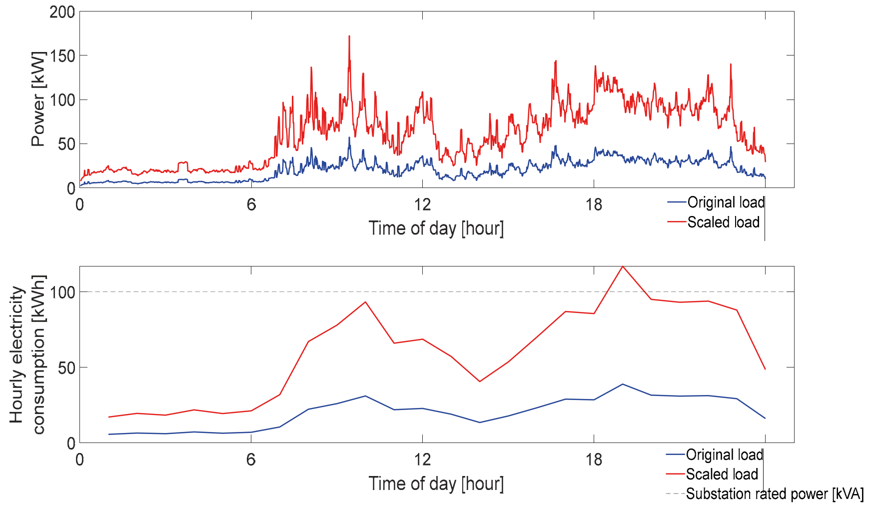

Figure 63. Aggregated load demand of the 55 loads connected to the test feeder. **Paper VI.**

(i.e., peak shaving), flexibility service and ancillary services, while the centralized BESS was scheduled for flexibility and ancillary services only. In the distributed ESS case, it was assumed that the connected BESSs were controlled centrally by an aggregator which operated the aggregated capacity on the considered markets. The test feeder comes with a set of load profiles for one day which were used for quasi-dynamic simulation of the test feeder. For the purpose of **Paper VI,** it was assumed that only one ancillary service was enough to include, where FCR-D up was chosen due to maturity of the market, availability of data and suitability of the ESS technology. Future studies could consider extended service portfolios to capture additional aspects and dynamics. Finally, to maintain the technical focus of the paper all economic KPIs have been left out of the analysis, and due to the short simulation time (1 day i.e., 24 hours) the effects on cycle aging were not considered either.

The main simulation results are compiled and presented in Figures 65 and 66. First, Figure 65 shows the original and adjusted load demand profiles for the two cases, indicated by (a) and (b). Considering the results for the case with centralized ESS in Figure 65 (a), it can be seen that the BESS successfully managed to provide flexibility during the evening peak when the hourly electricity demand was higher than the rated power of the substation transformer. It can also be noted that the BESS was activated with full power for FCR-D up provision four times which are indicated by the negative spikes in the upper graph in Figure 65 (a). Furthermore, the load demand shown in Figure 65 (b) indicates that the distributed BESSs could reduce the peak demand during the

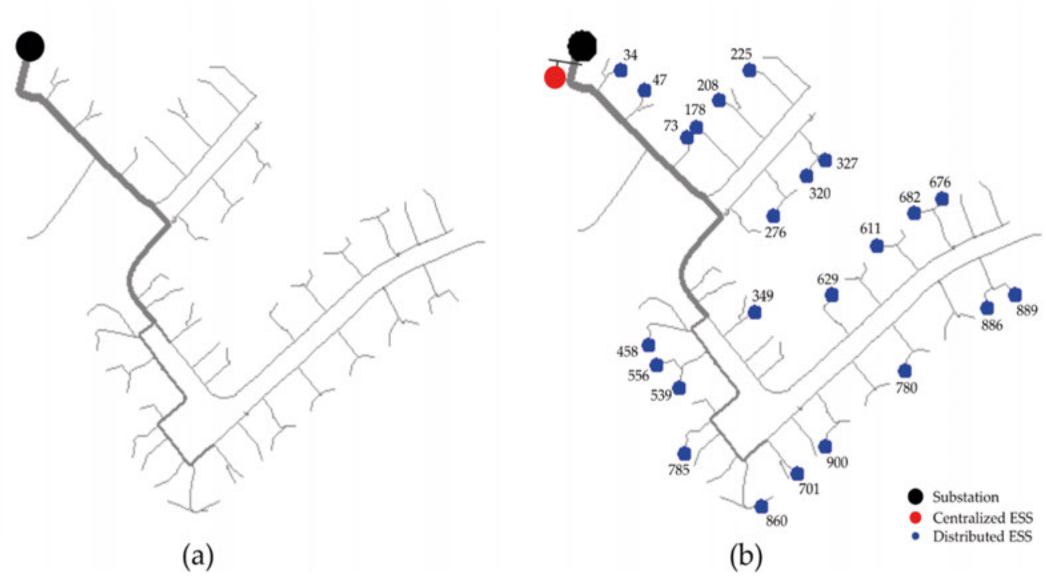

Figure 64. (a) One-line diagram of the IEEE European LV grid, (b) One-line diagram of the configured grid. **Paper VI.**

noon peak as well as providing flexibility during the evening peak. Considering the FCR-D up service provision, it was possible to schedule the centralized BESS for 23 hours together with the single hour for flexibility service. The aggregator on the other hand managed to meet the technical requirements for FCR-D up provision in 6 hours only, and during these 6 hours no activation was required. Finally, regarding the voltage profiles it can be seen from Figure 66 that small differences could be observed in the grid voltage indicating that the grid voltage was slightly higher in nodes far away from the substation in the case with distributed ESS capacity. Three such regions are marked with ellipses in Figure 66.

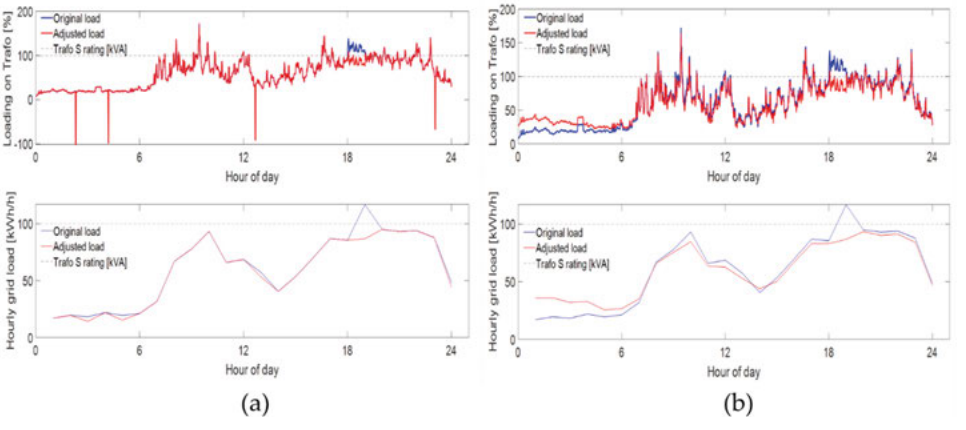

Figure 65. Minute power profile and hourly electricity demand of the substation. Blue curves show the original load while the red curves show the adjusted profiles after (a) centralized, and (b) distributed ESS implementations. **Paper VI.**

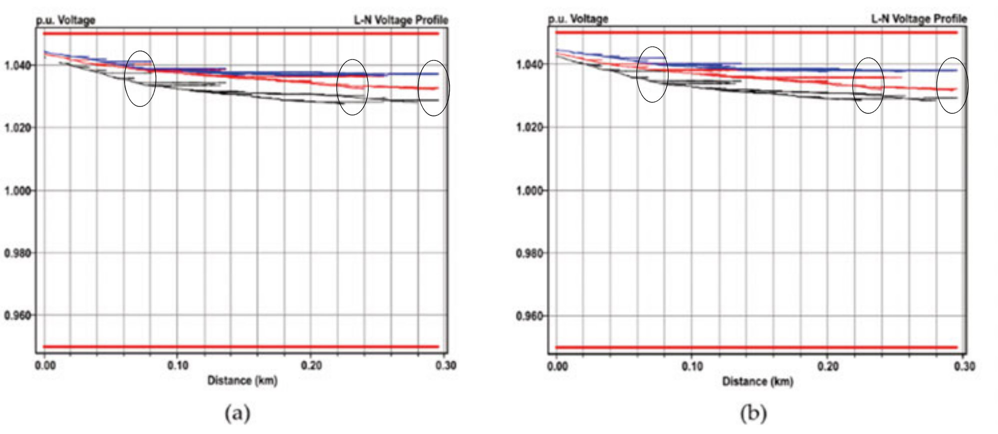

Figure 66. Voltage profiles with (a) centralized ESS, and (b) distributed ESS for Scenario 3. **Paper VI.**

6. Energy storage implementations for integration of renewable energy sources and electric vehicles

Chapter 6 covers the appended **Papers VII – IX**, where **Papers VII** – **VIII** focus on energy storage aspects regarding the integration of EVs, and **Paper IX** focuses on ESS solutions for power smoothing of RES. The appended papers in Chapter 6 are presented similarly to the appended papers of Chapter 5, where the aim, methods and main results of one paper are presented at the time.

6.1 Mobility houses

Paper VII

The aim of **Paper VII** was to analyze the potential impact on the regional grid load from the recently built *mobility house* in Uppsala, Sweden – known as "Dansmästaren". A mobility house is a large parking garage with the goal to facilitate transports around the city or neighbouring area while reducing the intensity of regular car traffic as part of the overall target for climate adaptation. Mobility houses have been selected as one of the tools which Uppsala Municipality uses to promote public transports by creating a natural hub where several types of transports can be accessed at the same location. In the long-term perspective this will concern car traffic, buses, trams, bicycles, scooters, to give a few examples. The considered mobility house is located in the Rosendal district in the central parts of Uppsala and is the first of several planned mobility houses in the city, and a photo of Dansmästaren is shown in Figure 67. Additionally, the facility has a 62 kW rooftop-mounted PV system on the roof and a 60 kW/ 137 kWh BESS located in connection to the garage which has 60 charging points for EVs that supports 22 kW charging. The maximum current supply to the garage is 500 A through the internal transformer, of which 400 A are allocated for EV charging and all peripheral services. To estimate the possible impact on the regional grid load, the electricity consump-

Figure 67. Dansmästaren, the first mobility house in Uppsala, Sweden. **Paper VII.**

tion of the facility was compared to the regional grid load for network area UPP during year 2021. Figure 68 shows a plot where the two time series were plotted against each other for all hours during the year, and in Figure 68 a selection of correlation and regression measures are included as well. It should be noted that the generation data from the PV system was excluded from the data of Dansmästaren. To enable analysis of daily trends and patterns within the data, the data sets were divided into three subgroups: (1) load demand during hours between 10 and 13, (2) load demand during hours between 16 and 19, and (3) the load demand during the remaining hours of the day. From Figure 68 it can be seen that there is a slight but still positive correlation between the regional grid load and Dansmästaren, shown by the three dashed lines. The exact values of the slopes can be found in the box in the upper left corner together with values for linear regression RMS-error, R-squared and the estimation for three common correlation coefficients namely Pearson, Spearman, and Kendall correlations. These estimate the correlation slightly different depending on the type of relationship between variables (linear or non-linear), distribution of the data and levels of measurements. Thus, the values of the three coefficients will vary slightly.

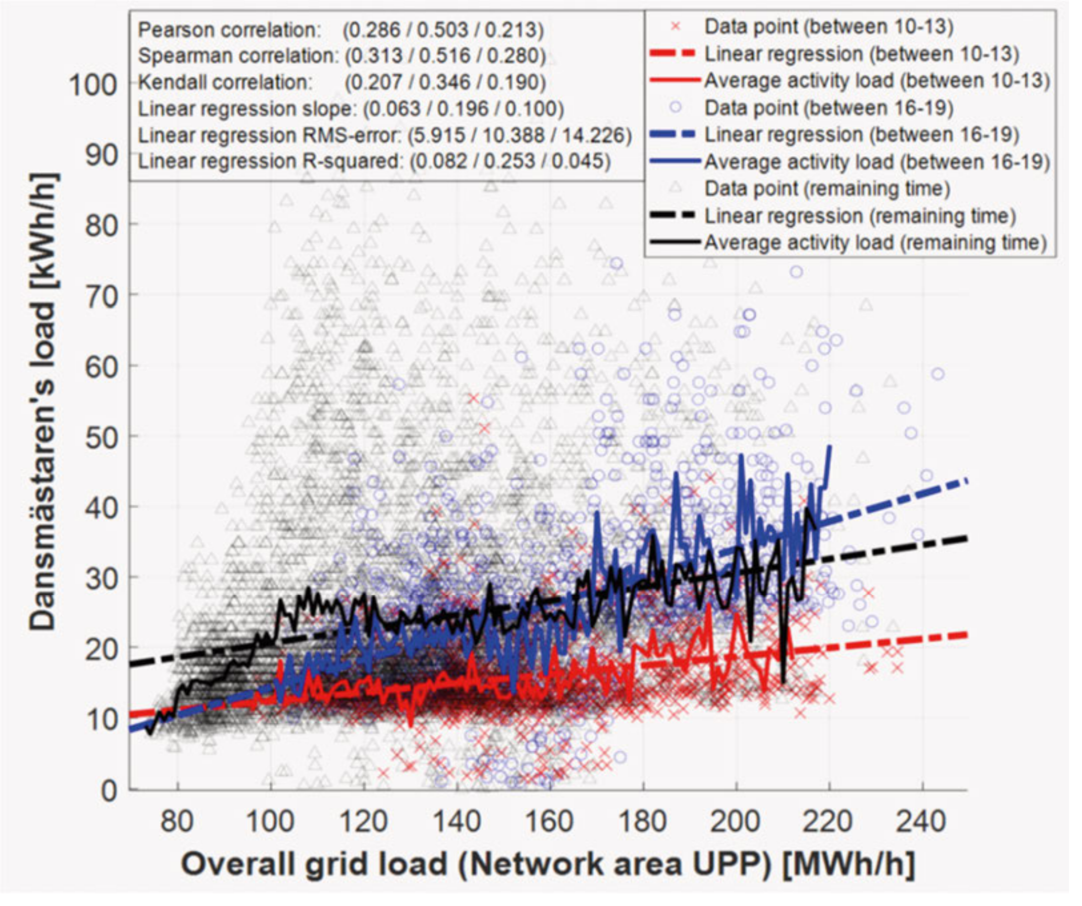

Figure 68. Grid load and Dansmästaren's parking garage load plotted against each other for all hours during year 2021. **Paper VII.**

Furthermore, the evaluation was also done based on the violin plot shown in Figure 69. The violin plot shows the distributions of all values included in the two considered time series, where the lower part shows the distribution of the load at Dansmästaren, and the upper part shows the distribution of the overall grid load in network area UPP. The red and blue sides of the graph separate the load demand during high load periods from the load demand during normal operation. From the violin plot it can be seen that the overall grid load in network area UPP was higher during the high-load period than during normal operation, which was expected. Regarding the load of Dansmästaren, it can be noted that the distributions are rather similar for the two periods, and only small differences can be seen for the 25th and 75th percentiles (i.e., the lower and upper quartiles which form the short sides of the boxes) as well as for the max and min values (indicated by horizontal lines at the end of each whisker).

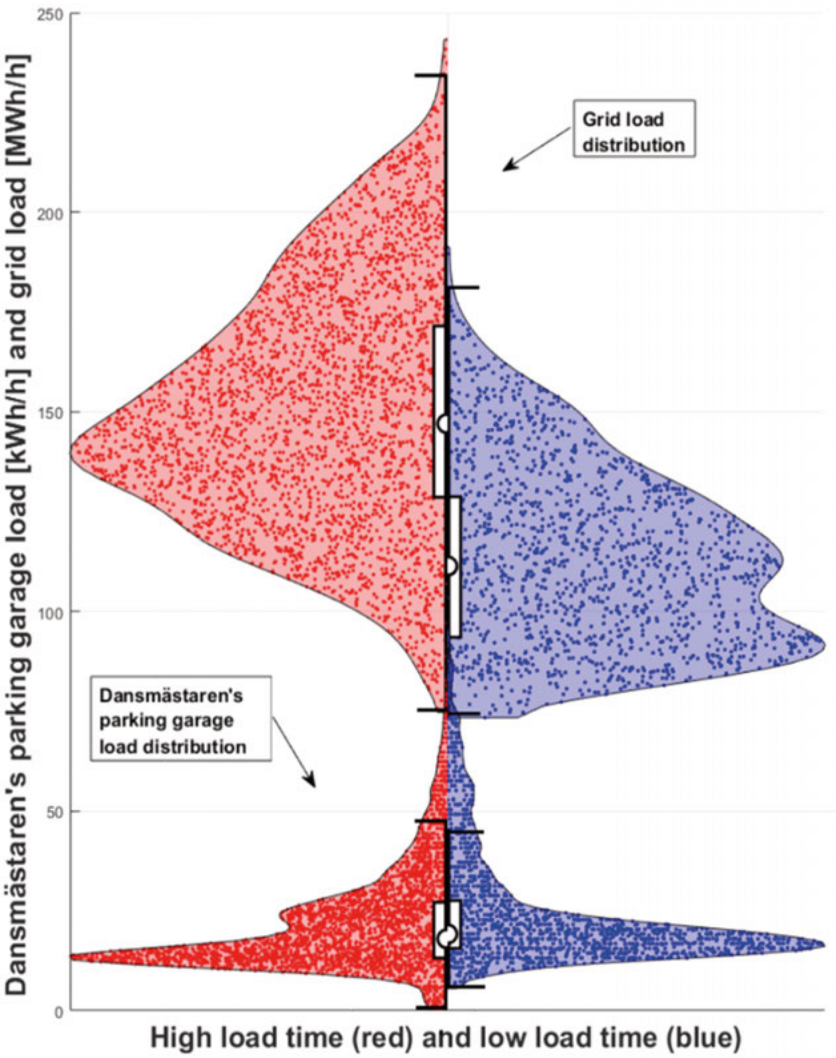

Figure 69. Violin plot showing the distribution of loads. **Paper VII.**

6.2 Charging and discharging strategies of electric vehicles

Paper VIII

The aim of **Paper VIII** was to provide an overview of the concepts for smart charging, V2G, V2H and V2X. Due to the expected development of EV integration and market expansion, it is important to investigate how the EVs can be charged and possibly used for other services as well from a general point of view. The first part of **Paper VIII** covered a minor review of charging strategies, together with possible effects on battery degradation and distribution grid resilience. From the literature it could be noted that four common types of charging and discharging strategies were used: (1) indirect control, (2) intelligent control, (3) bi-directional control, and finally (4) the multistage control. The main drivers for implementing more advanced control strategies than the uncontrolled charging is mainly customer-based, e.g., economic remuneration or other benefits that the car owner or operator can account for by adjusting the charging or by discharging the battery of the EV. There are several applications where controlled smart charging is interesting, e.g., peak load reduction, regional flexibility service, integration of local generation for increased self-sufficiency, or possibly ancillary services. Keeping the cost of charging as low as possible will always be a driving force among the car operators, thus it is important to estimate and evaluate the potential grid impact from such strategies.

Furthermore, the second part of **Paper VIII** covered an illustrative comparison between the different charging and discharging strategies, where a simulation model was created in MATLAB: Simulink to show possible interaction between a set of EVs and the grid. The operator of each car was given a daily driving pattern and it was also pre-determined if the particular operator would use the car for charging only or if bidirectional power flow was allowed. The most common and realistic approach was to assume that an aggregator controlled the EVs and coordinated the charging profiles according to the potential of each car/operator who makes decision based on some external control signal, in this case chosen as the electricity spot price. Figure 70 shows an overview of the considered system with involved actors and components and Figure 71 shows the implemented user profiles of the EVs.

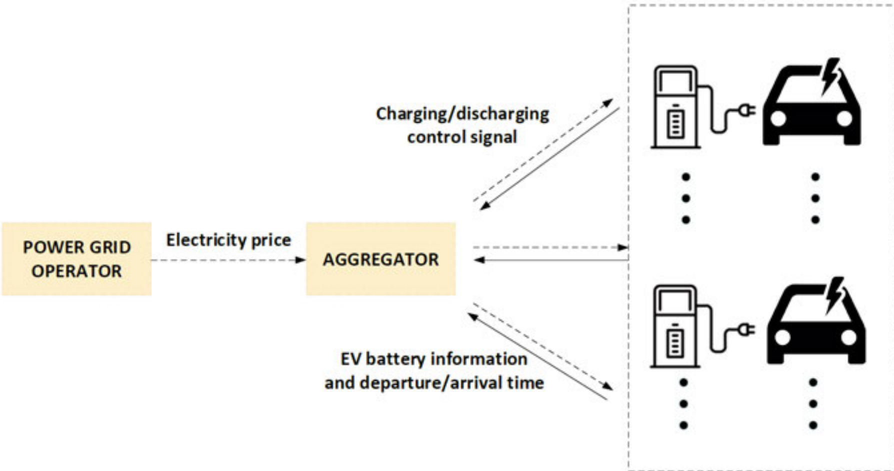

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Figure 70. Overview of the interaction between the EVs, a potential aggregator and the power grid operator. **Paper VIII.**

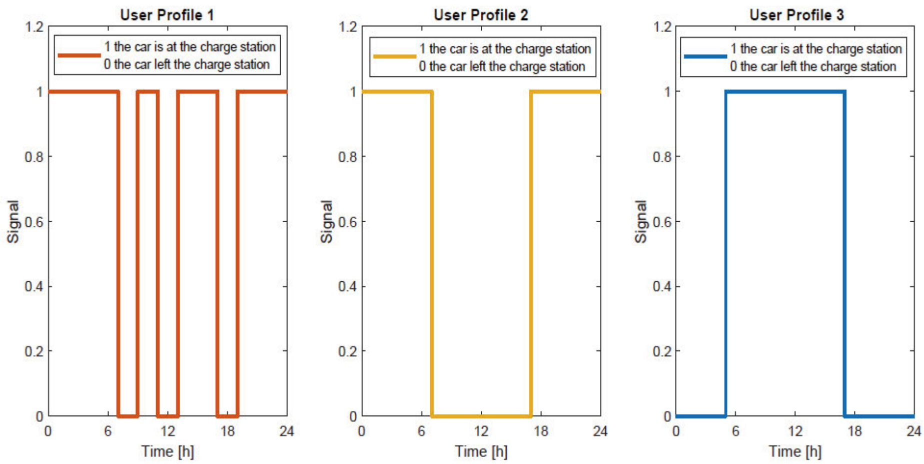

Figure 71. User profiles implemented for the EV operators. **Paper VIII.**

The main simulation results are compiled in Figures 72 and 73, where Figure 72 present the results for all EV users which only implemented smart charging while 73 covers the EVs which implemented V2G as well. First, by considering the results presented in Figure 72, it can be seen that all cars were charged in the morning to ensure enough capacity for the day with no knowledge of future events during the day. Furthermore, it can be noted that some of the EVs had access to charging points during daytime as well e.g., EV users 6, 8 and 10, and were thus charged with small amounts of energy to reach the targeted SoC level again. The EV users with no access to charging nodes during

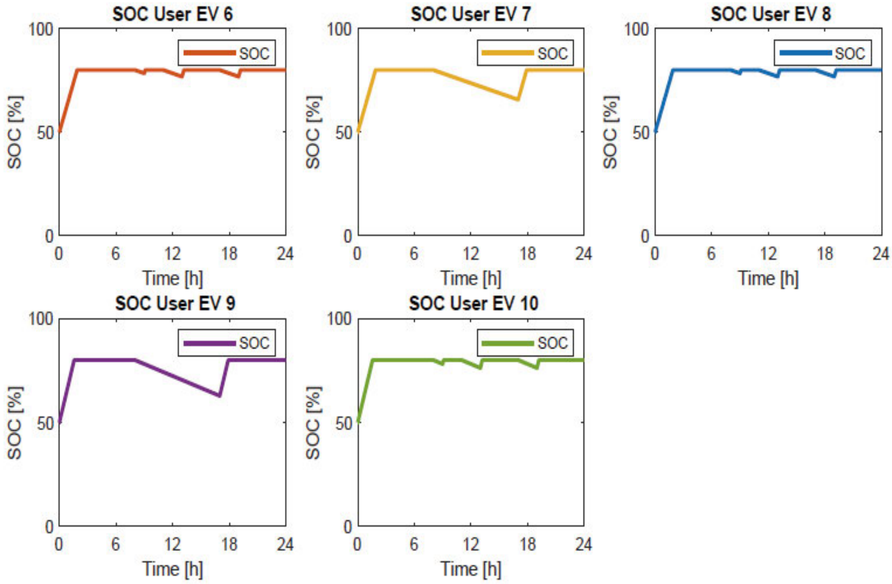

Figure 72. SoC profiles of the EV BESSs when implementing smart charging. Paper VIII.

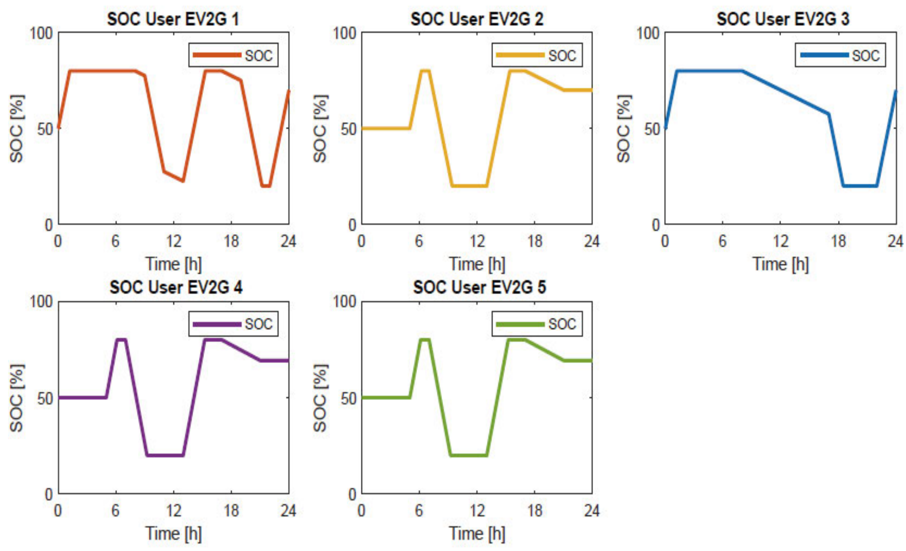

Figure 73. SoC profiles of the EV BESSs when allowing bidirectional power flow. **Paper VIII.**

daytime i.e., EV users 7 and 9 connected to the grid when arriving at home again after working hours.

Finally, Figure 73 shows the resulting SoC profiles for the EV users which allowed their cars for V2G provision as well. First, it can be noted from Figure 73 that EV users 1 and 3 also charged their cars I the morning while the remaining users 2, 4 and 5 didn't. Instead, they charged a few hours later before providing V2G service where the BESSs were used for feeding electricity back to the grid. All EV users included in Figure 73 used their cars for charging during the afternoon and evening to restore the SoC levels.

6.3 Power smoothing of wave energy converters using energy storage systems

Paper IX

The aim of **Paper IX** was to investigate the impact on the grid power quality for different configurations of wave energy converters (WEC) with and without the possibility of power smoothing using a BESS. Due to the increased interest in microgrids and nano grids, it is important to evaluate how RES with large power fluctuations could be connected to such grids without violating the grid codes for power quality. In this case, the evaluated type of RES was chosen to WEC and analysed for a set of different configurations when connected to a microgrid. The considered setup is illustrated in Figure 74 and shows the AC microgrid which is located at the Centre for Marine and Renewable Energy Ireland (MaREI) facility in Cork, Ireland. The microgrid is built as a hardware-in-the-loop (HIL) system where physical controllers are combined with virtual power plants and are executed using real time computer simulations. This is beneficial when evaluating controllers before implementation in large-scale applications, in order to find early-stage errors and have the possibility to tune controller performance – which can save a lot of money and reduce risks during later tests. The full description and discussion regarding the test grid are found in **Paper X**.

The implemented WEC configurations are illustrated in Figure 75, from which it can be seen that the number of converters and the placement of these was varied. The following scenarios were considered in **Paper IX**: (1) a single WEC, (2) 3 WECs for two different configurations, illustrated by the square in Figure 75 (a) in order to implement a time shift between the energy converters, and finally (3) 10 WECs with random time shift illustrated in Figure 75 (b). The zero time-shift would imply that all WECs starts to generate power at the same time when the incoming wave (see left side of Figure 75) passes by the WECs. By placing the WECs with a slight time shift the peak power from each WEC is distributed over a longer period causing less amplified peaks in the generation. Finally, the 10 WECs which are placed randomly were supposed to illustrate the behaviour of a wave power park (WPP) where WECs are located over a larger area.

When considering the power quality and stability aspects of variable RES in micro- and nano grids, there will be a significant difference in the control method based on whether the energy converters are connected using a grid-following or grid-forming control. When the microgrid is operated in island-mode, it is desired to operate the WECs in grid-forming control mode to increase the contribution to stability of the grid. Although, the need for grid-forming control is not as necessary when operating the AC microgrid in grid-mode, which was the case for this study. Thus, no grid-forming controls were implemented for the WECs nor the BESS in this paper.

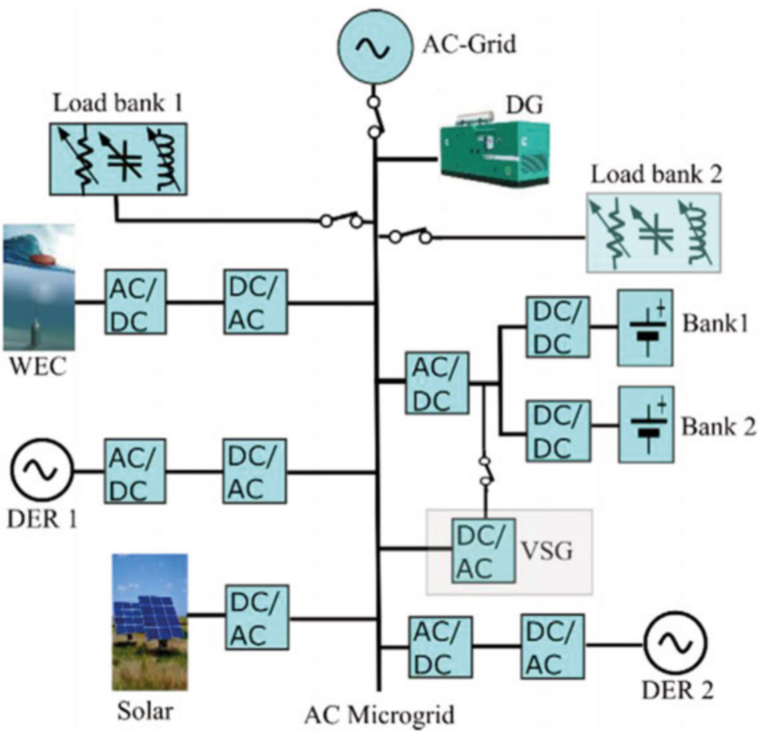

Figure 74. Structure of the AC microgrid at MaREI facility. **Paper IX.**

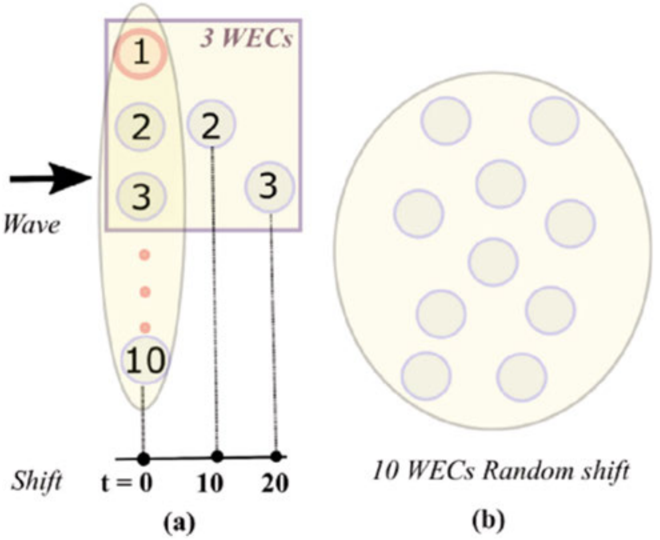

Figure 75. Overview of the layouts of the wave energy park. (a) fixed shifts, (b) random shift. **Paper IX.**

The main results from the power smoothing and power quality evaluations regarding ESS aspects are compiled in Figures 76 and 77. From Figure 76 it can be seen that the voltage variations over a 10-minute period could be significantly reduced by using the BESS, which is a satisfactory result and desired from a power quality point of view.

Moreover, the measurement results regarding the flicker levels are shown in Figure 77, and it can be seen that the short-term flicker levels (P_{st}) could be reduced for all scenarios when implementing the smoothing function. Finally, the measurement results from the harmonic analysis showed that the harmonic levels could be kept low for all configurations but where individual odd harmonics for the different phases varied in some cases – but still within the acceptable limits according to the standard requirements.

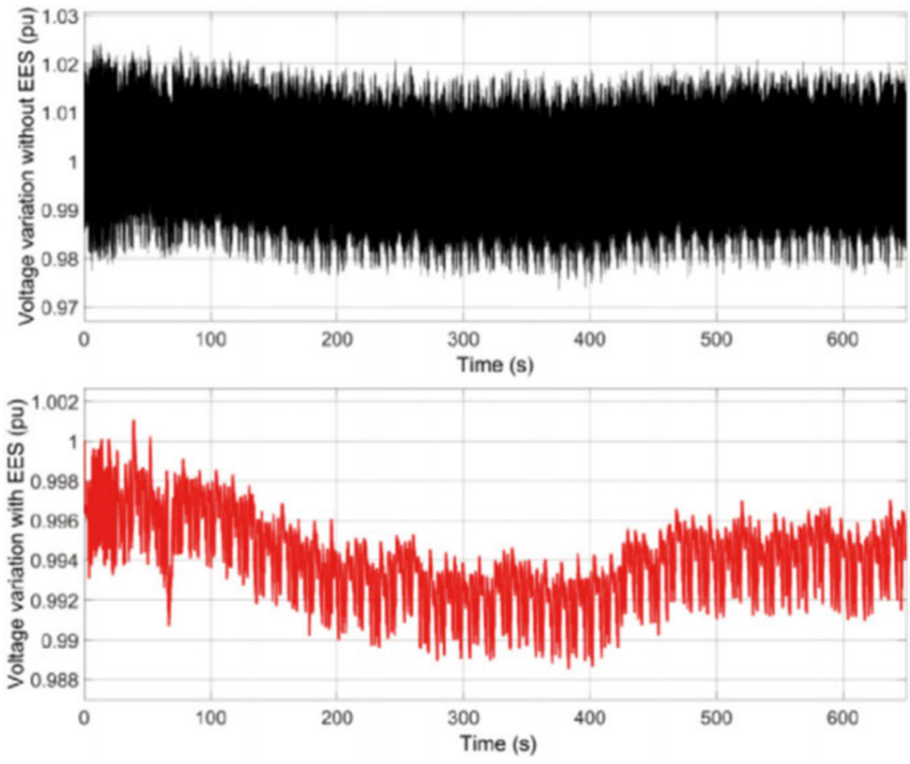

Figure 76. Voltage variations with and without ESS. **Paper IX.**

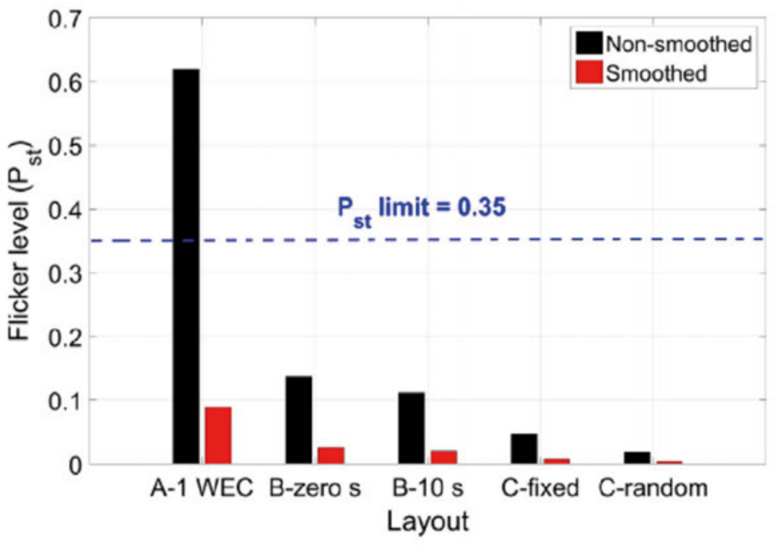

Figure 77. Grid impact in terms of short-term flicker level without ESS (black) and with ESS (red). **Paper IX.**

7. Discussion and conclusions

7.1 Discussion of the main results

Papers II – IV

According to the main results presented in **Papers II – IV**, service stacking has the potential to enable co-scheduling of multiple services during the same period and for different seasons. It was also possible to implement tools that evaluated both technical and economic KPI, in this case power profiles, cycle aging, NPV, PP and ROI. From the results it could be concluded that ancillary services seem more strategic advantageous to provide rather than energy arbitrage from both a technical and economic point of view. The estimated increase in cycle aging of service stacked portfolios clearly depended on the choice of services to include, and portfolios that promote provision of ancillary services should expect a small increase in the degradation only. Furthermore, the capacity allocation between services was sensitive to fluctuations in the electricity spot price, but the cycle intensity could be constrained in order to limit the daily energy throughput of the BESS. Linear programming was sufficient for scheduling of the considered services in **Papers II – IV**, but other methods have to be considered for more complex problems and if e.g., the nonlinear capacity loss life model should be implemented as an inequality constraint. When aiming for finding the maximum profit possible from service provision of an ESS at a specific location it is reasonable to include all available service which the ESS meets the technical requirements for. Although, this was not within the scope of **Papers II – IV** but is an interesting topic for future studies. One of the barriers with including all available markets in the analysis is the access to accurate historical market data for the same period. Some of the available services have recently been launched by the TSO, e.g., FCR-D down and FFR making the data somewhat biased or inaccurate, while other services e.g., flexibility was part of pilot projects with no public access to market data. Therefore, assumptions regarding clearing prices and volumes had to be made in the presented studies, and some services were left out from the portfolios completely.

Paper V

According to the aim of **Paper V**, the results showed that it was possible to stack services for a customer-sited BESS in a congested grid and where the fully stacked portfolio potentially could generate benefits and value both locally but also on a regional and system level. By providing local peak shaving and flexibility service only, the economic outcome will heavily rely on the value of flexibility contracts. If the remuneration for flexibility service comes from market participation only, the annual revenue should be expected to be small and will definitely not motivate ESS investments – as of the current CAPEX and OPEX levels in year 2023. Although, by providing ancillary service (FCR-D up in this case study) it is possible to capture large revenue streams that could motivate ESS investments. Moreover, regarding the sensitivity analysis of the BESS rated energy capacity, the results indicated that the increased storage capacity enabled the BESS. Another benefit from providing ancillary services with low energy throughput is that the estimated increase of cycle aging is low, which is a highly desired scenario for BESS operators – high economic output at low technical loss.

Regarding the modelling approach, the decision for choosing a metaheuristic solver was motivated by the complexity of the fitness function. Although, due to the size of the problem and long simulation period the total simulation time became long. In future work, it is recommended to aim for implementing other solvers that results in shorter simulation times e.g., neural networks.

The results from **Paper V** give valuable insights regarding the possibilities of stacking services using DER in congested grids, and also regarding effects on ESS degradation. Additionally, the results from **Paper V** also provide important guidelines regarding how BESS operators and investors can think strategically to form competitive business cases which could improve the chances of making ESS investments financially motivated.

Paper VI

The main results of **Paper VI** showed that it was possible to co-run the scheduling tool with a distribution grid test feeder to include grid dynamics as well. For both cases it was possible to co-schedule flexibility with ancillary services, and in the distributed ESS case it was also possible to include local peak shaving to the portfolio. Since the scheduling tool targeted markets and services with MTU of 1 hour it was not possible to target the minute peak power that was registered between hour 8 and 12. In order to catch such peaks that occur for a few minutes only it is more convenient to have a ESS being stand-by and activated if the load demand exceeds a pre-defined threshold rather than scheduling according to the hourly electricity demand.

Furthermore, the results also indicated that it was easier to co-schedule ancillary services for centralized storage capacity than for the aggregated capacity from several distributed units. This is mainly due to the conflicts in interest that arise since the distributed BESS are used for local peak shaving but is mainly a problem if the total aggregated capacity is limited and close to the requirement for minimum bid size. If the aggregator operates a larger capacity spread across a wider area this might not be as challenging as for the case in this paper.

Finally, since the activation of FCR-D up in **Papers III – VI** was based on probability for a large disturbance during each hour, the number of activations in one day can sometimes be slightly exaggerated – especially since the activation was set to 100 % of contracted power, which is a simplification made from the actual activation of FCR-D up. The stochastic approach was chosen mainly to consider a more generic behaviour and avoid dependence on a specific time series of frequency measurements. For a more accurate estimation of energy used for FCR-D up, a model for activation according to the technical requirements could be implemented and run with frequency data.

Papers VII - VIII

The analysis of the correlation between the grid load of network area UPP and the load demand of Dansmästaren showed that there was a slight positive relationship between the two data sets. Although, it should be noted that the charging of EVs could be controlled strategically to lower the correlation and the BESS could also be used to reduce the impact even further. Since there are many components with inverter-based grid connections at Dansmästaren, future studies could focus on investigating the aggregated effects on harmonic pollution from PV, EV chargers and BESS operation.

Since Dansmästaren was recently built, no advanced control strategies have been implemented for the energy management system (EMS) of the BESS located at Dansmästaren, and the charging nodes have only been used with unidirectional power flow i.e., charging of cars only. With proper incentives for supporting the local grid, Dansmästaren has a great potential to adjust the power flow in the area by using the capacity of the BESS, and possibly by using the cars for V2G services.

According to the overview of charging strategies, there are several possible methods to implement which all have the potential to adjust the impact of EV charging on the distribution grid. The methods could be separated into smart/controlled charging and methods that allow bidirectional power flow. The discussions regarding V2G, V2H and V2X have been ongoing for several years and most of the facts are clear: the technology is available but there are still barriers on the policy and manufacturing sides that have to be overcome before the concepts can be launched commercially.

Finally, according to the obtained simulation results it can be seen that it was possible to control the charging patterns of EVs based on an external control signal, in this case chosen as the electricity spot price. This caused both desired and undesired charging patterns if having the typical fluctuations of the grid load in mind. It is desired to schedule charge during the morning hours since the grid load is typically low at that time, but it is not strategically smart to schedule charging of cars in the evening or afternoon when the grid load experiences its daily peak (compare with e.g., the peak load of Uppsala in Chapter 5).

Paper IX

The aim of **Paper IX** was to evaluate the performance of an AC microgrid in terms of power quality measures flicker, voltage variations and harmonics as one or several WECs were connected to the grid for the cases with and without a BESS used for power smoothing. To perform these experiments, the AC HIL microgrid at the MaREI facility was used, and the results indicated that the BESS could be used successfully for improving the power quality.

It should be noted the power quality was sufficient without the BESS for all cases except for the case with 1 WEC, which resulted in flicker levels that were too high. It would be interesting to conduct similar experiments during worse power quality conditions from the beginning. The fast charge and discharge cycles of the BESS could motivate a hybrid storage solution in future experiments, where for example a supercapacitor could deal with the very fast fluctuations and allows the BESS to operate more smoothly.

7.2 The role of energy storage systems in distribution grids today and tomorrow

The decarbonisation of the energy system and other sectors of the society will require climate adaptation at a fast pace, and several of the solutions implemented today will imply a demand for increased flexibility on both the generation and end-user sides. This flexibility could partially be achieved by considering ESSs which have the potential to provide many of the mentioned services for various applications as explained in Chapter 3 and should be considered even further to ensure stable operation and good power quality throughout the power system. It is likely that ESSs will play an important role both as a stand-alone component but also as part of the next generation of flexible AC transmission system (FACTS) devices e.g., static synchronous compensators (STATCOM) with the ability to inject active power to the grid with very fast activation time. The results from **Paper I** indicate that ESSs could and should be used as a component with many purposes by bundling several services during one or over several seasons to increase the availability of the storage capacity for power system applications. Increasing the resilience and the reliability of the distribution grids is an important task and highly valuable for the society as the dependence on electricity (and thus also the vulnerability) continuously increases. Placement, rated energy and power capacity together with choice of storage technology will determine the potential to provide certain services and should be evaluated carefully when considering connection of an ESS. Since several of the available ESS technologies require access to special materials and strategic compounds, e.g., rare earth and ferromagnetic metals, it is crucial to promote technologies and research on technologies with low climate impact and small impact on the nature during prospecting.

7.3 Energy storage systems for congestion management in distribution grids

Congestion management is expected to become more challenging as more high-power applications will be connected to the distribution grids in combination with increased electrification and urbanisation. Using ESSs for congestion management is an interesting alternative due to several reasons, of which one is the short time required for connection and installation. Depending on where the bottlenecks arise, grid reinforcements may take many years to complete and may thus slow down or hinder regional processes and development, e.g., new establishment of industries and construction of new residential areas in urban districts. Therefore, finding efficient solutions which can relieve the distribution grids during the peak demand will be important for both municipalities and DSOs. The results from the appended **Papers I – VIII** also show that there are other reasons speaking in favour of using ESSs for congestion management as well, as the connection of storage capacity allows the opportunity to affect e.g., integration of EVs, local generation, provision of ancillary services, among many others.

7.4 Degradation and uncertainties in bid strategies

In **Papers III – V**, the effect on cycle aging was estimated for the considered ESS and is an important aspect to consider when implementing service stacking. The results indicate that the degradation will increase when stacking services, but the magnitude of the increase strongly depends on the service composition. Ancillary services with less energy throughput will result in a smaller contribution to the cycle aging compared to energy intensive services like energy arbitrage or time of use shifting and is a highly valuable insight for ESS operators when evaluating bundling of services. Since no ESS technology has characteristics that match all services and applications perfectly, one alternative is to consider hybrid storage solutions where technologies with different but matching properties can be combined. This could reduce the degradation of storage units that require gentler cycling and is an interesting topic for future research.

Furthermore, in the case studies presented in **Papers III – VI** historical data was used to create perfect predictions of fluctuations in market prices, load demand and local generation to eliminate the risk of bids not being cleared and estimate the full potential of service stacking. In real-world implementations, the ESS operators would be required to create bid strategies for each considered service which have to be based on forecasts or previous knowledge of the market fluctuations. Also, since most markets allow each operator to place multiple bids for several products, the bid strategies can be implemented with more or less risk and have to be evaluated carefully.

7.5 Conclusions

The aim of this thesis was to study energy storage systems in electrical grids for power distribution, with particular focus on use cases where service stacking was implemented. The main aim of this work was to illustrate, implement and evaluate use cases for energy storage systems connected to various parts of the distribution grid. According to the results of the appended **Papers I – XI**, the following conclusions can be drawn:

- Energy storage systems have a great potential to stack services to increase the availability of the storage capacity for power system services and applications. It is a method that can be applied to all storage technologies and should be considered whenever possible to maximize the benefits of the components.
- Ancillary services with small energy throughput are advantageous to provide from a degradation point of view, which result in the smallest impact on the cycle aging.
- Providing ancillary services is more strategic from an economic point of view compared to energy arbitrage, flexibility and local tariff optimization where the estimated ROI is higher, resulting in a shorter PP. Additionally, the degree of utilization of the component is higher as well.
- When the number of distributed storage units is limited in a distribution grid, it is easier to schedule centralized large-scale storage units for ancillary services due to the fewer interests in conflict. As the number of DERs

increases this might become less problematic as the aggregated capacity will exceed the minimum bid size of considered markets. Although, it will still be necessary to ensure that the technical requirements for market participation are fulfilled by all controlled DERs – which can be difficult.

The possible applications and services for energy storage solutions in distribution grids are many. It will certainly be interesting to follow the development of storage implementations in distribution grids and throughout the power system in upcoming years.

8. Future work

8.1 Hybrid energy storage systems and scheduling over several time scales

The considered services in **Papers II – VI** have all been scheduled on an hourly basis where the energy and power capacity support the grid during intra-hour and daily fluctuations. One of the interesting aspects to consider in future work is the utilization of ESSs for seasonal storage, which will increase the complexity for the optimization framework. The scheduling tool has to evaluate whether it is more strategically beneficial to use the available energy for service provision during present time or to store it for later use. One possibility to achieve an ESS with competitive characteristics with both highly dynamic power properties and good long-term storage efficiency is to consider a hybrid solution where two or more technologies are used. For example, an ESS technology with fast response and activation times e.g., BESS, FES, or SC can be paired with e.g., PHES, HESS or CAES. Additionally, the scheduling over several time scales should also consider intraday markets to provide important and valuable short-term balancing. As intraday and intra-hour fluctuations are expected to become larger as the generation mixes shift to higher shares of RES, the market for short-term balancing could be interesting for ESS to participate in.

8.2 Multi-objective optimization

A second topic of high relevance in this context which should be studied further is the implementation of multi-objective optimization. This is a powerful analytic tool where ESSs can be studied and evaluated for several parallel purposes and aims. In the appended **Papers III – VI**, the implemented objective functions considered the profit from service provision only. Although, there are several other possible and relevant objectives to implement as well, e.g., maximization of self-sufficiency of locally generated electricity, minimization of the correlation between the individual load and the regional grid load, minimization of the degradation, to name a few.

8.3 Probabilistic optimization and implementation of forecasting models

As mentioned in the discussion in chapter 7.3, participation on markets for ancillary services and energy trading requires carefully considered bid strategies to maximize the possible revenue. One suitable approach is to implement forecasting models for the considered markets that can predict the price fluctuations, which should be used as input to the scheduling optimization tool. The obtained estimations of the hourly prices in each market for the complete scheduling period will come with some error, which should be accounted for when making the final bid decisions.

Furthermore, another relevant method to implement to deal with the uncertainty of upcoming market prices is probabilistic optimization. This branch within optimization theory is interesting and relevant to consider for many applications where the input and output of the analysis are probability distribution functions (PDF). This provides valuable information regarding the spread and probability of the market prices in the upcoming period. Making decisions based on PDFs makes it possible to evaluate risk and chance more precisely compared to when using prediction models that tries to estimate the exact values.

9. Summary of Papers

This chapter summarizes the content of the papers on which this thesis is based upon.

Paper I

Service stacking using energy storage systems for grid applications – a review.

Energy storage systems (ESS) have the possibility to provide several services which support the power system. Although, some services and applications only require storage capacity during seasons or periods of the year. To increase the availability for power system applications and capture important revenue streams, it is crucial to co-schedule multiple services using the same storage unit. This is known as *service stacking* or *revenue stacking*, and the reviewed literature point at service stacking as promising and applicable for all storage technologies at all grid levels. Also, this review highlights how the service portfolio size and configuration may vary and which services that are most common but also most reasonable to stack.

Notes on my contribution: I compiled and analysed the literature and wrote the paper.

This work is published in Journal of Energy Storage, 60, 2023.

Paper II

Large scale energy storage in Uppsala, Sweden – an analysis of voltage fluctuations and a service stacked portfolio.

Uppsala is one of the largest cities in Sweden and has been suffering from congestion issues during the peak demand period, typically between October and March. One of the possible tools to implement to relieve grid congestions is energy storage systems, and this paper illustrates how a large-scale battery energy storage system (BESS) is used to support the grid in the region. The BESS was connected to the grid in year 2020, and in this paper the results of a test cycle which fulfils the requirements for both local flexibility service as well as those for frequency regulation (frequency containment reserve – disturbance (up), FCR-D) are shown. The grid voltage was examined during the test cycle period, and a service stacked portfolio was presented and discussed.

Notes on my contribution: I analysed the data and wrote the paper.

This work was presented by Johannes Hjalmarsson and is published in the 2nd International Conference on Evolving Cities in Southampton, UK, Hybrid conference, ICEC, 2021.

Paper III

Optimal Scheduling of Energy Storage Systems in Distribution Grids Using Service Stacking.

Energy storage systems which are used for congestion management have a great potential to implement service stacking to provide additional capacity for the power system due to seasonal variations in the electricity demand. In this article, a large-scale BESS like the one in Uppsala was considered and scheduled for a bundle of services using an optimization scheduling tool. By formulating an objective function that maximizes the profit subject to a set of constraints, the BESS could successfully be scheduled for several services during both winter and summer periods. The degradation aspect was also accounted for in the analysis by estimating the cycle aging using an empirically obtained capacity loss life model for all evaluated scenarios. The results show that ancillary services are strategically advantageous to provide due to the high economic value and small energy throughput.

Notes on my contribution: I developed the scheduling tool and wrote the paper.

This work was presented by Johannes Hjalmarsson and is published in the proceedings of the 27th International Conference & Exhibition on Electricity Distribution in Rome, Italy, CIRED, 2023.

Paper IV

Enhancing the value of large-scale energy storage systems in congested distribution grids using service stacking.

With the knowledge in mind that ancillary services with small energy throughput are strategically advantageous to provide as secondary services in stacked portfolios, it is important to evaluate how well such services can be matched with each other over longer periods. It is also relevant to investigate the possible impact on ESS scheduling from varying electricity spot prices. Therefore, this paper covers an extended portfolio compared to the one in **Paper III**, where the market prices also are significantly different for the considered periods. Additionally, it is also important to evaluate the amount of reserved energy for every hour to fulfil the activation requirements while ensuring the state-of-charge of the storage. The results from this article indicate that very high spot prices favour services like energy arbitrage but will result in increased cycle aging. Also, when reserving less energy for ancillary services like FCR-D it was possible to schedule the ESS for a large majority of the hours within the considered period.

Notes on my contribution: I developed the scheduling tool and wrote the paper.

This work is under review in Journal of Energy Storage, June 2023.

Paper V

Scheduling optimization of energy storage systems at large sports facilities in congested distribution grids

Grid congestions can be relived not only by large-scale ESSs connected close to substations, but also by using distributed energy resources (DER) connected at e.g., industries, larger enterprises or at households. One of the main conceptual differences with these storage components is the fact that the main purpose of these is some local service, e.g., store electricity from solar panels or supporting charging points for electric vehicles (EVs). In this article, a large electricity consumer within Uppsala Municipality was considered and one of their sport facilities was chosen for a case study where service stacking was implemented for a BESS. The scheduling problem was solved using a metaheuristic approach due to the complex objective function. The results indicate that both technical and economic benefits could be achieved by investing in an ESS and implementing a service stacked portfolio.

Notes on my contribution: I developed the scheduling tool and wrote the paper
.
This work is under review in Journal of Energy Storage, August 2023.

Paper VI

Evaluation of centralized and distributed energy storage systems in congested distribution grids with service stacked portfolios

As the clean energy transition continues and the pace of climate change adaptation increases, the number of DERs is expected to increase in distribution grids. With more mature technology and new business models it is important to evaluate effects of large-scale implementation of such components when used with advanced operation strategies. Stacking services using ESSs could account as one example of such, and this paper covers effects on congested distribution grids as the number of storage components increases. Central and distributed storage capacities were compared for a selection of portfolios and the congested distribution grid was analyzed using computer-based load flow analysis by simulating the IEEE European low voltage grid. The results indicate that the aggregated capacity of distributed ESSs can be valuable for managing distribution bottlenecks, and a third-party aggregator could provide ancillary services if enough storage capacity is managed. The load flow analysis also indicates that DER have the possibility to improve the local voltage quality by reducing the peak demand of customers.

Notes on my contribution: I developed the scheduling tool, executed the load flow analysis and wrote the paper.

This work has been submitted to Applied Energy, September 2023.

Paper VII

The potential impact of a mobility house on a congested distribution grid - a case study in Uppsala, Sweden

Mobility houses is one of the concepts which Uppsala Municipality has been implementing in their plan for climate change adaptation and is a communication and transportation hub with functionalities that supports the development towards smart grids. By connecting many charging points of EVs close to local electricity generation and energy storage the goal is to minimize the grid impact of the mobility house. Thus, the mobility house enables efficient integration of DER in low voltage grids while also creating innovative and compact solutions for parking and charging of EVs. This article demonstrates the recently built mobility house *Dansmästaren,* located in the central parts of Uppsala, Sweden. In this paper, the scope is to present how Uppsala municipality enables infrastructure for e-mobility in a situation where regional transmission capacity constrains are active. The electricity demand correlation between Dansmästaren and the network area was examined, and energy storage solutions are discussed as one promising alternative.

Notes on my contribution: I took part in the discussions during the working process and wrote parts of the paper, mainly regarding energy storage and distribution grid aspects.

This work was presented by Alexander Wallberg and is published in the proceedings of the International Conference & Exhibition on Electricity Distribution – Porto Workshop: E-mobility and power distribution systems, Porto, Portugal, CIRED Workshop, 2022.

Paper VIII

Analysis of charging and discharging of electric vehicles

As the electrification of the transport sector continues the need for knowledge regarding EV charging strategies increases. Eventually, the common knowledge regarding EV charging will be sufficient to stimulate business cases for advanced charging strategies on a larger scale, and it is therefore important to investigate the possible ways of integrating EVs with the distribution grid. The first step concerns adjusted charging of vehicles only. Although, it is expected that the technology will be used for bidirectional power flow to some extent too and function as distributed storage capacity. Compared to stationary storage solutions, the aggregated EV capacity will be a function of several varying parameters e.g., driving patterns of car owners, storage capacity of EVs on the market, standards of charging equipment, etc. In this article, the operational complexity of charging dynamics is highlighted where a set of cars was simulated using three different owner profiles to estimate driving and charging patterns.

Notes on my contribution: I took part in the discussions during the working process and wrote parts of the paper, mainly regarding aspects of battery aging, distribution grids and ancillary services.

This work was presented by Jessica Döhler Santos and is published in the proceedings of the 36th Electric Vehicle Symposium & Exposition in Sacramento, California, USA, EVS36, 2023.

This work was invited to the special issue "EVS36 – International Electric Vehicle Symposium and Exhibition (California, USA)" in The World Electric Vehicle Journal, and was submitted in September 2023.

Paper IX

Grid Impact and Power Quality Assessment of Wave Energy Parks: Different Layouts and Power Penetrations using Energy Storage

One common challenge with renewable energy sources is the widely fluctuating power output from the energy converters. By gathering many converters and forming power parks, the fluctuations can be smoothened to some extent but could be further improved by e.g., curtailing generation or by connecting energy storage systems. This article evaluates how the power penetration and quality vary with different layouts of wave energy converters in a wave power park, with and without the presence of energy storage. The results indicate that the energy storage system has a great potential to smoothen the power output from single wave energy converters as well as from aggregated power generation.

Notes on my contribution: I took part in the on-site experiments, in the discussions regarding the ESS control algorithm and proof-read the paper.

This work is published in IET the Journal of Engineering, 8, 2020.

Paper X

Power Hardware-in-the-loop simulations of Grid-integration of a Wave Power Park

In this article, an AC microgrid is evaluated for a set of wave energy converter (WEC) configurations. The WEC integration was done using a triphase power converter system, and the grid impact was evaluated for the cases when connecting 1, 3 and 10 WECs to the microgrid. Using a real time power hardware-in-the-loop simulation setup, the performance of the WEC grid integration could be evaluated in detail. The experimental work was conducted within the framework of the MaRINET2 project.

Notes on my contribution: I assisted in the on-site experiments and proof-read the paper.

This work was presented by Irina Temiz and is published in the proceedings of the 13th Wave and Tidal Energy Conference in Napoli, Italy, EWTEC, 2019.

Paper XI

Virtual Synchronous Generator Based Current Synchronous Detection Scheme for a Virtual Inertia Emulation in SmartGrids

This article shows how emulation of virtual inertia can be integrated in a wave energy converter (WEC) system which is part of a microgrid power management system in order to control the electrical grid frequency and terminal voltage. It was shown that the combination of a DC link capacitor and battery energy storage system (BESS) can reduce the need for a supercapacitor by introducing virtual inertia from the WEC. The experimental work was conducted within the framework of the MaRINET2 project where a microgrid was used for testing and control implementations.

Notes on my contribution: I assisted in the on-site experiments.

This work is published in Energy and Power Engineering, 11, 2019.

Paper XII

Power Hardware in-the-Loop Real Time Modelling using Hydrodynamic Model of a Wave Energy Converter with Linear Generator Power Take-Off

In this paper, the mathematical models of a real time power hardware-in-the-loop simulation are presented. Using a state space method to get the velocity and position of both the boy and the translator of the converter, the hydrodynamic model of the WEC could be integrated with the considered AC microgrid set up. After executed experiments, the profiles of WEC current and voltage could be presented. To smooth the voltage and current WEC output in the grid side, a RLC filter implementation is proposed as well. The experimental work was conducted within the framework of the MaRINET2 project.

Notes on my contribution: I assisted in the on-site experiments.

This work was presented by Tatiana Potapenko and is published in the proceedings of the 29th International Ocean and Polar Engineering Conference in Honolulu, Hawaii, USA, ISPOE, 2019.

10. Sammanfattning på Svenska

Den omfattande omställning som pågår globalt mot en ökad andel förnybar elproduktion skapar nya utmaningar inom alla delar av elnätet. Att säkerställa elnätets funktionalitet blir än viktigare då samhället blir alltmer beroende av en stabil elförsörjning med hög tillgänglighet och god elkvalitet. Ett viktigt steg i omställningen är att bevara och skapa ytterligare flexibilitet i elnätets olika delar för att kunna möta behovet av balansering samtidigt som kraven på stabilitet uppfylls. Energilager som ansluts till distributionsnät med kapacitetsutmaningar har en stor potential att stötta elnätet på många fronter och behöver vara en given del av diskussionen om morgondagens elnät. Ett sätt att öka tillgängligheten hos energilager för nättjänster och andra nätnyttor är att rikta in sig på flera tjänster och tillämpningar parallellt, vilket benämns som *service stacking* i den här avhandlingen. Genom att tillgodose lokala och regionala nätnyttor samtidigt som kapaciteten kan användas för stödtjänster förvaltade av systemansvarig myndighet för kraftsystemet kan energilager utnyttja sin fulla potential. Marknaden för flera energilagringsteknologier är snabbt uppåtgående, men ur ett historiskt perspektiv har investeringar i energilager inte varit ekonomiskt motiverade. Genom att inkludera flera tjänster i sin portfölj finns det däremot en större chans för investerare att skapa en lönsam och lukrativ affärsmodell för nätanslutna energilager.

Studierna vilka den här avhandlingen bygger på har fokuserat på flera aspekter av hur stackning av tjänster kan göras, där följdeffekterna har analyserats med avseende på såväl tekniska som ekonomiska faktorer. Genom att erbjuda flera tjänster kommer utnyttjandegraden hos dessa energilager att öka, och det blir viktigt att undersöka hur det påverkar åldringen hos komponenterna. Detta har gjorts i de fallstudier som är inkluderade i avhandlingen, och de trender som kunnat ses i resultaten tyder på att åldringen är starkt beroende av vilka tjänster som erbjuds samt av vilken intensitet man tillåter energilagret att cyklas med. Vidare har även effekter av det volatila elpriset tagits hänsyn till då det påverkar drivkraften för elanvändare att se över sin elanvändning samt de ekonomiska förutsättningarna för de tjänster och marknader där energilager kan verka på. Resultaten tyder på att energilager har goda möjlighet att minska elkostnaderna hos enskilda konsumenter genom att kapa lokala effekttoppar – framför allt under höglasttid, men att den stora ekonomiska potentialen ligger hos marknaderna för stödtjänster. I de fall där energilagren uppfyller de tekniska kraven och kvalificerar för deltagande på marknader för stödtjänster blir det därför en avvägning mellan lokal nätnytta och ekonomisk vinning. Vidare har även effekter av placering hos energilager som implementerar service stacking undersökts, där resultaten indikerar att utspridd lagringskapacitet har möjlighet att påverka nätbelastningen och elkvaliteten långt ute i distributionsnät medan samlad kapacitet som ansluts vid nätstationer huvudsakligen påverkar det aggregerade effektflödet i området. Centraliserade lager kunde däremot schemaläggas mer effektivt för ytterligare stödtjänster då det var färre intressen som hamnade i konflikt jämfört med decentraliserade energilager.

Slutligen har även energilager i samband med integration av elbilsladdning och elproduktion analyserats, vilka är ytterligare två viktiga aspekter att ta hänsyn till i omställningen mot ett fossilfritt energisystem. Genom att inkludera energilagring i dessa tillämpningar kan påverkan på elnätet från elbilsladdning hållas låg, och elkvaliteten från förnybara energikällor förbättras.

Den här avhandlingen berör flera viktiga aspekter av energilager och dess roll i morgondagens distributionsnät med effekter som berör hela energisystemet. Flera teknologier är för tillfället på forskningsnivå eller med små marknadsandelar jämfört med exempelvis Li-jon batterier, men som har god potential att stötta elnätet framöver. Att hitta affärsmodeller där energilager används på ett effektivt sätt genom att kombinera tjänster där nyttor skapas på flera fronter kommer vara en viktig nyckel och avgörande för utvecklingen hos nätanslutna energilager. Det finns goda möjligheter till fortsatt arbete inom fältet, där frågor och metoder som berör mer komplex optimering och schemaläggning kan implementeras. Vidare är det även viktigt och intressant att undersöka möjligheten där enskilda energilager eller hybridlösningar inkluderar säsongslagring och intradagshandel för att ta hänsyn till behov och möjligheter över flera tidshorisonter.

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