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Quantification Methods for the Demand of Flexibility

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Abstract

Climate change mitigation actions include an energy transition that significantly alters the energy resource portfolio. The changes lead to the evolution of power systems' behavior. Thus, both the flexibility resources and needs must be assessed more thoroughly. On the one hand, quantification methods are required to interpret and compare the flexibility needs of transmission system operators (TSOs) in different trajectories of future development. On the other hand, the evolution of flexibility potential must be examined to prepare for different trajectories.

A consistent definition for flexibility is determined, and its role in the electrical power system is explored via the use-cases of different power system actor types, flexibility needs of TSOs, the concept of flexibility potential layers, different flexibility resources, and execution mechanisms of flexibility.

The flexibility potential of distributed demand-side flexibility (DSF) resources is presented in the form of literature estimations and the assessment of key factors affecting its evolution. Predictability of flexibility needs is found to be one of the key drivers of the growth of commercial flexibility potential, which emphasizes the demand for the quantification of flexibility needs. Different flexibility needs, their representative metrics, input data sources, and quantification tools are assessed as options for the formation and application of quantification methods. The 1h power ramps are chosen as metrics for representing power ramp management flexibility needs, and two methods are developed for their quantification.

The results of the methods show that the most significant resource categories and resource groups can be determined in terms of power systems' power ramp behavior from electricity market simulation scenarios' data. The results expose the potential of comparing the impact of a singular presumption, i.e., electric vehicle (EV) charging logic. The resuling illustrations do not fully depict the ramping flexibility needs but provide seeds for future development. Due to the simplicity of the modelling, the results should not be considered as future forecast of power system behavior, but rather examples of how it can be quantified and interpreted.

Further research and development are proposed for the developed methods in the form of including curtailment and DSF information, more extensive mapping of other quantification methods and development of single methods, modifications of market modelling, and different perspectives of exploring the flexibility potential of distributed DSF resources.

Keywords Quantification of flexibility, flexibility needs, power ramp management, 1h power ramps, flexibility potential, drivers of flexibility, barriers to flexibility

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Tiivistelmä

Ilmastonmuutosta hillitsevät toimenpiteet sisältävät energiamurroksen, joka muuttaa energiaresurssikantaa merkittävästi. Muutokset johtavat voimajärjestelmien käyttäytymisen kehittymiseen. Täten sekä joustoresursseja että joustotarpeita tulee arvioida perusteellisesti. Yhtäältä tarvitaan kvantifiointimetodeja kantaverkko-operaattoreiden joustotarpeiden tulkitsemiseen ja vertailuun erilaisissa tulevaisuuden kehityskuluissa. Toisaalta joustopotentiaalin kehittymistä pitää tarkastella, jotta erilaisiin kehityskulkuihin voidaan varautua.

Joustolle asetetaan yhdenmukainen määritelmä, ja jouston roolia sähkövoimajärjestelmässä tutkitaan eri voimajärjestelmän toimijatyyppien jouston käyttötapausten, kantaverkkoyhtiön joustotarpeiden, joustopotentiaalitasojen konseptin, eri joustoresurssien ja jouston toteutusmekanismien kautta.

Hajautettujen kysyntäjoustoresurssien joustopotentiaalia esitellään kirjallisuuden arvioiden ja potentiaalikehityksen avainvaikuttimien muodossa. Joustotarpeiden ennakoitavuuden havaitaan olevan yksi avainajureista kaupallisen joustopotentiaalin kasvulle, mikä korostaa joustotarpeiden kvantifioinnin tarpeellisuutta. Eri joustotarpeita, niitä edustavia metriikkoja, lähtödataa ja kvantifiointityökaluja arvioidaan vaihtoehtoina kvantifiointimetodien moudostukselle ja soveltamiselle. Tunnin tehorampit valitaan metriikoiksi kuvaamaan tehoramppienhallinnan joustotarpeita, ja kaksi metodia kehitetään niiden kvantifioimiseksi.

Metodien tulokset osoittavat, että voimajärjestelmän tehoramppien kannalta merkittävimpiä resurssikategorioita ja -ryhmiä voidaan määritellä sähkömarkkinasimulaatiodatan perusteella. Metodien tulokset näyttävät yksittäisen lähtöoletuksen muuttamisen, t.s. sähköautojen latauslogiikan, vaikutusten arvioinnin potentiaalin. Metodien tuottamat kuvitukset eivät suoranaisesti kvantifioi tehoramppienhallinnan joustotarpeita, mutta antavat lähtökohtia tulevalle kehitykselle.Yksinkertaisen mallinnuksen vuoksi tuloksia ei tule tulkita ennusteina voimajärjestelmän tulevasta toiminnasta, vaan esimerkkeinä sen kvantifioinnista ja tulkitsemisesta.

Jatkokehitystä- ja tutkimusta ehdotetaan kehitetyille metodeille tehorajauksen ja kysyntäjouston tietojen sisällyttämisen muodossa, muiden kvantifiointimenetelmien laajempaa kartoittamista ja yksittäisten metodien kehittämistä, markkinamallinnuksen muutoksia sekä hajautettujen kysyntäjoustoresurssien joustopotentiaalin tarkastelua eri näkökulmista.

Avainsanat Jouston kvantifiointi, joustotarpeet, tehoramppienhallinta, tunnin tehorampit, joustopotentiaali, jouston ajurit, jouston esteet

Contents

Preface

First, I want to thank my supervisor Assistant Professor Mahdi Pourakbari Kasmaei and my advisor D.Sc. Tuomas Rauhala for their guidance throughout the thesis work. Mahdi showed outstanding enthusiasm for the subject and provided insightful feedback for the text. Tuomas really pushed the boundaries of my imagination and helped me to reach, for me, whole new levels of revelations about the realm of power system flexibility. I also want to thank Mikko Hyvölä for his kind peer support throughout our thesis projects.

The whole Market innovations team at Fingrid was an important piece in the puzzle of making this research possible by giving insightfull ideas and feedback for the work. Also, other experts at Fingrid, especially in the Strategic grid planning unit, were crucial in running the electricity market simulations, and aquiring knowledge for the various perspectives of the broad scope of the thesis.

This thesis would not have meant this much without the friends made along the journey of my studies. I heartily thank the Guild of Civil Engineers, Fuksis of 2016, Raato18, FTMK18, Fuksis of 2018, and Lämpövoimakerho for their warm supporting atmosphere and the amazing people organizing events for both fun and professional growth. Also, greetings for Veikko Sompa, and thanks for the flexibility.

Finally, I want to thank my partner Himmi for her loving support during the, at times, hectic process of writing the thesis.

Helsinki, 30 May 2020
Visa Simola

Symbols and abbreviations

Symbols

E	Energy [TWh]
h	Time in hours [h]
P	Power [MW or MWh/h]

Abbreviations

ACER	European Union Agency for the Cooperation of Energy Regulators
BRP	Balance Responsible Party
CEP	Clean energy for all Europeans package, Clean Energy Package
DA	Day-Ahead (Electricity marketplace)
DER	Distributed Energy Resources
DR	Demand Response
DSF	Demand Side Flexibility
DSO	Distribution System Operator
ENTSO-E	the European Network of Transmission System Operators
EU	European Union
EV	Electric Vehicle
FACTS	Flexible Alternating Current Transmission System
HEMS	Home Energy Management System
HP	Heat Pump
HVAC	Heating, Ventilation, and Air-Conditioning
ID	Intra-Day (Electricity marketplace)
IRES	Intermittent Renewable Energy Sources
ISP	Imbalance Settlement Period
PV	Photo Voltaic
TSO	Transmission System Operator
SoS	Security of Supply

1 Introduction

1.1 Background and motivation

Climate change mitigation is a big challenge for multiple sectors of society. The related energy transition that targets reduced emissions is seen to rely on increased intermittent renewable energy sources (IRES) as well as electrification and integration of sectors like transportation (Yuan;Thellufsen;Lund;& Liang, 2021), heating (Thomaßen;Kavvadias;& Navarro, 2021), and industry (Fais;Sabio;& Strachan, 2016). Great uptake in intermittent wind power generation, increasing electricity demand, growing number of distributed energy resources (DERs), and decreasing number of flexible fuel-based generation units are challenging the operational security of the electrical power systems.

The power system's flexibility is a key aspect in coping with future challenges, such as keeping the stability of power system frequency, ensuring adequate power generation to meet electrical loads, and transmitting growing amounts of IRES-generated electricity without exceeding voltage or thermal limits of the power transmission system. According to Akrami, et al. the literature consensus is that the penetration of IRES generation increases the flexibility needs on short-, mid-, and long-term time scales (Akrami;Doostizadeh;& Aminifar, 2019).

The evolution of both the flexibility needs of various power system actors and the flexibility potential of different energy resources must be analyzed better to address the most important issues. Particularly, novel demand resources, which are currently not extensively deployed in the power system portfolio, can provide new demand-side flexibility (DSF) but also strain the electricity networks with their consumption patterns. Such resources include, for instance, electric heating of households and electric vehicle (EV) chargers. However, it is worth mentioning that there are various uncertainties with the speed and effects of their deployment.

As electricity market actors and energy resources evolve, different use cases of flexibility also change and are in need of constant exploration. Especially, the flexibility needs of transmission system operators (TSOs) have versatile classifications and definitions. It is imperative to form coherent categorizations, informational data, and illustrations about future flexibility needs to assess their prevalence in different trajectories of power system evolution. The flexibility need estimates help to both assess and enhance the adequacy of energy resources that could provide flexibility for the needs. More specifically, the most critical, i.e., urgent in short to medium time horizons, flexibility needs, and the benefits of flexibility participation can be communicated in a more targeted and efficient manner. Then, electrical power system operation and research and development projects can also focus on resolving the key issues related to the adequacy of flexibility.

Currently, quantification methods of flexibility needs are seen as insufficient for a comprehensive analysis of all various forms of flexibility needs, and they are mostly in early development phases or not established. Thus, an extensive mapping and a consistent categorization of flexibility needs and more methods for quantifying the key flexibility needs are needed.

1.2 Objectives and structure

The main objective of this thesis is to map the flexibility needs of transmission system operators (TSOs) and develop suitable methods for quantifying their representing metrics. The methods are planned to be applied to day-ahead (DA) market simulation data that is based on future electric power system scenarios. Method descriptions are the main deliverables with the resulting data and illustrations formed. In addition to the main objectives, it is planned to map flexibility potential evolution estimates and development altering factors to support the selection of flexibility need metrics for the method development. This objective is planned to be reached by gathering flexibility potential evolution estimates from literature and identifying the critical factors affecting the flexibility potential evolution with stakeholder views and literature on the matter. Flexibility potential research is limited to distributed DSF resources that take less than 1 MW of power from the distribution network at maximum.

The aim of this thesis is to answer the following research questions:

- What are the future flexibility needs of transmission system operators, and which of them could be quantified?
- How can the selected needs be quantified with market simulation data?
- Which illustrations are suitable for the visual representations of the quantification results?

The remainder of this thesis is as follows. Section 1.3 presents the primary contributions of the thesis. The topic of flexibility in the power system is introduced in Section 2 by presenting the basics of electrical power systems in Section 2.1, the role of flexibility in the electrical power systems in Section 2.2, and the mechanisms for flexibility execution in Section 2.3. The flexibility potential evolution of distributed DSF resources is explored by presenting an overview of their flexibility potential evolution in Section 3.1, key factors affecting their flexibility potential evolution in Section 3.2, and outcomes of their flexibility potential evolution in Section 3.3. The definitions of the quantification methods are assessed in Section 4 by presenting the benefits of quantification in Section 4.1, introducing the input data options and used data in Section 4.2, introducing possible quantification tools in Section 4.3, presenting and applying a methodology for the evaluation of quantification methods of flexibility needs in Section 4.4, and describing the selection of the chosen quantification methods, i.e., 1h power ramp analyses. The chosen methods are described in Section 5 by presenting the power ramp calculations in Section 5.1, describing the processes of method 1, i.e., the system-level approach to power ramps in Section 5.2, and describing the process of method 2, i.e., power ramps of a resource group in Section 5.3. The results of the quantification methods are presented in Section 6.2 and Section 6.3 for methods 1 and 2, respectively. Section 7 includes discussions on the results conclusiveness in Section 7.1 and proposed follow-up research and development in Section 7.2. Finally, the findings of this thesis are concluded in Section 8.

1.3 Author contributions

Some parts of the empirical research process are created by or in joint efforts with another master's thesis by Mikko Hyvölä (Hyvölä, Sector integration's impacts on power system operation (WIP), 2022). These include re-parametrization of TSO-level demand resources for used electricity market simulation scenarios. A more detailed description of the re-parametrization tasks can be found in Section 4.2.1. Other contributions are the initial parametrization of scenarios and running the market model simulations. These efforts were executed by the strategic grid planning unit of Fingrid.

2 Flexibility in the electrical power system

This section includes power system introduction, definitions of flexibility, and mechanisms for flexibility procurement. The subjects are presented for the current state of power systems and future changes are discussed. The power system introduction includes descriptions of topology, marketplaces, and stakeholders. Definitions of flexibility consist of flexibility type, potential and demand categorizations. Finally, mechanisms of procuring flexibility are presented and their applications are discussed.

2.1 Electrical power system introduction

This section consists of electrical power system topology and energy resource description in Section 2.1.1, and system responsibility descriptions of TSOs in Section 2.1.2.

2.1.1 System topology and energy resources

A national power system topology generally consists of 3-phase alternating current (AC) powerline networks, cross-border links, generation sites, demand sites, and substations between grids with different voltage levels. High-voltage (HV), medium-voltage (MV), and low-voltage (LV) grids are connected via transformers that transfer electric energy, usually from higher to lower voltage levels. In Finland, HV grids and some MV grids are part of the transmission network which is mainly arranged in a meshed fashion. The transmission system topology of Fingrid Oyj is presented in Figure 1. Some MV grids and all the LV grids are included in distribution networks with meshed network topology in urban areas and radial composition in rural areas.

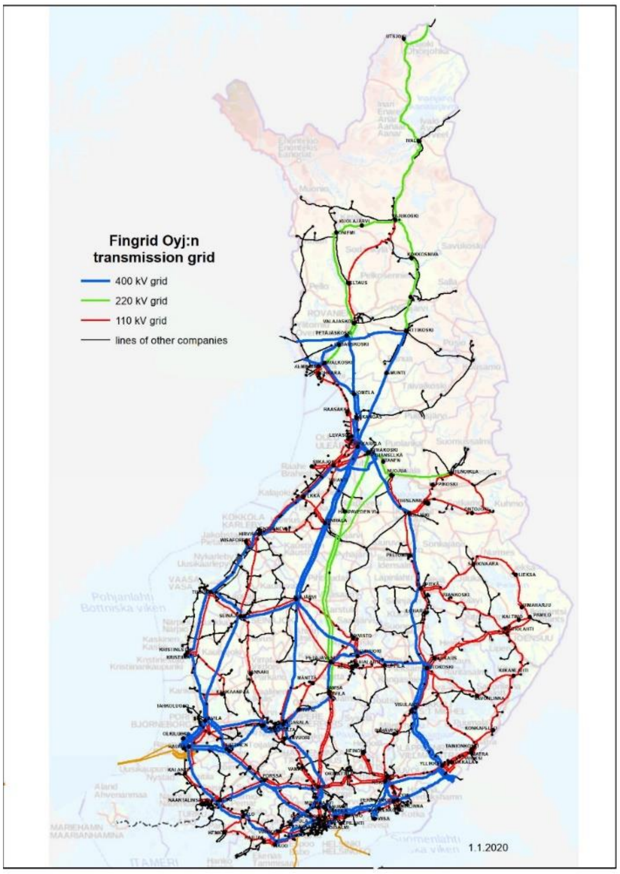

Figure 1: The electricity transmission grid of Fingrid Oyj. (Fingrid Oyj, 2020)

In addition to transmission and distribution networks, electrical power systems can have production grids and microgrids. Production grids are located near electricity generation sites and are connected to transmission or distribution networks. Microgrids, arranged in a meshed topology, are capable of for disconnecting from external grids and operating in grid-connected and island mode while they have internal electricity generation in addition to consumption. Their scale ranges between households and whole residential districts. However, they are currently legislatively challenging to form and operate (Valta;Mäkinen;Kotilainen;Järventausta;& Mendes, 2018).

A generation site is a generation unit or a generation resource group with a common connection point to a grid. The network codes of Fingrid apply to generation units with over 0.8 kW of rated power, which indicates it to be the minimum requirement of connecting generation to the transmission grid. (Fingrid Oyj, 2018). The larger the rated power of a generation site, the more likely it is connected to a higher voltage level. Demand sites are consumption sites or resource groups with a common connection point to a grid. Like generation sites, the larger a demand site is, the more likely it is to be connected to the transmission network, and the smaller it is, the lower is its connection grid's voltage level. Demand sites can have, besides electricity consumption loads, also electricity generation. Some industrial players like the forestry industry might have electricity generation resources on-site and be net producers of electricity, even though it is not their core business area. Thus, the binary division of demand and production sites is ambiguous.

The ambiguity is becoming even more apparent as households and communities invest in their own or shared generation resources and grid infrastructure. Such development changes the network topology since the share of meshed and looped structures increases and capabilities of isolated or islanded operation in smaller parts of the power system grow. With DER penetration, electricity generation sites disperse and their size decreases. This results in more bi-directional power flow compared to traditional one-directional power flow from higher to lower voltage level grids.

As consumption and generation sites can include multiple energy resources and different energy resource types, it is important to state the possible configurations of energy resource sites. Figure 2 depicts the general energy flows that can occur within an energy resource site with an electricity grid connection.

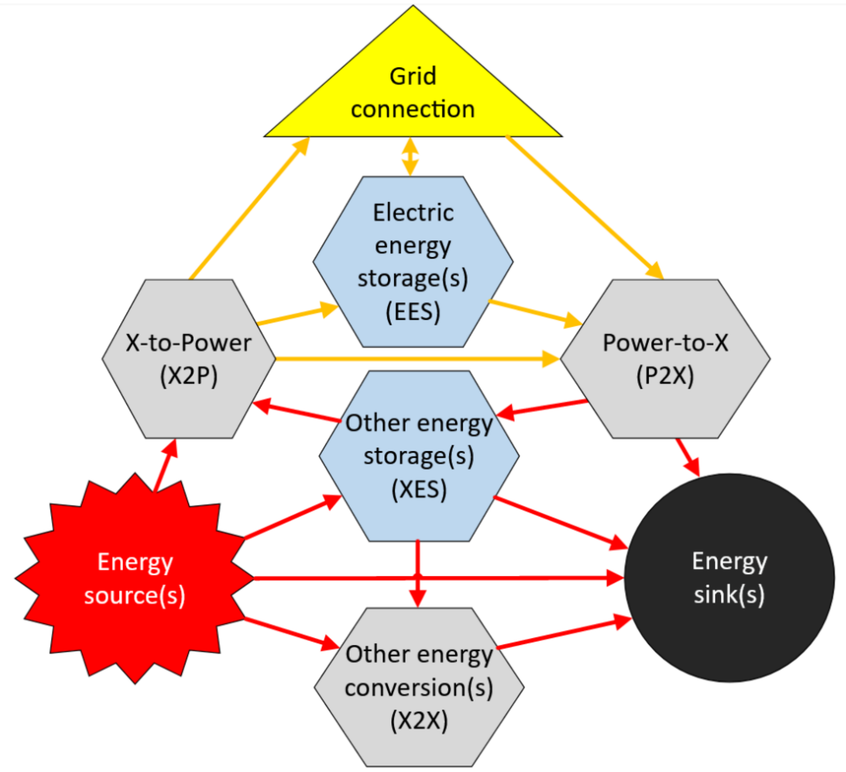

Figure 2: Possible energy flows of a grid-connected energy resource site. Electricity is depicted by yellow arrows and other energy vectors are represented by red arrows. The arrows indicate the possible directions of the energy flows. Own illustration.

Grid connection refers to the primary connection point to an electricity grid that is exchanging electricity between a site and an external grid. One form of flexibility execution from the electricity grid's point of view is to change the grid source that feeds or draws electricity from the site. The site can have the capability to switch to another grid feeder, such as a feeder from a local microgrid. The second way to alter the grid flows of a site is to alter the electricity generation which is referred to as *X-to-Power (X2P),* which stands for converting other forms of energy into electricity. The third option is to utilize *Electric energy storage(s) (EES),* which can shift the timing of electricity flows between the electricity generation, grid, and the on-site electricity consumption. On-site electricity consumption is marked as *Power-to-X (P2X)* which stands for converting electrical energy into other energy forms. As noted, P2X at a site can withdraw energy from on-site generation, grid connection, and EES. Thus, the fourth option for flexibility execution is to alter the electricity consumption. Beyond the electricity generation, the original *E*nergy source can also be changed, or the energy flow can be directed into *Other energy storages (XES)*, which stands for storing other forms of energy than electricity, or directly into an *Energy sink*. *XESs* can, by their part, enable temporal energy flow shifts that also affect the grid flows. Last of all, the *Energy sink*, which stands for the primary or end-user energy consumption, refers to the final events that the energy flows initiate, such as the movement of a vehicle. *Energy sinks'* need for supplying energy flows can be altered by rescheduling or limiting the end-use.

Spatial distribution of generation sites and magnitude of demand sites consumption are also predicted to change. For instance, wind power generation is expected to increase in central and northern areas of Finland, while electricity consumption is rising due to electrification, particularly heavily in southern municipalities. Also, the overall electricity demand is estimated to grow. Such changes alter the power flow dynamics that transmission networks are scaled to, which sets the needs to strengthen and alter the grid infrastructure (Fingrid Oyj, 2021).

In addition to national topology changes, international transmission links are growing in number and capacity-wise, such as the new inter-connector investment between Sweden and Finland (Fingrid Oyj, 2022). Thus, also the development of other countries' electrical power systems is important since their functioning will transition more across market areas in the future. Even pan-European ultra-high voltage direct current (DC) grids are suggested to balance out IRES generation variations between countries (Michi, et al., 2019).

Last of all, sector integration efforts are estimated to influence the electricity networks as various sectors such as electricity, heating, gas, and mobility are coupled together. Linking different energy carriers and their networks together might create local clusters of energy production and consumption, thus diminishing the importance of broad transmission systems. On the other hand, couplings could provide more flexibility and resilience via a more versatile system. However, the energy system's complexity will also increase as sectors are coupled, and different value chains interconnect in more numerous ways.

2.1.2 Power system responsibilities of TSOs

The responsibilities that TSOs have over an electrical power system, stem from various sources. EU directives are enforced to national legislation and EU regulation applies directly to the operation of electrical transmission systems. These EU-level legislative measures affect the network codes, pricing, and terms & conditions of TSO-provided services. Even though, responsibilities are national, cross-border frequency synchronization of transmission networks creates joint responsibilities among TSOs, for instance, between the Nordic countries.

Network codes are the direct application of EU regulation and national legislation. EU level network codes are implemented into the national codes. They are confirmed by the European and national energy authorities. Network codes are classified into connection, operating, and market codes. (Fingrid Oyj, 2022) The clean energy for all Europeans package (CEP) consists of four directives and four regulations (European Comission, 2022). As part of CEP, 2019/944 directive introduces many new concepts to be considered in transmission system operation (Directive (EU), 2019). National legislative implementation is planned to be accepted during the summer of 2022 and enforced by the end of 2022 in Finland .

In Finland, the Finnish electricity market act 588/2013 states general responsibilities of system operators (SOs) and TSO specific responsibilities. General SO responsibilities include the provision of electricity grid services, grid development, grid connection, transmission, measurement of transmission, and procurement of electricity transfer losses. Additionally, SOs must prepare for disturbances during normal conditions, rationing actions during power supply deficit, and operation during special act conditions. TSO specific system responsibility consists of ensuring the functionality, operational security, power balance of electricity generation and demand, and sufficient imbalance settlement of electrical power system of Finland. (Ministry of Economic Affairs and Employment of Finland , 2013)

As implied in the electricity market act, Fingrid has an obligation to connect other electricity grids, demand sites, and power plants to the transmission grid by request and against reasonable compensation. These actions are executed according to Fingrid’s general connection terms that are aligned with EU legislation. (Fingrid Oyj, 2021)

As connections are required, also the security of supply, or in other words, the certainty of fulfilling electricity transmission needs must be on a high level . Resource adequacy is a similar measure to the security of supply but focuses on the sufficiency of different resource categories such as electricity generation and transmission capacity compared to the gross electricity demand of the power system. Resource adequacy and the security of electricity supply are seen as international challenges that are usually considered on the Nordic scale in joint research of the Nordic TSOs.

Fingrid is also the responsible for developing the Finnish electrical power system to fulfill the other responsibilities, which means investments in both physical components needed for electricity transmission and information technology to measure and control the power system behavior. With the balance and imbalance settlement responsibilities, Fingrid also needs to develop different electricity markets and the settlement of the trade imbalances compared to the market outcome. Electricity marketplaces and imbalance settlement are described in section 2.3.1. The constant balance of electricity generation and consumption is indicated by the frequency level of the AC-power in the Nordic power system consisting of electric power systems in Finland, Sweden, Norway, and Denmark. The frequency drops if there is more consumption than production and frequency rises if there is more production than consumption. In addition to frequency, the voltage levels of the power system are important indicators of power system functionality. Both frequency and voltage are necessary to be kept within predefined levels due to energy resources being designed to function within the conditions.

To ensure the functioning electrical power system, a certain level of operational security must be achieved. EU commission regulation 2017/1485 provides guidelines for electricity transmission system operation. The regulation states: "*operational security means the transmission system's ability to retain a normal state or to return to a normal state as soon as possible, and which is characterised by operational security limits*". (Commission Regulation (EU), 2017)

The operational security can be divided into static and dynamic stability. Static stability is the power systems ability to keep the system frequency and regional voltage levels within predefined limits under normal operating conditions. Normal operating conditions refer to a state where no major faults are present. Dynamic stability refers to the power system's ability to return to its normal state after major faults without any cascading faults. The minimum dynamic stability condition is so-called dimensioning fault or N-1 fault that is the singular component malfunction with the biggest impact on the system state of a particular period. The contingency that is defined as the dimensioning N-1 fault can be different depending on which system state indicator is considered. For instance, electricity transmission capacity can have different dimensioning fault contingency than frequency drop level.

As part of the static and dynamic stability, the power system operation must be prepared to function during a planned outage and withstand a dimensioning fault. This stability during an outage can be called withstanding an N-1-1 fault. However, the term can be misleading since it can also mean a major fault with a cascading fault. Planned outages take place while fixing or maintaining the transmission system, and connecting new loads, generation, or grids to the transmission grid.

As there is a possibility for broader combinations of failures than singular components such as power outages in power system areas, TSOs have the responsibility to co-ordinate the restoration of system voltage and stability after such outages. Such failures can result in frequency synchronization area's division into regional frequency areas or even total black outs of regions or nations. After occurrence of such events, predefined procedures are followed to return the power system to a normal state.

As the power system topology, energy resources, and TSOs responsibilities are general, it is important to assess the power system in a more detailed manner. For instance, the power system responsibilities of TSOs can be met by fulfilling various flexibility needs.

2.2 Role of flexibility in the electrical power system

In this section, flexibility is introduced as a theme first in the section 2.2.1. Secondly, the meaning of flexibility is defined in Section 2.2.2. Then, the flexibility needs of different stakeholders are discussed on a general level in Section 2.2.3, and TSO flexibility needs are described in greater detail in section 2.2.4. Finally, the concept and classification of flexibility potential is defined in Section 2.2.5, and the scope of studied flexibility resources is presented in Section 2.2.6.

2.2.1 Introduction to power system flexibility

Since the electrical power system has many levels of complexity, power system flexibility is an extensive theme whose scope depends heavily on a context. However, with consistant definitions and scoping, it can help to encapsulate complicated power system dynamics into understandable concepts that can be assessed and compared in numerous ways. To understand the concept of flexibility, it can help to approach it as a product that can be delivered when its demand and supply match. Demand of flexibility consist of the use cases that flexibility is meant for in the power system, or in other words, flexibility needs. Supply of flexibility consists of behavior alterations of power system's energy resources that are possible, or in other words, flexibility resources with flexibility potential. The definition of flexibility is further discussed in Section 2.2.2.

Various actors of the power system have flexibility needs that can compete for the same flexibility resources. Thus, it is important to understand the nature of the flexibility needs of different power system actors, which is further explored in Section 2.2.3. Multiple use cases of flexibility can be identified as means of fulfilling the responsibilities of a TSO. These TSO flexibility needs and their fulfillment are critical foundations for a secure power system and are, thus, discussed in greater detail in Section 2.2.4. Flexibility resources' supply of flexibility can be described with the concept of flexibility potential that can embody varying degrees of flexibility's usability ranging between the theoretical and the commercial domain. Flexibility potential is further discussed and classified in Section 2.2.5. Finally, the energy resources that can provide power system flexibility are introduced and categorized, and the scope of studied flexibility resources is defined in Section 2.2.6.

2.2.2 Definition of flexibility

Flexibility as a concept is vague and can be defined in multiple ways with varying degree of detail and number of characteristics. Thus, it is imperative to have a consistant definition of flexibility that eases the scoping of this thesis and interpreting its findings. The following definition of flexibility, that is based on (Degefa;Sperstad;& Sæle, 2021) and (Ulbig & Andersson, 2015), is applied to this thesis: **an intentional[1] and incentivized[2] behavior alteration[3] of grid-connected energy resources[4] in relation to a predefined level[5] for a limited duration[6].** Next, the background for the definition is introduced.

Degefa et al. provide an extensive collection of literature definitions and their own definition criteria. The proposed definition criteria requires a clear definition for the type of flexibility resource, duration of activation of flexibility, and incentive for activation of flexibility. The compatibility of proposed definition criteria was tested for the literature definitions of flexibility and it was stated that all literature definitions were defective at least by one regard of the trifold criteria. The authors proposed their own definition of flexibility as follows: "*The ability of power system operation, power system assets, loads, energy storage assets and generators, to change or modify their routine operation for a limited duration, and responding to external service request signals, without inducing unplanned disruptions.*" The definition was partly applied to the thesis, but the 'external service request signal' was changed to a broader notion of 'intentional and incentivized' to include other flexibility execution strategies than explicit measures that are discussed further in Section 2.2.3. Also, most of the wording of the definition was changed, but the general scope was the same. (Degefa;Sperstad;& Sæle, 2021)

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[1] intentional = not random nor unknown, flexibility participation has a purpose

[2] incentivized = participation in flexibility provides benefits

[3] behavior alteration = energy resources' states change differently compared to a predefined level

[4] grid-connected energy resources = devices that feed electricity from/to electricity transmission or distribution network (grid exchange) directly or via conversions of energy forms. Behavior alterations affect the grid exchange. Grid components are also included.

[5] predefined level or baseline = average, routine, or planned profile of behavior

[6] for a limited duration = flexibility has a duration or, in other words, is a temporary event

To reach a conclusive definition of flexibility, the form of energy and types of energy resources needed to be addressed. Ulbig & Andersson defined flexibility as alterations that affect the electrical power system (Ulbig & Andersson, 2015). Their approach was applied to the definition of flexibility resources in this thesis since the focus of this thesis was on the flexibility of the electrical power system. Thus, any energy resource, whose behavior affects transmission system electricity flows, was considered as a plausible flexibility resource. In other words, a direct grid connection or a longer chain of energy vectors, that impacts the grid flows, were considered as prequisites for a flexibility resource. It should be noted that grid components were also considered as flexibility resources. Flexibility resources are described in more detail in Section 2.2.6.

To elaborate more on the flexibility's definition, several properties could have been considered as part of the term. Flexibility can be a power magnitude alteration of a flexibility resource. The power can be divided into active power and reactive power, and their combination, in other words apparent power. From this point onwards, power refers to the active power unless mentioned otherwise, since the active power is a more remarkable property for most of the TSO flexibility needs further examined in Section 2.2.4. Another property of flexibility is energy alteration. Energy alteration refers to the difference in energy consumption or production of a flexibility resource during a flexibility event compared to conditions without participation in the event. Thirdly, the power ramp-rate of an energy resource during a flexibility event describes how fast the power changes during the event. Ulbig et al. provided extensive analysis on the three flexibility properties and their interplay during a flexibility event. (Ulbig & Andersson, 2015) Other properties of flexibility include voltage level alteration, duration of the flexibility event, recovery time after the event, rebound effect, and the quality of the flexibility event execution. Power is the primary attribute to quantify flexibility in this thesis since it provides a general overview of the capabilities of flexibility resources and magnitudes of flexibility needs. It should be noted that other properties are also discussed when considering different kinds of flexibility needs.

Last of all, flexibility was defined by the context of its execution. Firstly, a flexibility event was determined to be an intentional alteration of energy resources' behavior. In other words, it would not be random nor would the controller of the resource be oblivious to the occurrence of the event. Secondly, a flexibility event would have an incentive. The incentive for flexibility participation would come from either achieved benefit, such as savings or avoided harm, such as economic sanctions. Thirdly, the magnitude of flexibility would be the difference between a predefined level and the actual outcome of a flexibility event. A predefined level, or alternatively, a baseline, could be defined in various ways, but generally, it can be either an average profile or an estimation of flexibility resource's behavior in conditions where flexibility events would not materialize (Vilkko, 2021). Lastly, flexibility would be a temporary change with a limited duration, rather than a measure that would have a long lasting effect on the flexibility resource's behavior.

The flexibility, as a behavior alteration, could have meant several different types of control of energy resource's state, such as load shifting and generation curtailment. However, they are not elaborated further as flexibility is analyzed on a general level focusing on power alteration's magnitude as the main property.

2.2.3 General flexibility use cases and stakeholders

Flexibility has various use cases. Thus, it is essential to understand different stakeholders' needs for flexibility. After all, there is a limited number flexibility resources, and stakeholders can have contradicting flexibility needs. To address this issue, stakeholder categories' interests are mapped out and reflected in the use cases of flexibility that are presented in the following paragraphs. Flexibility use cases can be categorized into four types of usage: ease-of-use, energy efficiency, implicit flexibility, and explicit flexibility.

Ease-of-use refers to flexibility activity that has intentions to enhance primary processes execution at the energy resource site, such as improving the comfort of household inhabitants and maximizing the productivity of a manufacturing factory. The enhancements can be done, e.g. by rescheduling or automizing the control of appliances that use electricity. Home energy management systems (HEMSs) are a key technology group to achieve these kind of functionalities (Xu;Chen;Washizu;Ishii;& Yashiro, 2018) in buildings.

Energy efficiency is an umbrella term of measures that conserve energy by reducing energy losses of energy flows that are used to fulfill end uses of energy. Degefa, et al. did not consider energy efficiency as flexibility since it was seen as mostly measures that reduce electricity consumption permanently, such as new insulations and windows for old buildings (Degefa;Sperstad;& Sæle, 2021). However, energy efficiency can be considered a flexibility use case when the measures alter the energy resource behavior in short durations by, e.g., rescheduling electricity consumption closer to the actual end-use or utilizing as much of the on-site generation as possible.

Implicit flexibility refers to the flexibility that is incentivized by price signals and that it is executed by on-site decisions (Hermans, et al., 2019). The incentive comes from potential savings from energy price differences on alternative energy consumption schedules or avoiding increased costs from, e.g., peak power tariffs.

Explicit flexibility is activated via an external signal from outside of a energy resource site (Hermans, et al., 2019). Explicit flexibility participations can be incentivized by straight remunerations like payments or discounts in the energy bills.

The four proposed flexibility use cases are a simplification of the versatile field of flexibility resources' utilization. Thus, some discussive points should be mentioned. Implicit and explicit flexibility resources cater to power system's balance and reliability while receiving monetary benefits. On the other hand, ease-of-use and energy efficiency use cases mainly serve on-site needs, but they also impact the power system. It can also be argued that ease-of-use and energy efficiency are more likely factors that set limits for the utilization of implicit and explicit flexibility rather than being significant flexibility use cases themselves. It should be noted that energy efficiency and ease-of-use measures can be categorized under an umbrella term demand-side management (DSM) that also includes demand response (DR). As stated by Degefa, et al. the terms are not synonyms but rather different parts of the definitions of flexibility (Degefa;Sperstad;& Sæle, 2021).

The main stakeholders of the flexibility markets of DSF were collected by Villar, et al. in their literature review. They included TSOs, DSOs, BRPs, aggregators, and retailers in their listing of key stakeholder types. They also denoted that the players could have several roles, such as aggregators with balance responsibility (Villar;Bessa;& Matos, 2018). Other remarkable actors of DSF are generators and the users of flexibility resources. It should be noted that there are also other stakeholders that have roles in the flexibility market landscape, such as original equipment manufacturers, flexibility solution providers, i.e., retailers of devices and developers of software, that ease flexibility activations, national and EU legislators and regulatory authorities, and nominated electricity market operators. However, they were left out of the scope of the flexibility use case analysis since they do not utilize flexibility but rather intermediate or enable its execution.

The primary flexibility use cases of stakeholder categories are presented in Table 1. It should be noted that the importance of the use cases varies within stakeholder categories depending on the flexibility resource, ownership dynamics, and market environment.

Table 1: The general use cases of flexibility for different stakeholders. The symbol ‘x’ denotes confirmed use cases and the symbol ‘?’ depicts unusual or unsure use cases for the stakeholder category. BRP stands for balance responsible party.

	Ease-of-use	Energy efficiency	Implicit flexibility	Explicit flexibility
TSO			x	x
DSO			x	x
Generator			x	x
Retailer			x	?
BRP			x	x
Aggregator			?	x
Flexibility resource user	x	x	?	?

The system operators are primarily focused on balancing their electricity networks and thus focus on explicit and implicit flexibility. **TSO** flexibility use cases are broader than DSOs’ due to the TSOs’ responsibility of entire national electrical power systems. TSO flexibility use cases or in other words flexibility needs are further discussed in section 2.2.4. **DSOs** need flexibility for various use cases (Villar;Bessa;& Matos, 2018). DSOs utilize implicit flexibility with e.g., distribution tariff pricing. For instance, peak power tariffs are used to incentivize cutting of consumption peaks and thereby reducing congestion of distribution grid electricity flows. When it comes to explicit flexibility, DSOs can activate external flexibility resources such as batteries to stabilize the distribution network voltage or to enhance the security of supply during fault events.

Electricity **generators** actively alter their generation output based on electricity market equilibrium and can offer their generation resources for external control, such as reserve markets.

Retailers procure implicit flexibility to enhance their profits. Procurement can be executed by incentivizing pricing schemes and, in some cases, by control of flexibility resources based on price levels. However, the latter ,i.e., the external spot steering, is still quite rare.

Balance responsible parties (BRPs) oversee maintaining the consumption or generation balance set by the electricity market outcome of their energy resources. Thus, BRPs are willing to utilize flexibility to maintain their balance to avoid economic sanctions of imbalances. Different electricity marketplaces enable the corrections of imbalances via implicit flexibility but explicit flexibility procurement of BRPs is not a very well-known use case.

Aggregators are intermediaries that can provide flexibility resources’ flexibility to other parties in need of flexibility. Aggregators can control several flexibility resources and offer their flexibility as a pool with a greater magnitude of flexibility than singular resources could on their own. Aggregators need explicit flexibility from energy resource to be offered to needers of flexibility since they operate outside of the energy resource site premises. However, it could be argued that aggregators also control flexibility resources based on implicit price signals, which could count to implicit flexibility.

Finally, the **flexibility resource user** refers to people that are using the energy resources participating in flexibility events. Their primary flexibility use cases are ease-of-use and energy efficiency, although implicit and explicit flexibility can be used to achieve financial benefits. However, the implicit and explicit flexibility participation of end-users is still quite rare.

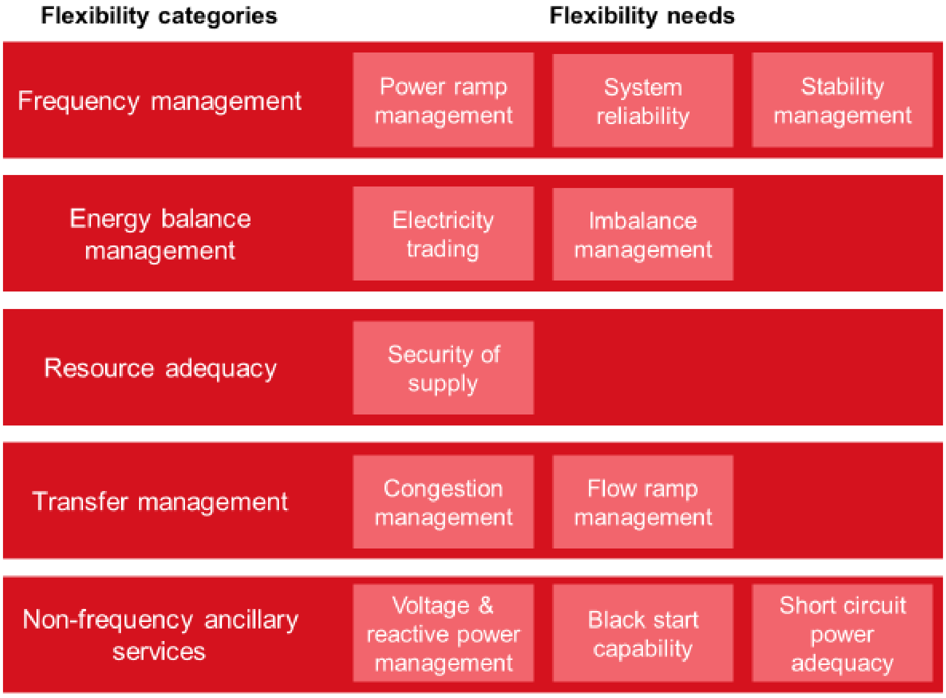
2.2.4 Flexibility needs of TSOs

As described in section 2.1.2, transmission system operators are required to enable sufficient electricity transmission, system stability and operational security of an electricity transmission system. Thus, TSOs need flexibility to fulfill the responsibilities. As the power system evolves, the flexibility needs also change and are emphasized differently. These flexibility needs have various definitions and categorizations between studies. This section describes the literature definitions and categorizations of TSO flexibility needs and provides a synthesis to be applied in selecting quantification methods in Section 4.4.

Literature has varying categorizations of TSO flexibility needs. Hillberg, et al. categorized flexibility needs into four categories: frequency (second-hour), energy (hours-year), transfer capacity (minutes-hours), and voltage (seconds-minutes) in their discussion paper (Hillberg, et al., 2019). Sæle et al. categorized flexibility needs into balancing & non-frequency ancillary services, and congestion management (Sæle;Morch;Degefa;& Oleinikova, 2020). The Belgian TSO Elia provided an analysis of some specific adequacy and flexibility needs of the Belgian power system from few points of view. Their categorization consists of slow (5h), fast (15min), and ramping (5min) flexibility (Elia, 2019). Hegarty et al. categorized SO flexibility needs into two tasks "*matching generation with demand and ensuring that power flows do not exceed network thermal and voltage limits*" and focused only on the former, whilst noting it being the most common scope of the flexibility need evaluations in the literature at the time (Heggarty;Bourmaud;Girard;& Kariniotakis, 2020). ENTSO-E provided flexibility need categories for ramping and scarcity periods (ENTSO-E, 2021) but no indication of a broad mapping of different flexibility needs. Loutan et al. presented in their technical study that Californian power system operator's classification for flexibility needs are Base Flexibility, Peak Flexibility, and Super-peak Flexibility which were determined by power ramp calculations (Loutan;Zhou;& Motley, 2019).

"*Matching the generation with demand*", or power balance in short, consists of actions that ensure the constant balance of electricity production and consumption that is indicated by the frequency of the AC power system (Heggarty;Bourmaud;Girard;& Kariniotakis, 2020). The flexibility needs of frequency management are harder to define due to the versatile portfolio of mechanisms that contribute to the stabilization of frequency. The power balance is mainly achieved with electricity market trading, but some deviations cannot be predicted while trading. Thus, deviations in the market balance occur constantly. Imbalance pricing incentivizes the market players to trade the actual amount of electricity that they are going to produce or consume, but predictions are inevitably subject to some errors. More real-time balancing is executed with reserve market products to resolve unforeseen imbalances and ensure stable frequency. Thus, real-time balancing flexibility needs can be categorized as frequency management, and energy balance management can refer to short- to long-term trading of electricity.

Even though, to the best of my knowledge, consensus on the flexibility need categorization or flexibility need definitions were not present in the literature, the proposition for the grouping of flexibility needs is presented in Figure 3. It should be noted that several other flexibility needs could be classified, but the presented synthesis is seen as sufficient to provide an overall picture of the main flexibility needs of TSOs.



Flexibility categories	Flexibility needs		
Frequency management	Power ramp management	System reliability	Stability management
Energy balance management	Electricity trading	Imbalance management	
Resource adequacy	Security of supply		
Transfer management	Congestion management	Flow ramp management	
Non-frequency ancillary services	Voltage & reactive power management	Black start capability	Short circuit power adequacy

Figure 3: Flexibility need categories and flexibility needs. Own illustration based on sources (Hillberg, et al., 2019) and (Sæle;Morch;Degefa;& Oleinikova, 2020).

Frequency management flexibility needs can be further divided into power ramp management, stability management, and system reliability.

Power ramp management means the need for energy resources to provide fast power alterations during periods where the magnitude of power generation or consumption changes. This can refer to e.g., market period shifts where some generation units increase their production faster than other resources in the power system, resulting in frequency deviations. Recently, power ramp management has been linked to residual load changes. Residual load means the remaining net load of the power system after IRES generation is subtracted from the gross load. However, the definition is problematic since it only considers how IRES generation can match the electricity demand that is to some extent flexible rather than fully static. A more meaningful way of defining ramping flexibility needs would be to dissect the power ramps of IRES generation and how much flexibility would be needed to balance their power ramps. The ramping could be estimated by comparing the average power between consecutive market periods.

Frequency stability management refers to the need to change the power system characteristics to be more resilient to frequency deviations. Generally, the electro-kinetic inertia, later referred to as just inertia, of the electricity generator units' rotating masses dictates the impacts of power balance deviations to the frequency levels. With high power system inertia, power balance deviations cause slower and smaller frequency deviations, which gives more time for other balancing measures to be activated. The stabilizing effect of the power system's natural inertia can be compensated to some extent with synthetic inertia or fast responding flexibility resources (Ørum, ym., 2018). It can be argued that stability management is not part of frequency management and could be under non-frequency ancillary services. But since it has a strong effect on the frequency behavior of the power system, it is kept under the category.

System reliability (Reliability of supply, load, and grid components) refers to flexibility needs that stem from power balance deviations of grid-connected energy resources caused by a range from minor disturbances to major faults. Usually, these deviations are counteracted with reserve resource activations which complicates the definition of the flexibility needs. However, some evaluations of the flexibility needs can be indicated by the required N-1 dimensioning fault preparedness level and deterministic imbalances of electricity generation and loads. It should be noted that these flexibility needs' activation time, duration, energy, and power requirements vary based on the rates that the frequency is needed to be changed and the system inertia levels. The flexibility needs for system reliability during a period are different for needed capacity and the actual expected activation needs due to the unpredictable nature of power balance deviations.

Energy balance management refers to flexibility needs that realize via **electricity trading** and **imbalance management**. Various marketplaces are used to trade electricity and, thereby, to reach an equilibrium that sets the overall balance for the demand and supply of electricity. This overall balance is then supervised and deviations from the agreed trades, i.e., imbalances are managed and settled. Thus, flexibility is needed in the form of reaching a trading balance and mitigating its imbalances. The marketplaces and imbalance management are further discussed in section 2.3.

Resource adequacy or **security of supply,** refers to flexibility needs for ensuring the delivery of electricity from generation to loads. The reference point for resource adequacy is to meet the system load with adequate generation. Both national and international energy and transmission resources are assessed due to the interconnected nature of the European transmission systems. European Union Agency for the Cooperation of Energy Regulators (ACER) provided a methodology for resource adequacy assessment and calculation (ACER, 2020) that are utilized by ENTSO-E in their Mid-term Adequacy Forecast for Europe (ENTSO-E, 2020).

Transfer management means the need for flexibility that alters the electricity flows in the system to avoid congestion or fast power system ramps. As stated by Sæle et al., **congestion management** can refer to the management of market, structural, or physical congestion. Physical congestion was at the focus of their article and is also elaborated in this thesis. The physical congestion was defined as ”*any network situation where forecasted or realised power flows violate the thermal limits of the elements of the grid and voltage stability or the angle stability limits of the power system*”. (Sæle;Morch;Degefa;& Oleinikova, 2020) Another transfer management-related flexibility need is **flow ramp management** that can apply to high voltage direct current (HVDC) interconnectors or whole market area net flows in the form of ramping constraints. Such means are applied to mitigate fast power balance deviations caused by the HVDC links that have faster ramping capabilities than other energy resources such as generator units. (Chatzigiannis;Dourbois;Biskas;& Bakirtzis, 2016)

Non-frequency ancillary services refer to services that are not affecting the power balance of the power system. EU directive 2019/944 defined them as follows: “‘*non-frequency ancillary service’ means a service used by a transmission system opera-tor or distribution system operator for steady state voltage control, fast reactive cur-rent injections, inertia for local grid stability, short-circuit current, black start capability and island operation capability*” (Directive (EU), 2019). They are utilized to keep other system properties within acceptable limits, provide adequate conditions to detect faults, and restore system stability after outages. Three major flexibility needs were found for the category. Firstly, **voltage & reactive power management** refers to the flexibility that ensures voltage levels and power angles to be within agreed limits (Sæle;Morch;Degefa;& Oleinikova, 2020). Secondly, **black start capability** means the availability of energy resources that can restore the electrical power system voltage after a blackout (Asheibi & Shuaib, 2019). Thirdly, **short circuit power adequacy** is a measure of how sufficient the fault currents of an electricity network are to trigger protective equipment such as circuit breakers (Bolacell;Venturini;Issicaba;& da Rosa, 2020).

2.2.5 Flexibility potential

Firstly, this section presents literature definitions and categorizations of the term flexibility potential. Secondly, chosen definition and a new concept for flexibility potential categorization are presented.

Energy resources can have property state alteration abilities, or in other words, they are able to provide flexibility. The magnitude of available flexibility provision is called flexibility potential. As discussed in section 2.2.2, flexibility can mean alterations of various properties, such as the power of energy consumption. Thus, flexibility potential can also describe several properties. However, power is a very common metric to quantify flexibility potential of energy resources (Fingrid Oyj, 2021) (Söder, et al., 2018) (Gils, 2014), most likely due to a greater focus on flexibility needs that need fast flexibility activations.

Power is a common property to quantify flexibility potential, but power as a metric is not uniformly defined since it can mean, for instance, the maximum or average power of flexibility and different directions of the power alteration. This leads to potential estimations that cannot be sensibly compared. Also, by Cambridge Dictionary's definitions, the potential is "*possible when the necessary conditions exist*" and "*someone's or something's ability to develop, achieve, or succeed*" (Cambridge University Press, 2022). This leads to the question of how the necessary conditions and the degree of flexibility provision ability are defined. Finally, the temporal variation of flexibility potential poses a challenge to estimating conclusive flexibility potential values for long periods such as years.

To address the complex nature of flexibility potential, it can be categorized into flexibility potential layers. Ulbig, et al. proposed the categorization of flexibility sources to be potential flexibility resources, actual flexibility resources, flexibility reserves, and market-available flexibility (Ulbig & Andersson, 2015). Gils provided estimations of theoretical DR potential that give a general overview of demand resources' flexibility abilities (Gils, 2014). Salpakari, et al. made estimations for technical and commercial flexibility potential (Salpakari;Mikkola;& Lund, 2016).

The formed categorization in this thesis consists of theoretical, technical, and commercial flexibility layers of flexibility potential. The layers are visualized in Figure 4. The theoretical layer refers to the rated power of flexibility resources that are being analyzed or quantitatively to the maximum realized power during an analysis period. As indicated by the naming of the layer, the flexibility potential is theoretical and thus not expected to be available for full utilization. Technical layer stands for the share of flexibility resources' rated power that can be controlled via automation or electronic commands, or in other words smart control. The goal of defining the technical layer is to expose flexibility potential that could be provided without manual actions that can be trying and unreliable. A quantitative definition for the technical flexibility potential is the greatest realized power of flexibility events during an analysis period. Finally, the commercial layer stands for the share of rated power that is available to actual flexibility activation and is also economically desirable. A quantitative definition for the commercial flexibility potential is the average power of flexibility events during an analysis period.

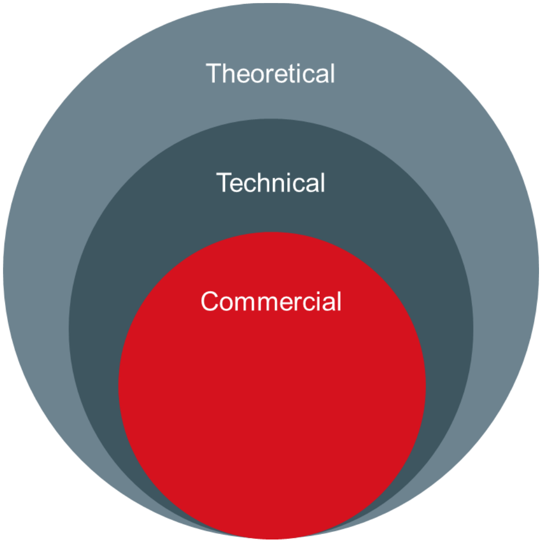


Figure 4: Proposed categorization of flexibility potential. Own illustration.

The proposed categorization is not without its shortcomings due to its simplified nature. For instance, the utilizable share of flexibility potential is integrated into the commercial layer even though it could also limit the other layers or be its own layer. In that context, the utilizable share stands for the flexibility potential that is available without obstructions to the primary use of the flexibility resources. It should also be noted that primary use can have graduated levels of usability that can set various acceptable price levels of flexibility events (Kubli;Loock;& Wüstenhagen, 2018). Another simplification applies to the commercial potential that could also be viable without smart control and could thereby be partly outside of the technical layer's subset. The proposed categorization is kept as intended to have a clear foundation to compare flexibility estimations on. However, further literature reviews and definition proposals should be conducted to form a more definitive categorization to be applied across the research field.

2.2.6 Flexibility resources

First, a flexibility resource is defined as an energy resource that is grid-connected, i.e., produces, converts, stores, transfers, or consumes energy that is either supplied by or fed into an electricity grid. The flexibility resource type refers to a class of similar flexibility resources, such as electric heating that includes, eg. electric boilers and heat pumps. The flexibility resource category is a more general class of flexibility resources, such as generation, which includes, e.g. wind turbines, nuclear power plants, and gas turbines.

On a general level, the flexibility resources of a power system can be divided into four resource categories or '*flexibility solutions*': load, generation, network, and storage (Heggarty;Bourmaud;Girard;& Kariniotakis, 2020). Similarly, Cruz, et al. classify flexibility resources into the supply side, demand side, network side flexibility, and other sources of flexibility that consist of energy storages, energy system integration, energy markets, and regulatory policies (Cruz;Fitiwi;Santos;& Catalão, 2018). To keep the classification simple, only four categories are considered since system and market actions can be included in the network group. The chosen classification is presented in Figure 5.

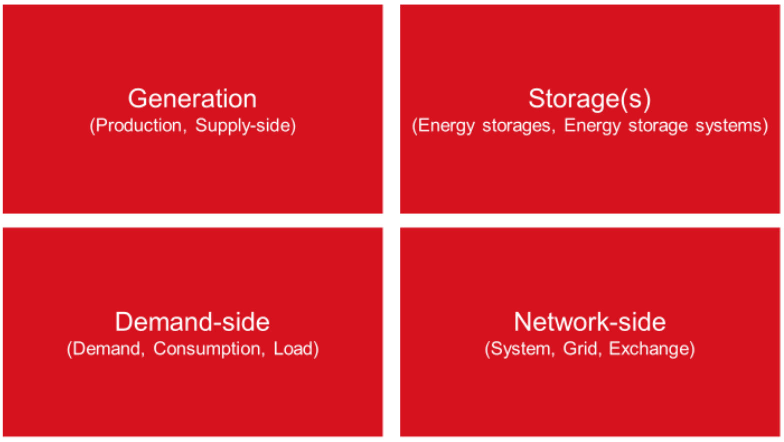


Figure 5: Power system's flexibility resource categories and their alternative names. Own illustration based on (Cruz;Fitiwi;Santos;& Catalão, 2018) and (Heggarty;Bourmaud;Girard;& Kariniotakis, 2020).

The word generation stands for the group of energy resources that feed electrical power to electricity networks. They can also be referred to as production or supply-side. The word demand-side refers to energy resources that consume electricity from the electricity networks. They can also be called demand, consumption, or load. It should be noted that demand-side, i.e., DSF can also refer to generation and energy storages at electricity demand sites (Hermans, et al., 2019), which is also considered in the scoping of the studied flexibility resources. The class storage includes the energy resources that can store electrical energy from the electricity grid and feed part of the stored electricity back to the grid. Alternatively, the class storage can be called storages in plural, energy storages, or energy storage systems. The term network-side comprises energy resources that are owned and operated by system operators. The network-side can also be called system, grid, or exchange. It should be noted that the terms are not synonyms but rather similar categories with different weighings of energy resources. Network-side flexibility resources include, e.g. reserve power plants, power transmission lines, flexible alternating current transmission system (FACTS) devices, such as Static Volt-Amps Reactive Compensators (Chopade;Bikdash;Kateeb;& Kelkar, 2011), and cross-border transmission capacity, such as HVDC-links.

Since the pool of possible flexibility resources is vast, the flexibility potential analyses in this thesis are limited to DSF resources. The reason for choosing the DSF resources is their less well-known properties compared to other flexibility resource categories that are more commonly exploited by TSOs.

Another approach in categorizing flexibility resources is to divide them into TSO and DSO level resources that can, respectively, be called centralized and distributed flexibility resources. Kolster, et al. defined distributed flexibility as the flexibility of sub-transmission network-connected energy resources (Kolster;Krebs;Niessen;& Duckheim, 2020), which can be simplified, in Finland, to mean energy resources that are connected to the distribution grids. Other attributes of distributed flexibility resources are defined in this thesis to be rated power of under 1 MW and their allocation in segments of society, i.e., power generation, electricity grids, the industrial sector, the commercial sector, and the residential sector. The division into centralized and distributed flexibility resource types is not unambiguous because the same flexibility resource types can locate in both types of electricity grids and have multiple scales of rated power. However, some flexibility resources are more common in one grid type than the other. A rough estimation based on the knowledge of the author of this thesis was used to form the division into centralized and distributed flexibility resource types in the Finnish power system that is presented in Figure 6.

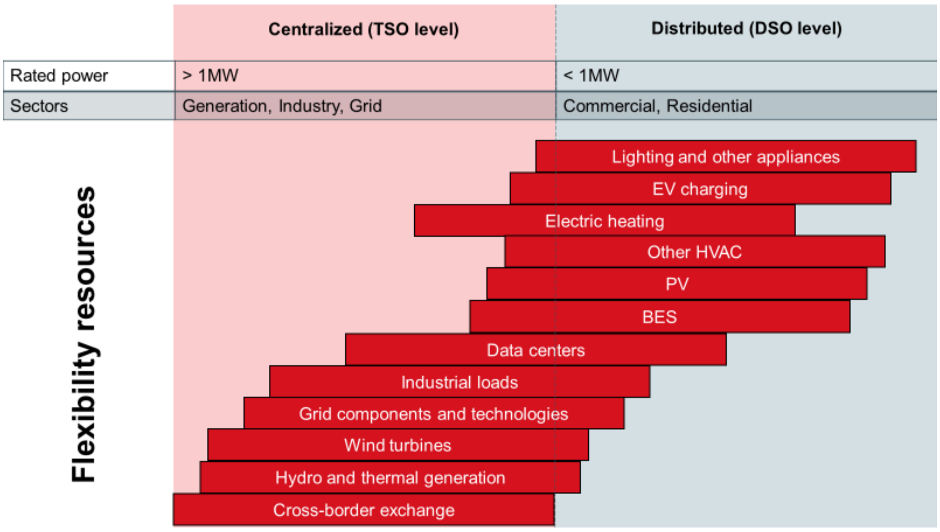


Figure 6: Flexibility resource types and their division into centralized (TSO level) and distributed (DSO level). The division is based on the author's perception of the current state of the Finnish power system and future trends.

The locations of the bars indicate how the proportion of resource types is distributed between the TSO and DSO levels. Own illustration.

Lighting and other appliances are mainly situated in residential and commercial premises that are connected to distribution grids. They are also partly included in industrial loads. Lighting and other appliances are challenging in terms of flexibility activations since their electricity consumption is closely connected to their end-use. The charging of EVs is mostly fed by distribution grids, but some heavy-duty vehicles and charging stations could also be connected to the transmission grid. Due to the battery energy storages (BESs) integrated into all EVs, they can reschedule their electricity consumption, i.e., charging, without strongly affecting their end-use, i.e., mobility. BESs can provide flexibility by storing electricity as electro-chemical energy. They are mostly connected to distribution grids, but transmission-scale batteries are also available. It should be noted that there are other electrical energy storages, such as pumped hydro and compressed air energy storages that are mostly connected to transmission grids due to their large scale.

Heating, ventilation, and air-conditioning (HVAC) devices form a flexibility resource group on their own, but electric heating is here described as its own flexibility resource type. Electric heating includes, e.g. radiators, electric water heaters, and various types of heat pumps. They have a wide range of rated power since they are used in scales ranging from singular rooms to municipality districts. Electric heating can also be used in industrial processes. In addition to the rated power of electric heating, the flexibility properties of electric heating depend on available thermal storages, losses, and the criticality of the end-use of the heat. Other electrical HVAC devices include, e.g. cooling devices, ventilation pumps, and mechanical air filtering systems. They are mostly fed from distribution grids, but some HVAC loads can also locate in industrial premises. It should be noted that electrical cooling could also be considered as electrical heating since it heats other spaces than the cooled space. HVAC devices are challenging in terms of flexibility execution due to their role in keeping primary processes and indoor comfort at tolerable levels.

PV panels and wind turbines are connected to both transmission and distribution grids. PV systems have lower rated power and are more commonly located on demand sites. Although, some PV farms are large enough for a transmission grid connection. Wind turbines have higher rated power and restrictions in regard to inhabitation proximity. Hence, they are centered on large wind farms in remote locations and connected mainly to the transmission grid. PV and wind generation can provide flexibility by curtailing their electricity production. Hydro and thermal generation are mostly large centralized power plants that are connected to the transmission system. However, some thermal generators, such as diesel and gas turbines, can be smaller and connected to distribution grids. Hydro generation is sourced from the potential energy of water bodies, and thermal generation is based on either burning fuels or fission reactions of atoms. They can provide flexibility by adjusting their primary energy input to the electricity generation and thus provide controlled upward and downward power adjustments. It should also be noted that hydro and thermal generators provide electro-kinetic inertia with their rotating masses.

Industrial electrical loads are usually large due to the sizes of factories and their processes that consume electricity. Thereby, they are mainly connected to transmission grids. Some industrial facilities do not consume as much electricity, so they are connected to distribution grids. Industrial loads include, e.g. machinery and feeding electricity to chemical processes. Industrial loads can provide flexibility by lowering or rescheduling their consumption, but their flexibility is challenging to exploit due to their critical primary processes that consume electricity. Data centers have critical primary processes fed by electricity, but they are also prepared for electricity black-outs with energy storages and on-site generation. Thus, they could possibly provide flexibility during normal operations. They could be connected to either type of the two grids due to the scalability of their processes and thereby their rated power.

Lastly, grid components and technologies are utilized in both types of grids. However, as discussed in Section 2.2.3, TSOs have more versatile responsibilities than DSOs. Thus, transmission grids have a broader portfolio of flexibility resources in terms of grid components and technologies. Transmission grids also have cross-border interconnectors that can provide flexibility in terms of electricity exchange from foreign transmission grids.

To narrow down the scope of research even further, distributed flexibility resources are chosen as a subcategory of DSF. In other words, the focus of the flexibility potential analyses is on DSF resources that are connected to the distribution network and take less than 1 MW of power from the grid. These resources are referred to as “distributed DSF resources”. The main flexibility resources contributing to distributed DSF resources’ flexibility potential were assumed to be EV charging and electric heating. Also, other HVAC devices, PV panels, BES, data centers, and small-scale industrial loads could provide distributed DSF.

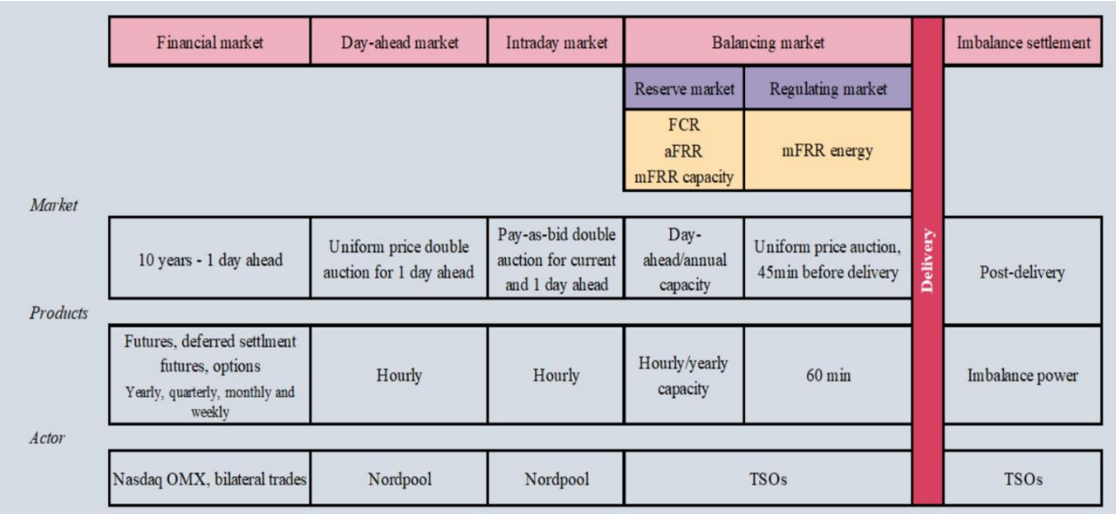
2.3 Mechanisms for the execution of flexibility

As there are several flexibility needs and a diverse portfolio of flexibility resources, a wide range of different mechanisms are needed to meet the flexibility demand with supply of flexibility. Understanding the available mechanism portfolio and its planned additions and alterations is important to develop processes that support the electrical power system’s functionality. The mechanisms presented in this section are divided into conventional, i.e., currently applied, and novel, i.e., not yet broadly applied mechanisms in

Finland. The scope of mechanism presentation is mainly set to the Finnish power system to avoid possibly lengthy analysis on differences of flexibility execution mechanisms between the Nordic, let alone European, countries. Further classification is formed into three categories: marked-based, pricing, and utilization of TSO resources. Section 2.3.1 describes the conventional mechanisms, and section 2.3.2 discusses the estimated future trends of stakeholders and provides a collection of expected mechanism development.

2.3.1 Conventional mechanisms

In their working paper, Spodniak et al., provided an overview on the Nordic market-based flexibility procurement methods, i.e., financial and physical electricity markets that is presented in Figure 7. Financial markets of electricity consist of long-term trading of finance products such as futures. The the existence of long-term bilateral contracts and trades was noted. They include, e.g. power purchase agreements that could be considered as part of financial markets, but they are not included in the overview. Day-ahead (DA) market is a wholesale marketplace that is coupled with transmission capacity between price areas which helps to constrain the cross-border power flows. The uniform double auction closes on the previous day before delivery of electricity between traders. Similarly, intraday (ID) market is a coupled wholesale marketplace, but it has pay-as-bid double auction trading that has previously been closed one hour before delivery. ID market changes are discussed in section 2.3.2. Balancing markets consist of reserve and regulating markets operated by TSOs that are discussed in more detail in the next paragraph. Imbalance settlement takes place after the delivery of electricity. Trading counterparties' imbalances from the agreed trades are sanctioned based on imbalance pricing. (Spodniak;Ollikka;& Honkapuro, 2019)



	Financial market	Day-ahead market	Intraday market	Balancing market		Delivery	Imbalance settlement
				Reserve market	Regulating market		
Market				FCR aFRR mFRR capacity	mFRR energy		
	10 years - 1 day ahead	Uniform price double auction for 1 day ahead	Pay-as-bid double auction for current and 1 day ahead	Day-ahead/annual capacity	Uniform price auction, 45min before delivery		Post-delivery
Products	Futures, deferred settlment futures, options Yearly, quarterly, monthly and weekly	Hourly	Hourly	Hourly/yearly capacity	60 min		Imbalance power
Actor	Nasdaq OMX, bilateral trades	Nordpool	Nordpool	TSOs			TSOs

Figure 7: Nordic electricity markets, products, and actors on a timeline. (Spodniak;Ollikka;& Honkapuro, 2019)

Fingrid Oyj provides a more detailed description of the balancing markets and their products (Fingrid Oyj, 2022) that is visualized in Figure 8. The reserve products are categorized by their activations' automation capabilities and sorted by the reaction time of their activation. Fast frequency reserve activates in one second and is automated. Fast frequency containment reserves for disturbances and normal operation activate in seconds up to minutes and are automated. Automatic frequency restoration reserve activates automatically in minutes. The only manual reserve product is manual frequency restoration reserve that activates in up to 15 minutes. Replacement reserves are not in use in the Nordic countries. Some of the products are further divided into capacity and energy products but are not elaborated more in this thesis. The manual frequency restoration reserve's energy product can also be called as the regulating power market. (Fingrid Oyj, 2022)

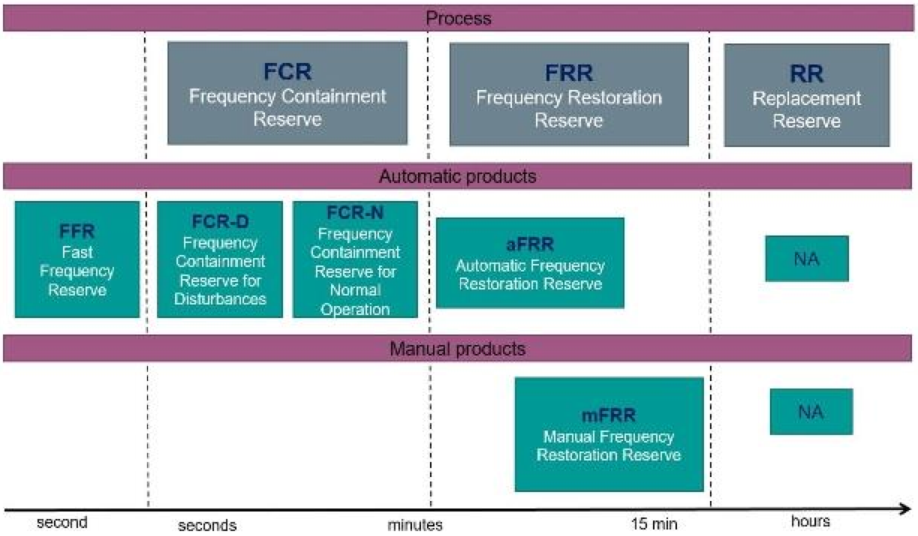


Figure 8: Balancing markets and products of Fingrid that are called reserve and regulating power markets. (Fingrid Oyj, 2022)

In addition to financial, wholesale, and balancing markets and imbalance settlement, retail electricity markets are a significant piece of market-based flexibility procurement scheme, since not all generators and consumers of electricity are able to participate in trading at the wholesale markets. Generally, retail players buy electricity from generators and sell it to consumers. It should be noted that there are several ways to conduct retail trade such as providing own generation resources or fully focus on the broking.

Pricing-based procurement methods include grid service fees, i.e., network tariffs, imbalance fees, and retail contract pricing. Fingrid requires various fees from different customers for the usage of grid services such as consumption fee and generation capacity fee (Fingrid Oyj, 2022). Also, DSOs have network tariffs that have energy and capacity components to mitigate congestion during peak loads (Huang;Wu;Shahidehpour;& liu, 2019). Imblance fees provide incentives for electricity market players to keep their traded balance and thus power balance in enhanced (Fingrid Oyj, 2022). In addition to fixed tariffs, retail contracts incentivize implicit flexibility by providing consumers with energy tariffs that are not fixed such as time-of-use tariffs and wholesale market-based pricing or spot-pricing in short (Annala, et al., 2018).

TSO resource utilization can be done by direct control or via electricity markets. Currently common flexibility procurement mechanisms are increasing transmission capacity, restricting power flows or network connections, and using FACTS devices. (Heggarty;Bourmaud;Girard;& Kariniotakis, 2020). It should be noted that TSOs also own reserve power plants that they can operate to keep the power system functional.

2.3.2 Novel mechanisms

As IRES and new distributed energy resources imminently penetrate the electricity markets, old flexibility procurement mechanisms need to be changed to adapt to the new challenges like lowered power generation adequacy and smaller flexibility resources' unit sizes. When it comes to stakeholders, future trends include more prosumers, i.e., electricity consumers that also have electricity generation, more independent aggregators, i.e., flexibility service providers that do not have imbalance responsibility, and energy communities (Directive (EU), 2019). Another key stakeholder development is increasing the TSO-DSO coordination to enhance operational security of both electricity transmission and distribution networks (Villar;Bessa;& Matos, 2018).

Market mechanism future trends include several reform projects and more uncertain evolution of alternative trading schemes. One of these alternative concepts is peer-to-peer trading that stands for prosumers trading their DER generated electricity between each other instead of monetizing their generation with feed-in-tariffs. Tushar, et al., provided a state-of-the-art analysis on the peer-to-peer trading concepts and their challenges by the time of their publication. (Tushar;Saha;Yuen;Smith;& Poor, 2020)

According to Madlener & Ruhnau, wholesale market trading is expected to shift partly toward the ID marketplace due to the uncertainty of IRES generation (Madlener & Ruhnau, 2021). As of writing the thesis, the Nordic ID marketplace Nord Pool Elbas has an ongoing extended pilot that enables the market closure time up until the delivery hour for intra-zonal trades (Fingrid Oyj, 2022). Another development trend of ID-markets is the inclusion of location data of the bids and offers, which enables congestion management with countertrades between zones of the power systems. Fingrid Oyj has an ongoing pilot for cross-border countertrades on the ID market that focuses on congestion management during cross-border interconnector faults

(Fingrid Oyj, 2021). In the Netherlands, the congestion management with ID countertrades is more specific, since the bids and offers are locationally indexed on the level of the distribution systems, which enables congestion management within the Dutch power system via ID countertrades between distribution system areas (GOPACS, 2021). In Finland, the internal congestion management is done with counter trades as special regulation from the reserve markets (Fingrid Oyj, 2022).

The Nordic TSOs have a joint electricity market reform project called Nordic Balancing Model (NBM). The project roadmap is presented in Figure 9. Currently, single price model for imbalance settlement and aFRR capacity markets of Finland and Norway are implemented. The upcoming major milestones include Nordic aFRR capacity and mFRR automated energy activation markets by the end of 2022, 15-minute imbalance settlement period (ISP) and market trading resolution in the second quarter of 2023, and European reserve market harmonization during 2023 and 2024 under project names MARI and PICASSO. (Nordic Balancing Model, 2022)

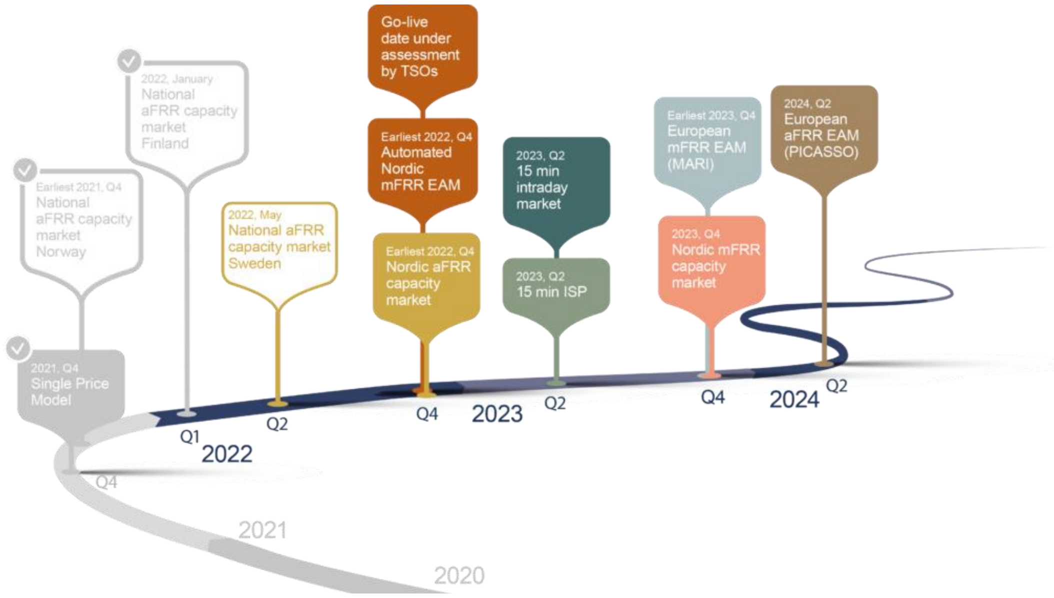


Figure 9: Nordic Balancing Model (NBM) project roadmap. Situation at the first quarter of 2022. (Nordic Balancing Model, 2022)

Market coupling of the electricity markets and transmission capacity is to be changed from coordinated net transmission capacity to flow-based market coupling. Currently, the go-live of the flow-based method is expected to happen earliest in March of 2023, since 12 months of parallel runs are needed in order to national regulation authorities to accept the implementation (Nordic Regional Security Coordinator, 2020), and the parallel runs started in March of 2022 (Nordic Regional Security Coordinator, 2021). Bø et al., provided calculations on the benefits of the flow-based method compared to the current practice, such as lower average electricity price and lower price difference between market areas (Bø;Kallset;Oleinikova;Farahmand;& Refsnæs, 2020).

The Finnish retail market data exchange platform Datahub was implemented in February of 2022. It centers the data exchange of retail electricity markets that was previously distributed between separate platforms of retailers and DSOs. (Fingrid Datahub Oy, 2022) Future development of the Finnish Datahub has already started and the updated version 2.0 is planned to be released in January of 2023. The new version includes 15-min metering, 15-min settlement, accounting point energy netting and energy communities. (Fingrid Datahub Oy, 2022)

The data exchange developments are strongly connected with the CEP implementation and NBM development. They provide a platform for even further development that could include centralized data exchange of explicit flexibility of retail level energy resources. Such flexibility hubs and flexibility market platforms are already in operation. They include among others, Piclo Flex in the United Kingdom (Open Utility Ltd., 2021), and StockholmFlex in Sweden (Ellevio, Svenska Kraftnät, Vattenfall Eldistribution, 2021). Currently, Horizon 2020 projects called INTERRFACE and OneNet pilot flexibility co-ordination platforms between TSOs and DSOs in several demonstration clusters around Europe (OneNet, 2022) (INTERRFACE, 2022).

In terms of pricing, the future trends focus on transition towards dynamic network and retail tariffs from previously mostly fixed rates. Annala, et al. cited the EU directive 2012/27 (Directive (EU), 2012) by the notion that dynamic pricing may be utilized in retail and network tariffs in form of time-of-use tariffs, critical peak pricing, real-time pricing, and peak time rebates. It was also noted that transmission and distribution tariffs should not hamper participation of DR in flexibility procurement. (Annala, et al., 2018) Huang, et al. introduced dynamic power grid tariffs in their study and compared their congestion management costs to previously more common dynamic tariffs (Huang;Wu;Shahidehpour;& liu, 2019). Another approach to pricing could be to change the pricing of imbalances. The current imbalance fee structure, i.e., single pricing scheme, introduced in late 2021, can be found on the Fingrid Oyj's website (Fingrid Oyj, 2022). For instance, Ntomaris, et al. provided an analysis on the optimal participation of RES aggregators in two imbalance pricing schemes called single pricing and dual pricing of Greek power market simulations (Ntomaris;Marneris;Biskas;& Bakirtzis, 2022).

When it comes to the future trends of TSO resource utilization, new transmission capacity and connections are built to avoid congestion in the power system. For instance, a cross-border transmission line investment will be made between the Finnish and the Swedish power systems (Fingrid Oyj, 2022) and several new powerlines are built inside the Finnish power system, e.g., (Fingrid Oyj, 2021). Since the power transmission lines take several years to be built, other mechanisms are needed to prevent congestion. A faster way to alleviate congestions is to increase transmission capacity with the utilization of FACTS-devices (Chopade;Bikdash;Kateeb;& Kelkar, 2011). Fingrid will build parallel compensators to four substations in Finland in the following years (Manninen;Harjula;& Janhunen, 2021). Another option is a flexible connection contract that is a promising way of utilizing grid connection restrictions with mutual agreement of both the connected energy resources and the TSO (Kuusela;Ala-Mutka;Nikkilä;Peltoketo;& Rauhala).

3 Flexibility potential evolution of distributed DSF resources

This section maps flexibility potential evolution via reference studies from other countries and estimates of the Finnish development in Section 3.1. Then, stakeholder and literature views are presented to address key factors affecting the growth of flexibility potential and its usability in Section 3.2. Lastly, the outcomes of flexibility potential evolution are discussed in Section 3.3. It is noteworthy to mention that the flexibility of distributed DSF resources is at focus.

3.1 Overview of flexibility potential evolution

This section presents some past, present, and future flexibility potential estimates. As discussed in Section 2.2.5 flexibility potential is an abstract concept that is challenging to define and quantify. Due to the varying definitions of flexibility potential, its quantification estimates can also be challenging to compare with each other. Thus, most reference studies will not be analyzed thoroughly.

3.1.1 Historical and present flexibility potential evaluations

The understanding of the evolution of energy resources' flexibility potential is critical since it provides context for the analysis of power systems' behavior. Historical evaluations of flexibility potential can be combined with the market outcomes and historical data to assess different flexibility resources impact on the power system dynamics, such as power balance. Then also the implications of flexibility potential can be assessed better and key energy resources and developments can be taken into closer observation. They also lay foundations for forming present and future estimates for energy resources even if they were prone to evolve with time. For instance, the observed trends of flexibility potential growth could be extrapolated for the future. On the other hand, the valuations of present flexibility potential provide a picture of the current availability of flexibility that can help to select actions that ensure the adequacy of flexibility, and anchor points from which possible future trajectories can be set to start from.

Nordic Energy research provided some estimates of the flexibility potential in the Nordics for the year 2018 based partly on the estimates presented in (Söder, et al., 2018). They expressed the flexibility potential as a percentage of peak load. The flexibility potential estimates were for the Finnish peak load of 15 105 MW as follows: Industry 9%, household heating 15.9%, and other flexibility 12.5%, which results in a total share of the peak as 29.1-31.1% (Nordic Energy Research, 2019). Söder, et al. presented flexibility potential more accurately by the attributes of power, energy, and duration for different electricity loads in 2016 (Söder, et al., 2018). Salpakari, et al. showed similar results of electric loads' ability to shift their consumption, which was the result of analysis considering the enabling of the utilization of VRES with control of district heating and DR (Salpakari;Mikkola;& Lund, 2016).

Present flexibility potential estimations were not found for power system areas, but site-specific and resource type-specific flexibility potential evaluations have been conducted. The absence of extensive power system areas' flexibility evalutions for the present could be caused by the long time that the acquisition of required data takes. Hence, the power system area evaluations are either outdated or based on past assumptions of the future evolution. Site and resource-specific analyses exceed in providing present flexibility potential evaluations, because their narrower scopes enable smaller sets of data that can be analyzed faster. Hence, the there are shorter delays between the analyses' preconditions and the publications of results compared to more extensive analyses. For instance, Khajeh, et al. provided flexibility potential and service applicability estimations for air-conditioners, electric water heaters, EVs, and battery energy storages (BESs) by utilizing mathematical models. They also provided a literature review on the existing methodology for behavior modelling of the three appliance types and then assessed the applicability of the appliances to participate in the current reserve markets of TSOs (Hosna Khajeh, 2022).

In addition to Finnish power system area and resource type evaluations of past and present flexibility potential, another approach is to analyze international reference cases, such as flexibility market platforms with public data of offered flexibility from DSF resources. Such sources include Piclo Flex (Open Utility Ltd., 2021) in the United Kingdom, GOPACS (GOPACS, 2021) in the Netherlands, Stockholm flex (Ellevio, Svenska Kraftnät, Vattenfall Eldistribution, 2021) in Sweden, and NODES (NODES, 2022) in Norway, Sweden, and United Kingdom. It should be noted that deriving the flexibility potential estimates from these sources requires several assumptions, let alone when converging the results to match the Finnish flexibility potential. These market data sources could also give an indication of the flexibility needs of DSOs procuring flexibility via the markets.

3.1.2 Estimates of future flexibility potential

The time span of interest for the searched flexibility potential estimates was from the year 2020 to 2035 so that they reflect the transition towards the carbon-neutrality target of Finland by 2035 (Ministry of the Environment, 2022). Low-carbon roadmaps of various sectors of society (Ministry of Economic Affairs and Employment, 2021) are the basis for the three found future estimate references that are presented in Table 2 and discussed in the following paragraphs. EV charging and electric heating were chosen to be presented since they were the only distributed DSF resource groups that were found in multiple future flexibility potential estimates.

Table 2: Collection of flexibility potential estimates of EV charging and electric heating. The estimates are not fully comparable due to varying definitions of flexibility potential and resource groups.

RESOURCE GROUP	YEAR	FLEXIBILITY POTENTIAL [GW]		
ELECTRIC VEHICLE CHARGING	2020	-	-	0.00***
	2025	-	0.2-0.4	0.17***
	2030	-	0.4-1.0	0.95***
	2035	0.6-3.2	0.7-2.4	1.8***
ELECTRIC HEATING	2020	-	-	0.03
	2025	-	1**	0.2
	2030	-	1.6**	0.9
	2035	0.5-3.0*	2.1**	2.3
REFERENCE		(Fingrid Oyj, 2021)	(Forsman, et al., 2021)	(Energiateollisuus ry, 2021)
COMMENTS		*includes other household loads	**households	Derived with current building stock *** derived with 6 kW average charger power

The network vision of Fingrid included four scenarios of the Finnish electrical power system for the year 2035, mainly to assess their future needs for transmission capacity. They presented estimates of demand-side response capacity in the formed scenarios, which could be interpreted as flexibility potential. The estimates were based on the differences in initial electricity consumption profile and final electricity consumption of energy resource groups in electricity market simulations. However, it was not stated precicely if the values were averages or maximums, so the values could be either technical or commercial flexibility potential. EV charging was classified into fixed charging, smart charging, and vehicle-to-grid that were varied between scenarios, which resulted in a wide range of flexibility potential, since vehicle-to-grid chargers could also supply electricity to the grid, in addition to consumption, doubling their flexibility potential. Electric heating and households were combined in the same resource group whose flexibility potential varied significantly between scenarios. Thus, the actual flexibility potential of electric heating could not be detected, but it gave at least an indication of its maximum to be lower than 3 GW (Fingrid Oyj, 2021).

Forsman, et al. provided an analysis of the impact of the carbon neutrality target on the power system. They assessed the future power system dynamics from different points of view, such as power adequacy, spatial distribution of generation units and loads, price of electricity, and flexibility capabilities of different energy resource groups. Three scenarios were formed and simulated on a level of DA electricity markets to resemble different development trajectories of electrification. The flexibility potential of EVs was expressed as the maximum available power of flexibility that could be interpreted as technical flexibility potential. Notably, the later the scenario year, the larger the differences in flexibility potential values between scenarios. The flexibility potential of electrical heating in households was referred to both as the potential of new heat pumps and the potential of total electric heating loads of households. The reasoning was that most of the new heat pumps are able to easily adjust their electricity consumption, which leads to significant flexibility potential. The flexibility potential estimates of electric heating were interpreted to represent all distributed electrical heating resources since industrial heating processes were presented in another section of the report. It should be noted that commercial buildings and electrical district heating were not discussed in the report, which could have changed the flexibility potential estimates. The electric heating flexibility potential values for each year were the same in all three scenarios (Forsman, et al., 2021).

Thirdly, Finnish Energy published a consultant study of DSOs' role in the energy transition. They assessed the impacts of the energy transition in the operation of distribution networks and provided estimates of the number of different types of energy resources and their flexibility qualities. With few assumptions, the full technical potential of the two resource groups could be derived. The share of EV chargers was expressed for different building types, and their share of smart chargers was also stated. The flexible share of electric heating was presented for different building-types, and the building type specific flexibility potential was also stated. (Energiateollisuus ry, 2021)

By multiplying the smart charger shares from Finnish Energy's estimates (Energiateollisuus ry, 2021) with the Finnish building stock quantities for 2020 (Statistics Finland, 2021) the count of smart chargers could be derived for each year. To give a power rating of EV charging's flexibility potential, the number of smart chargers was multiplied by 6 kW, which was assumed to be the average power of smart EV charging. It should be noted that the changes in building stock quantities and EV charging power would change the power rating of flexibility potential. The flexibility potential of buildings' electrical heating could be derived by multiplying the Finnish building stock of 2020 (Statistics Finland, 2021) by the flexible shares of building types, and their building type-specific flexibility potential was also stated (Energiateollisuus ry, 2021).

International future flexibility potential studies could be another way to assess the evolution of the Finnish flexibility potential. For instance, Elia evaluated the future availability of flexibility of Belgian energy resources and cross-border transmission in their technical report. They assessed the prerequisites for flexibility participation for different generation and load types in order to express their flexibility potential in a probabilistic distribution. The probabilistic values were used to assess their adequacy in fulfilling three types of flexibility needs (Elia, 2019). It should be noted that deriving conclusions about other countries' flexibility potential evolution requires multiple assumptions to be relevant for the Finnish power system but could still be helpful in forming the basis for creating scenarios of the flexibility potential evolution.

As seen in Table 2, the estimations of the future flexibility potential of DSF resources are sparse and expressed in different definitions. Thus, the development of the definition of flexibility potential layers should be emphasized to help form comparable estimates. Another imperative research topic is to find the factors affecting the flexibility potential development. By understanding the barriers and drivers of flexibility potential evolution, plausible future flexibility potential evolution trajectories could be formulated and argued more profoundly. Simulating these trajectories would help to detect critical power system impacts of the evolution and how the factors affect it. Such analyses could even help to concentrate measures for influencing these factors to enhance desired trajectories, such high availability of commercial flexibility potential from certain energy resources. The key factors for the evolution of flexibility potential are presented in the following section 3.2.

3.2 Key factors affecting flexibility potential evolution

This section describes factors contributing to the flexibility potential evolution of distributed DSF resources. The definition of factors is introduced in Section 3.2.1. The factors are explored for theoretical in Section 3.2.2, technical in Section 3.2.3, and commercial in Section 3.2.4 potential layers..

3.2.1 Introduction to factors and scope

Sneum, et al. provided an extensive analysis of the barriers to the flexibility of district heating systems, which could be used as a reference point for mapping the factors affecting the flexibility potential of distributed DSF. The barriers' characteristics were described in relation to technologies, point of origin, and project life cycle (Sneum, 2021). In the context of this thesis, factors consist of developments that have either increasing or decreasing effects on the flexibility potential of distributed DSF resources. It should be noted that several factors that increase flexibility potential can be enabled by removing or solving growth hampering factors or more commonly known as barriers. Factors are presented generally for all distributed DSF resources, and resource category-specific differences are noted. Some factors were also found to affect several potential levels.

The scope of studied flexibility resources was limited to public EV charging and electrical loads, storage devices, and microgeneration of buildings. More precisely, considered building types were residential and commercial buildings, thus excluding industrial buildings. The focus is on factors for mid-term development before the year 2030. Presented factors are based on literature and stakeholder interviews. The stakeholder interviews are described in Appendix A

3.2.2 Factors impacting theoretical flexibility potential

Distributed DSF resources have several common factors affecting their theoretical flexibility potential development. The factors are depicted for general impact, and resource type-specific factors are noted. Generally, electrification of heating, mobility, and industry is seen as a major contributor to theoretical flexibility potential growth since it results in new installations of electrical loads, energy storages, and micro-generation that could theoretically participate in flexibility events. The main drivers for electrification stem from personal preferences, techno-economic factors, and climate targets. Firstly, personal preferences refer to perceivably advantageous properties of electricity-based resources, such as reduced noise, and local or global pollution. Secondly, techno-economic factors enhance the functionality of the electricity-based resources or lower their costs compared to other alternatives. For instance, decreasing electricity prices incentivizes the replacement of fossil fuel-based heating with electrical heating solutions. Lastly, climate targets lead to regulations and incentives that support electrification on multiple levels of society, such as EU regulations and directives, national support schemes, municipality programs, and company campaigns.

Next, the main drivers for the increase of electricity-based energy resource’s count are introduced. The growth in the number of **EVs** and their charging equipment is inter-related, because the deficit of chargers reduces the end-user experience of EVs and a high surplus of chargers is not financially feasible. However, this chicken-and-egg problem can be overcome by adequate demands and supporting incentives, such as tax relief schemes and the technology learning of both types of devices. The technology learning also enhances the ratio of EVs’ charging power and battery capacity to the purchase price, making them a more tempting alternative to other types of vehicles. HVAC devices are another important group in terms of distributed DSF resources’ flexibility potential. One of its subcategories, i.e., **electric heating** devices, such as heat pumps, electric boilers, radiators, and heat storages, is expected to grow in number due to the replacement subsidies of fossil fuel burners, energy efficiency requirements of new buildings, and lower heating costs compared to other alternatives. The number of **other HVAC**

devices, such as ventilation pumps and air conditioners, is expected to stay approximately the same since they are already broadly installed in the Finnish dwelling stock. The count of **PV** electricity generation devices, mainly PV solar panels, is expected to increase due to consumers' preferences for self-sufficiency, energy cost savings, and available purchase subsidies. Technology learning is estimated to still drive the purchase prices down, even though some material deficiencies have had a raising effect on the prices. The number of **BESs** is expected to grow due to investment cost reductions by technology learning and the growing demand for self-sufficiency combined with PV solar panels. However, the payback times of BES investments are still seen as too long for domestic customers and thus mitigating the growth. On the other hand, DSOs have started to invest in BES to enhance their operational security and thus partly increase the flexibility potential of BES.

In addition to the changes in the number of electricity-based devices, changes in the rated power of devices affect the flexibility potential evolution. For instance, EV charger power and battery capacity are expected to increase, which grows their theoretical flexibility potential, while charging power limitations and charger availability deficit limits the potential. Energy efficiency measures can reduce the electricity consumption required to fulfill the primary energy demand of end-users. This results in lower electrical rated power of new electrical load installations such as electric heating and other HVAC devices and, thereby, reduces the overall theoretical flexibility potential in cases where less efficient electrical loads are replaced. Even though policies and energy efficiency improvements decrease the rated power of some resorces (Economidou, et al., 2020), energy efficiency directives also set requirements for buildings to be better equipped to participate in flexibility activities with their DSF resources (European Commission, 2022). As a phenomenon affecting the technical flexibility potential, it is further discussed in Section 3.2.3.

One could also argue that energy efficiency reduces system operators' flexibility needs as peak loads and overall decreases energy usage. Thus, possible energy efficiency improvements could be seen as long-term theoretical flexibility potential. When it comes to PV electricity generation, energy efficiency improvements can increase the solar panels' generation capacity per roof-top area and thus increase their theoretical flexibility potential.

Synthesis on the most impactful barriers/drivers: climate, electrification, energy efficiency measures, technology learning

3.2.3 Factors impacting technical flexibility potential

Annala, et al. identified the lack of automation as a major barrier to DR utilization (Annala, et al., 2018). As part of the used definition of technical flexibility potential, smart control devices are critical resources to be assessed. Smart control devices can be classified into three main categories as smart meters, smart management systems, and integrated smart attributes of energy resources. Firstly, smart meters can enable remote and automated control of DSF resources' grid exchange through adjustments in the metering board's connections. Secondly, smart management systems can adjust the grid exchange of DSF resources either by directly controlling their load or power output or by adjusting their connections in the electricity metering device. Smart management systems include, i.e., home energy management systems that control household loads and microgeneration, which results in more versatile possibilities in providing flexibility than with individual devices. Thirdly, singular devices can have a built-in ability to manage their electricity consumption or generation based on predefined algorithms, such as load shaving during electricity prices above a certain threshold.

The increased number and rated power of new energy resources, such as EV charging, and PV solar panels, introduce issues to the electrical systems like households with limited electricity transfer capacity. Smart control devices are practical solutions to operate electrical systems of energy resource sites, such as utilizing microgeneration. Thus, the increased amount of new energy resources also drives the deployment of smart control devices. However, three main barriers to investments in smart control devices can be defined.

Firstly, the insufficient profitability of the smart control device investments is a major issue hampering their roll-out to distributed DSF premises. As the barrier is strongly linked to the commercial flexibility potential, it is further discussed in Section 3.2.4.

Another barrier to smart control device investments is the prioritization of more urgent investments, such as plumbing and renovations. Some renovations, i.e., installing more energy-efficient windows, can partly be driven by energy efficiency incentives. However, the new smart readiness indicator for buildings, as an energy efficiency measure, can be seen as an incentive to invest in smart control devices (European Commission, 2022). It should be noted that the smart readiness indicator could possibly affect mainly constructed buildings. Thus, its effect would be low on the smart control device investment unless it is enforced on the existing building stock.

Thirdly, a barrier is caused by the miscellaneous technical specifications that hinder the co-ordination of different DSF resources and increases the investment costs of smart control devices. Similarly, Annala, et al. identified a barrier to DR automation and suggested that the standardization of data systems and appliance interfaces should be conducted (Annala, et al., 2018).

Synthesis on the most impactful barriers/drivers: the need for management of EVs and PV solar panels increases, prioritizing more urgent investment is a barrier, and dispersed technical standards hamper the smart solution deployment

3.2.4 Factors impacting commercial flexibility potential

There are several classifications that have been formed for DR participation's barriers and drivers, i.e., political, economic, social, technological, legal, and environmental (Mlecnik, et al., 2020) and market access, business models and services, end-user incentives/obligations, information/examples, attitudes, and technical issues (Annala, et al., 2018). Based on the definition used in this thesis, these can be interpreted as factors affecting commercial potential. For simplicity, the factors were narrowed down and classified into three categories: profitability of smart control devices, willingness to participate, and capability to participate. Enhancing the profitability of smart control devices makes them more appealing investments and thus drives their deployment. The increased deployment results in a better capability to participate in flexibility events and thus also increases willingness to participate in flexibility events.

The profitability of smart solutions consists of the related costs and financial benefits. They can be used to determine the payback period of smart solution investments, which are the common indicator of the profitability of investments. The barrier of long payback periods can be solved by either reducing costs or increasing financial benefits. Separate smart control devices and meters bring additional investment costs, whereas appliances with native smart control capabilities have higher purchase prices than so-called "dumb" appliances. Also, the smart control devices might cause additional operational and maintenance costs, but it could also be argued that they reduce the need for maintenance by preventing faults and straining behavior of appliances. It should be noted that, in addition to smart control devices' costs, participating in flexibility can also cause other cashflow reductions, such as increased electricity bills or lowered rate of manufacturing goods that should be taken into account in the profitability assessment of smart control devices.

Mlecnik, et al. identified the financial benefits and incentives as critical political and commercial barriers to the DR participation of buildings (Mlecnik, et al., 2020). Annala, et al. had the same discovery for distributed DSF resources (Annala, et al., 2018). Financial benefits can refer to reductions of costs, such as electricity bills, or remunerations, such as compensations for activated flexibility. To raise the financial benefits, the price of electricity should be more volatile or expensive, or the remunerations of flexibility activations higher. Since investment decisions rely on assumptions about future financial benefits, a clear barrier for the smart control device deployment is the uncertainty of financial benefits in the future. Thus, estimates on future flexibility needs and financial benefit factors should be informed by TSOs and other actors that need flexibility. Other barriers to financial benefits are the large number and unclear roles of the beneficiaries involved in value chains of flexibility, which can lead to lower shares of financial benefits.

Although, the beneficiaries of the value chain can ease the capability of end-users to participate in flexibility events. The value chains should be further researched, and market designs developed accordingly to clarify the interrelations and value distribution among value chain members.

A key enabler of the commercial flexibility of distributed DSF resources is the capability to participate in flexibility. As mentioned, smart control devices aid the flexibility participation by means of automation and remote control. On the other side of the participation prerequisites, there exist the flexibility procurement methods, such as retail and reserve markets. They have specific market designs and set requirements for the execution of flexibility. As identified by Annala, et al., insufficient market models and lack of ready-to-use practices and services were seen as key barriers to DR participation (Annala, et al., 2018). Thus, the flexibility markets should be developed to suit the capabilities of distributed DSF resources better and include clear participation requirements. For instance, public EV charging equipment is capable of fast short-term flexibility, but not for large constant volumes due to the primary usage of charging EVs quickly. Their flexibility could be harnessed more with the aid of eased aggregation rules on reserve markets or specific flexibility products. However, the development should be predictable so that flexibility value chains can be formed efficiently, and smart control device configurations can be adjusted in the installment phase instead of costly additional update maintenances. There can also be smart control devices with inactivated functionalities that can improve the capability to answer to market requirements, such as EV chargers that utilize a lower metering resolution than their maximum capability.

The capability of participation increases the willingness to participate in flexibility activities. However, there are several other factors affecting the willingness, such as security concerns, primary processes, financial benefits, and environmental benefits. Mlecnik, et al. proposed that lack of user control and privacy issues are major legal barriers to buildings' DR participation since the flexibility events can require data with properties that could be linked to, e.g., individual households. The barriers could be solved by guaranteeing user override and data security (Mlecnik, et al., 2020). The primary processes of DSF resources set limitations to the willingness of flexibility participation. For instance, Kubli, et al. stated that consumer behavior is strongly affected by routines and inertia to change behavior. They referred to high financial compensations or discomfort costs and minimal effects on daily routines as factors removing barriers from DR participation. Another promising incentive for flexibility participation was found to be environmental benefits mediated via electricity products with high shares of IRES. (Kubli;Loock;& Wüstenhagen, 2018) Similarly, based on a survey conducted by Ruokamo, et al., the willingness of households to participate in DR is increased by perceived emission reductions (Ruokamo, Kopsakangas-Savolainen, Meriläinen, & Sventoa, 2019). Thus, it is important to quantify the emission reductions of flexibility activity in easily understandable ways. It could also be argued that other benefits, such as deferring network investments with load peak shaving could incentivize the willingness of DSF resources' users to participate in flexibility by perceiving the potentially lowered network tariffs in the future.

Synthesis on the most impactful barriers/factors: Market design, value chains, financial benefits, capability to participate, willingness to participate, promoting other benefits

A recap of the factors affecting flexibility potential and their interrelations are presented in Figure 10. The DSF resources types are only presented for the theoretical flexibility potential layer, and the rest of the barriers and factors are presented generally.

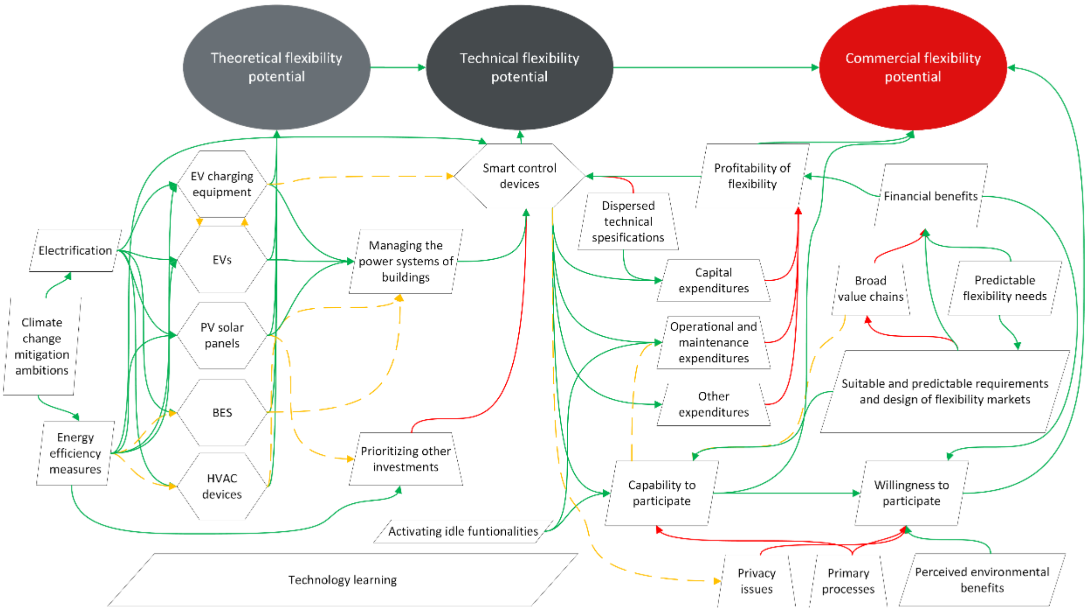


Figure 10: A collection of key factors affecting three layers of flexibility potential of distributed DSF resources. The green arrows indicate increasing effects, the red arrows indicate decreasing effects, and the yellow dashed arrows indicate mixed effects. Drivers of flexibility potential growth are marked with parallelograms, and barriers are marked with trapezoids. Technologies that increase the flexibility potential are marked with hexagons.

3.3 Outcomes of flexibility potential evolution

As the count of distributed DSF resources and their flexibility potential is expected to grow, as mentioned in Section 3.1.2, the behavior of the power system is prone to change. The behavior change of the power system stems partly from the changing spatial distribution of energy resources that leads to changing individual and interrelated dynamics. The changes include the replacement of old energy resources, such as electric boilers with new technologies, such as heat pumps that have different operational logics. Another change is the installment of large quantities of new loads, such as EV chargers that introduce new types of load profiles and could also lead to different behavior of other energy resources at same sites. Different challenges to the operational security of electricity grids are caused by the evolution of different flexibility potential layers.

Firstly, the growth of theoretical flexibility potential of distributed DSF resources, without increasing technical and commercial potential, could result in behavior of energy resources that decreases the grid stability in the regard of imbalance, congestion and voltage managements. For instance, purely end-use determined EV charging loads could create large electricity demand peaks that could be challenging in terms of unpredictable power balance and grid congestion. Another issue is the distributed PV generation that can cause local and regional over-supply and thus over voltages that are harmful to other energy resources connected to the electricity grids. Increasing the technical and commercial potential of these energy resources could help to alleviate the issues by enhancing control mechanisms for their behavior.

Secondly, the increase in commercial flexibility potential of distributed DSF resources could lead to a larger number of flexibility participations that induce other flexibility needs than the flexibility needs that were targeted. For instance, Haakana, et al. estimated the theoretically possible increase in heating loads caused by their DA market price optimization, which was found to increase the burden on distribution transformers (Haakana, et al., 2021). Similarly, explicit flexibility procured by a TSO could cause congestion in distribution grids. These issues can be overcome with better allocations of different flexibility execution mechanisms and TSO-DSO co-ordination schemes and platforms that are researched and piloted by, e.g. OneNet (OneNet, 2022) and INTERRFACE (INTERRFACE, 2022) projects.

Thirdly, the increased technical and commercial flexibility potential of distributed DSF resources could increase the complexity of their behavioral drivers. Technical flexibility potential, achieved with smart control devices, could cause more versatile grid exchange behavior of demand sites than previously, such as maximizing the utilization of on-site generation or adjusting indoor conditions of households. Also, commercial flexibility potential would introduce financially incentivized flexibility participation on top of the primary processes that have previously had the biggest role in their grid exchange profile. The increased complexity could lead to larger errors in forecasts of energy resource behavior, such as electricity demand forecasts. Errors could reduce the preparedness for acquiring a suitable amount of flexibility that is used to balance the energy resources' power system impacts, such as imbalances or congestion.

To better understand the challenges of increasing count of distributed DSF resources and their behavioral complexity, electricity market simulations could be used. They enable forming adjustable scenarios whose assumptions and input parameters can be altered to make sensitivity analyses of power system behavior. By conducting a sensitivity analysis of, e.g. distributed DSF resources' flexibility parameters, the resulting power system behaviors can be compared. The comparison helps to define how remarkable roles different energy resources or other factors have in terms of power system behavior and even flexibility needs. The found sensitivities can be considered to more efficiently allocate the efforts in parametrization improvements and to define behavior forecasts of different energy resource.

4 Quantification method definitions

This section describes the benefits of flexibility's quantification in Section 4.1, introduces input data in Section 4.2 and quantification tool options in Section 4.3, presents the method selection criteria and process designed for the purposes of this thesis in Section 4.4.1, introduces different flexibility need metric options in Section 4.4.2, and provides a detailed description of the selected flexibility need metric in Section 4.5.

4.1 Benefits of quantification

A key benefit of quantifying future flexibility needs is the encouragement of investments that enable energy resources to provide flexibility, as endorsed by the stakeholder interviews that are further discussed in Section 3.2 and Appendix A. However, proposing future flexibility need estimations is challenging due to the uncertain pace of the electrical power system evolution during the ongoing energy transition. Though, it should be noted that future scenarios can help to prepare different actors of the electrical power system for possible trajectories of development and enhance the continuity of business models that are developed for the utilization of flexibility.

The quantification of flexibility needs enables a more concrete basis for analyses of power system behavior with the help of numerical values than qualitative analysis methods that are restricted to more verbal descriptions. Concrete numbers also help with comparisons of different scenarios and how their presumptions affect certain dynamics of the electrical power system, such as power shifts between market periods. More specifically, as noted in Section 3.3, different flexibility resources, such as distributed DSF resources, can be modelled with versatile parametrizations to reveal their impacts on the power system behavior. Quantification is a key enabler in interpreting the differences caused by divergent parametrizations.

When different flexibility needs have concrete valuations that can be compared between each other and the availability of flexibility resources, the adequacy of flexibility could also be assessed. Hence, the utilization of flexibility resources to meet the needs can be prioritized. This prioritization can be conducted based on the criticality of the flexibility needs in question and the set of available flexibility resources. However, this type of extensive analysis of different flexibility needs, the adequacy of flexibility resources, and the needs' prioritization still require much development of methodology. The possible compositions of a quantification method are presented in Figure 11.

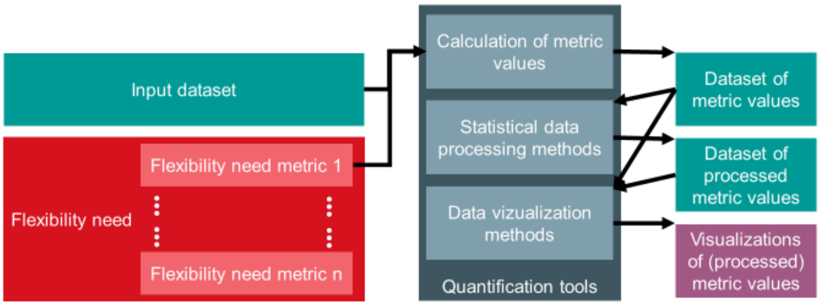


Figure 11: The possible compositions of a flexibility need's quantification methods. A quantification method consists of a combination of a metric representing a flexibility need and quantification tools that are used to process input data into datasets and visualizations of the metric.

The numerical values that represent the magnitude of flexibility needs are henceforth called flexibility need metrics, or metrics in short. It should be noted that definitive metrics, which would fully expose the properties of flexibility needs, are challenging to form, but metrics can provide an indication on the scale of flexibility needs compared to, e.g., energy resource's capabilities or between different flexibility needs. To reach the metric values, quantification tools are needed. One quantification tool type is the calculation of a metric from an input dataset. Plain series of metrics' values for long periods, such as hourly timeseries of a calendar year can be laborsome to interpret. Thus, other quantification tools, i.e. statistical data processing and visualization methods, are needed to aggregate information and highlight noteworthy datapoints and trends of the metric data. It should be noted that statistical data processing methods are not necessary between metric calculations and visualizations, but they can enhance the interpretation of a quantified flexibility need if used appropriately.

4.2 Input data

Data is a critical aspect of quantification of any phenomenon, because no quantification can be done without a quantitative source of information. To quantify the future flexibility needs with metrics, some form of input data is required. There are several options for input data sources for flexibility need metrics' quantification that are not individually suitable for all metrics. Thus, four categories of input data options are presented in the following paragraphs. They include reference case data, historical data, electricity market simulation data, and grid simulation data.

Firstly, **reference case data** of foreign electrical power systems could be used if they were seen as representative of the functionalities of the assessed circumstances in the future, such as high IRES penetration. This could be a tempting approach, but it has its challenges due to the versatile differences between, e.g., electrical power systems' climate conditions, and electrical load, generation, and grid component portfolio and the trajectories of their evolution that could lead to false conclusions about the behavior in the assessed system.

Secondly, **historical data** of the assessed electrical power system could be used to quantify the flexibility needs of the future. As a benefit, results would reflect real behavior but could, on the contrary, provide outdated volumes and cyclities of energy resources' grid exchange behavior, especially if the assessment and historical periods are several years apart or prominent power system or climate condition alterations are present. For instance, the broad deployment of EVs could significantly alter the electricity consumption patterns of buildings and historical wind generation data could give false annual production volumes for years with divergent wind conditions. Other issues with the historical data utilization are the availability and sensitivity of the input data. Similarly, historical data can be utilized in scaled or otherwise manipulated form, which can mitigate the volume and timing issues. However, the behavior of, e.g., demand can change with new types of electric loads and changing consumer habits. It should also be noted that the penetration of new energy resources is seldom linear but rather exponential, which poses another challenge in approximating future trajectories of power systems' energy resource portfolio.

Electricity market models are used to simulate power system behavior. They enable a holistic approach to electrical power system analysis in multiple time horizons from days to decades. They can be conducted with reasonable effort, as previous simulation parameters can be modified to create new scenarios and sensitivity analyses. However, **electricity market simulation data** is highly dependent on its presumptions that are, thereby, important to scrutinize while interpreting the outcomes of the simulations. Major disadvantages of the electricity market simulation data are the uncertainty of the evolution of energy resources' deployment and the complexity of their behavioral drivers. There is a dilemma in the parametrization of the simulations. Detailed model parameters lead to more sophisticated outcomes in the simulation, but they also require more effort and computational power. Thus, the models are often simplified to some extent to reach adequate results with reasonable efforts.

Some flexibility need metrics, such as regional congestion, require determining **grid simulation data**. Historical grid data is mainly used for assessing power system conditions during extraordinary events, such as faults. Thus, it is not considered as an option for future analyses. As electrical power systems are under constant reinforcements and new generation units and loads are installed, grid simulations provide input data for quantification methods of future circumstances. However, as noted by Summanen in their master's thesis (Summanen, 2021), grid simulations of future power systems would also require electricity market simulations and challenging data conversions from the market simulation data into the grid simulation tools. It should also be noted that grid simulation data is suitable for only part of the quantification methods of flexibility needs, such as congestion management and voltage & reactive power management.

4.2.1 Electricity market simulations

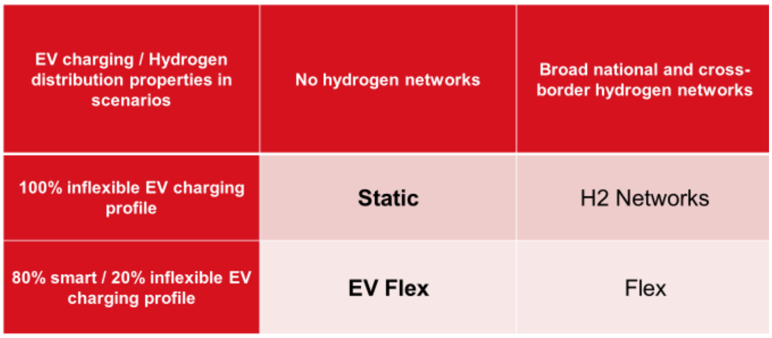
Wang et al. presented that electricity market simulations can be conducted by solving optimization problems targeted at multiple objective options, such as optimal power flow or minimal generation cost. They also noted that the models could utilize a versatile set of optimization algorithms. Notably, two simulation strategies, namely agent-based and system dynamics approaches, were introduced and applied in the study. In addition, a combined hybrid model of the two simulations was introduced (Wang;Wu;& Yanbo Che, 2019).

The input data used in this thesis was created by executing electricity market simulations with AFRY's BID3 (Better Investment Decisions 3) power market modelling software which is an agent-based electricity market simulation tool (AFRY, 2022). Närhi provided a comprehensive introduction to the electricity market simulation with BID3 in their master's thesis (Närhi, 2020) about heating electrification's power market impacts. They stated that the BID3 simulations were based on minimizing the cost of electricity generation for each market period hour, which is also the case in this thesis. They also referred to backtests that tested the validity of the BID3 model, and they discussed the model's limitations and uncertainties.

As electricity market modelling is not at the core of this thesis' analysis, it was not introduced extensively. However, some descriptions of assumptions and applied scenarios are necessary to give context to the quantification results. It should be noted that the objective of this thesis was to develop methods for analyzing the output data of electricity market simulations. Thus, the assumptions made for the simulations should only be considered as a context for the acquired quantification results rather than forecasts of the future evolution of power system portfolio and behavior.

4.2.2 Scenarios and key assumptions

The scenarios used in this thesis are modified from a Fingrid's scenario at the time. The scenario was formed in late 2021, so it is not representative of the current estimates made by Fingrid anymore. The scenarios were modelled for the year 2035 due to its position as a target year of carbon neutrality in Finland, entailing high IRES penetration. The weather year 2009 was used in the simulations due to its average weather conditions in relation to other weather years. Two scenario simulations out of four were used as input data for this thesis. They are presented in Figure 12.



EV charging / Hydrogen distribution properties in scenarios	No hydrogen networks	Broad national and cross-border hydrogen networks
100% inflexible EV charging profile	**Static**	H2 Networks
80% smart / 20% inflexible EV charging profile	**EV Flex**	Flex

Figure 12: Differences in input parameters of EV charging and hydrogen networks between four electricity market simulation scenarios called *Static*, *EV Flex*, *H2 Networks*, and *Flex*. The scenarios whose data were used, i.e. *Static* and *EV Flex* are bolded in the figure. Own illustration.

This master's thesis and another master's thesis (Hyvölä, 2022) joined efforts to assess both DSO (Simola) and TSO (Hyvölä) level DSF resources that were introduced in Section 2.2.6. The way of modifying the best estimate scenario was to make rough assumptions of DSF resources' flexibility parameters that would differ substantially between scenarios. This approach enabled a crude way for sensitivity analyses of different DSF resources' impact on the power system dynamics. Two DSF resource groups were selected for the re-parametrization. They were EV charging and electrolyzers.

In this thesis, EV charging was re-parametrized by applying an hourly varying but fixed daily charging profile for inflexible chargers. The charging profile was derived from three different empirical charging profiles of EVs in the United Kingdom (Pareschi;Küng;Georges;& Boulouchos, 2020) by giving them weighing factors. The used profiles and weighings are further described in Appendix B. The difference between the two scenarios, *Static* and *EV Flex*, was the proportion of inflexible and smart EV charging in the EV fleet. The scenario *Static* had 100% inflexible chargers, whereas the scenario *EV Flex* had 20% inflexible chargers and 80% of smart chargers. Smart chargers minimized their electric energy costs by re-scheduling their charging.

The contribution of Hyvölä was in the re-parametrization of electrolyzers, which were considered as TSO level DSF resources. It resulted in an inflexible and flat demand profile of electrolysis in all four scenarios. The assessed scenarios *Static* and *EV Flex* did not have any hydrogen networks. Two other scenarios, i.e., *H2 Networks* and *Flex*, included broad domestic and cross-border hydrogen distribution networks. It should be noted that Hyvölä shifted their focus more towards the re-parametrization of electrical district heating. Also, modelling in Hyvölä's thesis was executed on different datasets and simulation scenarios than in this thesis (Hyvölä, 2022).

4.3 Quantification tools

To present the flexibility need metrics in a concise and understandable way, several quantification tools can be used. As described in Figure 11, three types of quantification tools, i.e., calculation of metric values, statistical data processing methods, and data visualization methods are considered. Examples of the tools are presented in Table 3.

Table 3: Examples of three quantification tool types, i.e., calculation of metric values, statistical data processing methods, and data visualization methods.

Metric calculation	Statistical data processing	Data visualization
Programming language scripts (Python…)	Statistical numbers (mean, variance, standard deviation, minimum, maximum, median, fractions, and percentiles)	Statistical numbers (tables, including into other figures)
Spreadsheet software (Microsoft Excel…)	Correlations and comparisons	Correlations and comparisons (matrixes, heatmaps, line fitting, line comparison)
	Sorting	Distribution plots (scattered points, boxplots, violin curves, histograms, lines, and duration curves)
	Clusteration	Clusteration (scattered points)
	Segmentation	
	Signal analysis (Fourier analysis)	Signal analysis (line plots)
	Snapshots	Snapshots (line plots)

When it comes to the calculation of flexibility need metrics, two major types of calculation strategies were discovered. On the one hand, programming languages, such as Python can be used to write scripts that calculate metrics from input data sources. Their advantages are the scripts' ability to process large quantities of data, the modularity in terms of utilization of the same scripts with minor modifications to calculate different metrics, and the possibilities to automate tasks. However, the scripts require much effort to write. On the other hand, spreadsheet software, such as Microsoft Excel enable easy access to simple calculations. Their disadvantages are the requirement for more manual tasks, especially, when processing large datasets.

Statistical numbers, such as mean, variance, standard deviation, minimum, maximum, median, fractions, and percentiles, can provide aggregated information on temporal and spatial sets of metric values. However, they can be rather generic on their own. Correlations provide an indication of relationships between different datasets. Correlations can be visualized with correlation matrixes, heatmaps, and approximations, such as line fitting of dataset's relations and plotting temporally matching datasets on the same figure. To assess the range and variation of a metric's values, several types of distribution curves can be used. The distribution of a metric's values can be indicated with scattered points, boxplots, violin curves, histograms, lines, and duration curves. The figures can include markings of statistical numbers such as median, fractions, and standard deviation that ease the understanding of distributions shape.

In addition to the distribution of time series values, it is also valuable to assess the temporal locations and behavior of the values. For instance, high values of the time series can be clustered together or located evenly. Another worthy analysis approach is to segment the time series into separate periods that can then be compared with each other or temporally matching segments of other time series. Finally, the frequency of values can be assessed with signal analysis methods, such as Fourier transformations that approximate datasets as combinations of trigonometric functions. These types of analysis methods can expose behavior patterns that can be visualized with line plots on multiple timescales depending on the time series dataset's scale.

Since flexibility needs can vary quite a lot temporally, extreme values are great metrics to map the scale of flexibility needs. Percentiles and fractions of datasets provide smaller sets to be analyzed. For instance, the hourly time series of an entire year has 8760 data points and can be challenging to visualize, whereas, e.g., the 99th percentile of the same dataset has only 88 hours. When combined with multiple time series values of the same temporal locations, visualizations can help to detect anomalies from general trends. However, percentile and fraction datasets can lose some context of holistic system dynamics. This can be corrected by further examining the vicinity of the temporal locations of the data points. These sorts of snapshots can, thereby, visualize behavior of the dataset in the proximity of the remarkable data points.

Electricity market simulation data is labeled with many useful attributes that can be exploited in terms of comparing datasets. First, energy resource groups have time series values of their grid exchange that can be compared within the time dimension. Some other attributes that can be the basis of the comparison are simulation scenarios, resource groups, and weather years. Metric values can even be compared with other metrics. Lastly, it is important to give context to the simulation scenarios' electricity system portfolio, i.e., the annual grid exchange or capacity of generation, demand, grid, and storage. The context is imperative for interpreting the quantification results of flexibility need metrics. Also, the electricity system portfolios provide opportunities for the comparison of scenarios' results.

4.4 Evaluation of quantification methods

In this section, the selection process of quantification methods is presented for the purposes of this thesis in Section 4.4.1, and flexibility need metrics are presented and their prequisites for quantification are discussed in Section 4.4.2.

4.4.1 Quantification method selection process

To select the flexibility metrics and tools for quantification, an evaluation process is determined. The process is presented in Figure 13. First, a pool of flexibility needs is assessed and narrowed down based on three criterion groups demand, applicability, and novelty. Out of the selected needs, representative metrics are then picked. Similarly, a pool of quantification tools is narrowed down based on the criteria of demand and applicability. Out of the selected quantification tools and metrics, preliminary combinations are formed for further testing. When the methods are developed further, the focus of the quantification can be assessed and changed to emphasize certain metrics or tools. As a result of the assessment, methods can include various tool and metric combinations. For instance, a method can consist of a single tool for multiple metrics, multiple tools for a single metric, or a single tool for one metric.

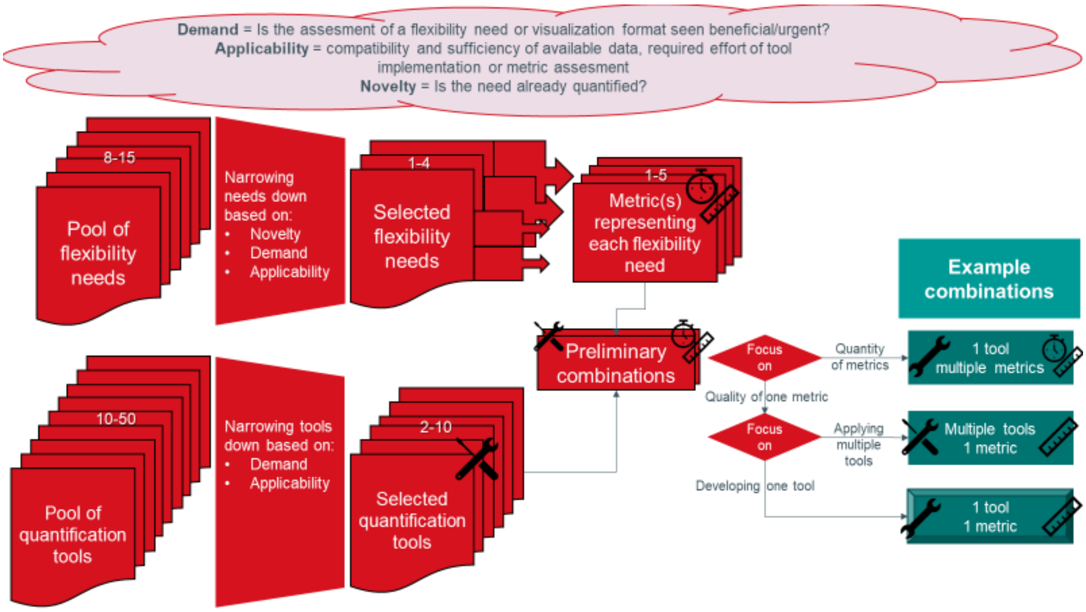


Figure 13: The used selection process for flexibility need metrics and applied tools. The pool sizes are indicative. Own illustration.

To evaluate the needs, metrics, tools and methods, the following questions were considered:

Assessment of the demand for the metric's quantification

- Is the flexibility need that the metric represents seen relevant?
- How urgent is it to quantify the metric?
    - asap, in the following years, on the mid-term horizon, or on the long-term horizon?

Preliminary assessment of analysis method applicability

- How comprehensively does the metric represent the flexibility need?
- Required effort to form the method
    - Are there existing method concepts?
    - Are the required analysis tools available?
        - If not, how easy are they to implement?
    - Is the available market simulation data sufficient for the analysis?
- Data sensitivity
    - Can the results be published with actual values?
    - How much effort does the masking of results require?
    - How much does the masking deteriorate the results' interpretations?

Novelty of the method

- Is it already known in the TSO organization?
- Are there upcoming efforts to develop the method?
- Is it already in use in the TSO organization?
    - Is it a finished tool or in need of further development?

To express the rating of the methods, symbols and their meaning are defined as follows:

- The more demand there is for the flexibility needs quantification, the better
- The less effort the method requires to be formed, the better
- The less sensitive information the source data and the results contain, the better
- The more novel the method is, the better
- The methods are rated based on criteria and marked with "+" for positive and "-" for negative ratings

The process of quantification method selection could also be derived for different power system actors, such as other TSOs. It would, however, require readjustments of the selection criteria to fit the actors' unique needs. It could even be modified to assess general flexibility need quantification opportunities and challenges of the research field, but the criteria should be then generalized for an extensive analysis. Another approach would be to narrow the scope down to single flexibility needs to enable a more in depth analysis and method development.

4.4.2 Assessment of flexibility need metrics

Each of the flexibility needs of TSOs presented in 2.2.4 have several possible metrics that represent them. The following chapters describe the evaluation of the metrics based on the three criteria presented in Section 4.4.1. A summary of the evaluation of flexibility need level, and the most promising methods are presented in Table 4. A precondition of the assessment was that DA electricity market simulations would be the input data source to be used for the quantification. Since the number of possible metric and tool combinations was vast, the metrics are mainly discussed. A more extensive list of the flexibility need metrics is presented in appendix C. The selected metric and applied tools that combine into the applied methods are evaluated in more detail in Section 4.5.

Table 4: Rating of flexibility needs' quantification prerequisites for market model data analysis based on authors qualitative assessment. Novelty, demand, and applicability ratings give a general indication, on a scale from --- to +++, on the most worthwhile needs to develop quantification methods for in the context of this thesis. Proposed method for further examination is presented for each flexibility need.

Flexibility need	Demand	Applicability	Novelty	Proposed method
Power ramp management	++	++	++	1h ramp rate correlations and duration
Frequency stability management	-	-	---	Post N-1 fault inertia distribution
System reliability	+	-	-	N-1 fault power
Energy trade of electricity	+++	+	+	Wholesale market price volatility
Imbalance management	+	--	-	DA forecast errors of IRES generation
Resource adequacy	++	-	---	Loss of load expected
Flow ramp management	--	--	--	1-hour ramps of interconnectors without limitations
Congestion management	+++	+	-	Transmission needs and correlations
Voltage & reactive power management	++	--	-	
Black start capability	--	---	--	
Short-circuit power adequacy	+	--	--	Minimum SC power threshold

Frequency management flexibility needs include power ramp management, frequency stability management, and system reliability. Frequency management metrics that require high temporal resolution to be determined, such as generation variations inside market periods, could not be defined based on the hourly resolution of DA market simulations. However, some metrics, such as average power differences between market periods were expected to be simple to calculate.

Power ramp management flexibility need metrics, or power ramp-rates, can be classified by the duration of the average power shifts between market periods. Power ramp period lengths are commonly based on the length and multiples of market periods. For instance, 15 minutes, one- hour, three hours, or eight hours could be used as a period length. Then, power ramp metrics can be referred to as, e.g. 15-minute (15min), one-hour (1h), or three-hour(3h) power ramps. Commonly, in the context of system operators' flexibility needs, power ramp-rates are calculated for the residual or net load of the assessed power system area (ENTSO-E, 2021). Power ramp management flexibility needs could also be defined with other methods whose focus is more on metrics that describe the availability of energy resources to provide controlled ramping (Villar;Bessa;& Matos, 2018).

Power ramp metrics were seen to have high demand for quantification due to the high deployment pace of wind turbines in Finland. The applicability of the market simulation data was assessed to be good for the calculation of power ramps, even though some information, such as activated DSF would be challenging to extract. Power ramp quantification from market simulation data was found to be quite novel for Fingrid, even though power ramp-rates have been quantified for historical data of different generator types.

Frequency stability management flexibility needs can be represented by metrics that indicate the adequacy of inertia. EirGrid presented several operational metrics that can be used to indicate insufficient inertia. The metrics included system non-synchronous penetration, inertia floor, rate of change of frequency, and the minimum number of units. Set limits for the metrics enforced the stability of the Irish power system (EirGrid, 2021). The Nordic TSOs developed methodology for the estimation of power system inertia (Ørum, ym., 2018), and provided forecasting tools for its future evolution and mapping of resources to mitigate low system inertia conditions (Ørum, ym., 2018). The metrics that the mitigations would be targeted to were the system inertia, magnitude of a dimensioning incident, and utilization of energy resources' active power. An ENTSO-E study noted that the Nordic TSOs update long-term inertia forecast periodically and that '*Preliminary results of ongoing studies indicate that future inertia may decrease more rapidly than previously estimated*' (ENTSO-E , 2021).

The quantification of frequency stability management's metrics was not seen urgent since the system inertia levels have already been estimated to not lower to the extent that available flexibility resources would not suffice during the first half of the 2020's. There are several metrics that can be calculated from market simulation data with assumptions of generator types' inertia. The methodology is very established, periodically applied, and does not need much development.

System reliability flexibility needs stem from deviations from expected energy resources' grid exchange and power flows. For instance, Elia presented forced outages as metrics that have probabilities and durations that were derived from historical forced outage records and Monte Carlo simulations. The forced outage probabilities and durations were used to calculate slow and fast flexibility needs. They also defined forecast errors of load and IRES generation to be metrics that represent flexibility needs. Most notably ramping flexibility needs were the closest to frequency management time-horizon of minutes (Elia, 2019). The slow and fast flexibility needs could possibly be applied to the need for the procurement of different reserve products.

System reliability metrics would be beneficial to quantify due to the expected changes in energy resource portfolio. The applicability of the methodology would be challenging to apply to the available DA market simulation data, but additional information, such as probabilistic forced outages would help to quantify the metrics. The methodology is similar to the reserve procurement analyses that are part of the operation of Fingrid, but scoping to system reliability should be applied to better expose the frequency related needs out of the large pool of use cases that reserves are used for.

Energy balance management flexibility needs feature electricity trading and imbalance management. Compared to frequency management they entail reaching a power balance on a longer time-horizon. Since the available electricity market simulation data is represented by the DA wholesale market that is based the minimization of electricity generation costs, the electricity trading is ideally balanced. Thus, the need for trading, and management of imbalances can not be determined straight from the simulation data. However, some modelling changes, alternative metrics, or additional assumptions could be used to derive more concrete evaluations of the needs.

The flexibility need for **electricity trading** could be quantified with the volumes of traded electricity on different timescales. However, this approach would require additional simulations of different marketplaces, such as ID markets. Another approach could be to analyze the wholesale price of electricity, whose variations could indicate the need for graduated offers and bids instead of fixed quantities of electricity production and generation.

Quantifying the need for electricity trading was seen beficial, because it is imperative to understand how well the power balance can be achieved with electricity market trading outcomes in the future. Direct metrics of the trading volumes are challenging to derive, but some alternative metrics as price volatility could be calculated from the available data. The methods are not frequently used for future estimates, but historical evaluations have been made.

Due to the ideal and simplified nature of the simulations' power systems, **imbalance management** flexibility need could also be challenging to quantify. Possible metrics for the imbalance management could be the forecast errors of loads and IRES generation, and relations of electricity trades to the realized and transferred volumes. Elia separated presented these metrics as slow and fast flexibility. Slow flexibility was determined by the DA forecast errors, i.e., the difference between DA trades and ID trades. Fast flexibility was based on the ID forecast errors, i.e., the difference between ID trades and real-time power balances (Elia, 2019). However, these metrics would require additional historical data, or more intricate electricity marketplace simulations to be calculated, respectively.

There was demand for the quantification of imbalance management flexibility need. However, the metrics were close to the system reliability metrics and challenging to grasp. Their application to the available market simulation data would require additional historical data of, e.g. forecast errors. Imbalances are already managed via reserve and regulation markets and they are settled with fees. However, the quantification of the need for management is still a novel concept.

Resource adequacy, i.e., security of supply, has been quantified with several metrics, such as loss of load expectation, residual load, and expected energy not served (ENTSO-E, 2021). The mid-term adequacy forecast of the European power system addresses continental and national levels of resource adequacy (ENTSO-E, 2020). The Nordic TSOs have also assessed their power adequacy on national and Nordic levels with a metric called power margin that indicates the need for imports or DSF to achieve the power balance (Energinet, Fingrid, Statnett, Svenska kraftnät, 2021).

The security of supply is a frequently discussed and assessed flexibility need metric whose meaning is emphasized by the high penetration of IRES generation. The application to the available data is challenging due to the need for additional Monte Carlo simulations. However, the methodology is well established and practiced frequently by many TSOs in the EU.

Electricity transfer management consists of flow ramp management and congestion management. Their flexibility need metrics are challenging to quantify from electricity market simulation data since some of the flexibility answering to the needs are already integrated into the constraints of the market models and the network topology is excluded from the electricity market simulations.

Flow ramp management of HVDC interconnectors is executed via ramping limitations of their power flows. Their meaning could be quantified with sensitivity analyses that alter their resrictions. The magnitude of resulting power ramps could expose the usefulness of the restrictions. One could also argue that flow ramp management is just a subclass of power ramp management since it is targeted to mitigate power imbalances caused by interconnector flows with high ramping capabilities.

There was no indication of demand for flow ramp management's quantification, because flow ramp management is already covered by constraints of cross-border HVDC inter-connectors. They could be assessed relatively easily as a sensitivity analysis, but additional simulations would be needed and their meaning would be required to be defined better. The phenomena is familiar to power system operation, but its quantification was not found to be common.

Congestion management was also integrated into the market models via constraints of physical power flows of interconnectors that simulates the dynamics of coupled electricity markets. Congestion management flexibility need can be quantified for national cross-sections and regional nodes that supply distribution grids, but it also requires grid simulations to address the regionality of the congestions (Summanen, 2021). The calculation of transmission capacity is based on thermal and stability constraints that are determined for different transmission grid flow conditions. However, electricity market simulation data with higher spatial resolution can be used to assess the transmission needs between sub-areas of a power system, which can give some indication of the magnitude of possible congestion management needs with assumed transmission capacities.

There was a high demand for the quantification of congestion management due to the expected major changes in the location of generation units with the penetration of wind generation to the Northern parts of Finland, while electrical loads increase in the Southern parts. The electricity market simulation data is not sufficient for analysis of the congestion management metrics, but higher spatial resolution could be used to better simulate the transmission needs. The congestion management metrics and their quantification methods are actively developed.

Non-frequency ancillary services stand for flexibility needs, such as voltage and reactive power management, black start capability, and short circuit power adequacy. The needs are local or regional in nature, which makes them challenging to quantify with the available electricity market simulation data.

Voltage and reactive power management flexibility needs have spatial variation within a power system due to their regionality. Thus, they cannot be quantified directly from the available electricity market simulation data that has low spatial resolution, i.e., only three power system areas in Finland. Chopade et al. presented FACTS devices as flexibility resources to answer to reactive power management and voltage control needs (Chopade;Bikdash;Kateeb;& Kelkar, 2011). Voltage stability can be quantified, e.g., with a metric called line voltage stability index (Ratra;Tiwari;& Niazi, 2018).

Black start capability could be quantified by analyzing the generation portfolio of the electricity market simulation data. However, it would require additional assumptions. The assessment of black start capability has actively been conducted through other means than electricity market simulations and its additional quantification was not seen as urgent as other flexibility needs.

Short circuit power adequacy is another flexibility need that would require more intricate power system topology data than the available electricity market simulations provide. An analysis of short-circuit levels were described by (Australian Energy Market Operator, 2020).

4.5 Selected method: 1h power ramps

The variability of IRES generation, especially wind generation, poses several challenges to the operation of the power systems that have high penetration rates of IRES. Ramping of wind generators' power output is one of the key issues since wind power output is not necessarily constant within electricity market periods. Hence, real-time power of wind generation can alter from the average power output even if the generated energy was equal to the traded quantities. This can also result in power ramps that do not match the market period shifts, whereas, e.g. thermal generation units ramp their generation in a controlled manner. Methods for forecasting wind ramps have been developed to foresee them based on weather phenomena and to more efficiently allocate flexibility resources to balance them (Dalton;Bekker;& Koivisto, 2021) (Cui;Krishnan;Hodge;& Zhang, 2019). Wind generation is not the only resource group that has power ramps outside of the market period shifts. Many loads follow end-use patterns rather than the average power of traded energy within a market period. The substraction of a power system area's IRES generation from loads is called residual load or net load. For instance, there has been efforts to forecast the 3-hour ramps of net loads (Yurdakul;Meyer;Sivrikaya;& Albayrak, 2020).

Forecasts of single resource groups' power ramps on their own are not necessarily enough to determine ramping flexibility needs in different situations. Electricity market simulations can help to assess the ramping behavior of resource groups and their interrelation in multiple conditions of a power system. Although, depending on the simulation resolution, they can lack the information of power ramps within market periods and reveal only the power shifts between market periods. Thus, it is beneficial to calculate power ramps of market period shifts in as high a resolution as possible. The flexibility need for power ramp management could be divided into providing the bulk power shift between market periods and balancing the disproportionate timing of energy resources' ramps. The former was chosen due to the limited simulation resotulion and since the larger the difference between market periods' average power the more possibilities for unsynchronous timing of real-time power ramps.

The proposed method for the power ramp management's metric was to calculate 1h power ramp rates of energy resource groups based on hour time series data from the electricity market simulations and present their distribution, extreme situations, and correlations. The hour time series consisted of the values of the average grid exchange of an energy resource group for each hour of the simulation year. The 1h power ramp was calculated by subtracting values of two consecutive hours. The fact that average grid exchange values of hours were used, means that momentary power ramps could differ from the approximation, and the actual ramping flexibility needs would be relatively higher or lower at times.

As for the applicability of the method, power ramp management metrics are presented in several quantification concepts that have informative visualizations (ENTSO-E, 2021). However, the available input data was challenging to converge to the residual load ramp-rate analysis without losing the

DSF indication of the gross load of the power system. Thus, the approach was shifted to resource categories and resource groups. Another disadvantage was the lack of pre-existing analysis algorithms that required much effort to formulate. Data sensitivity of the method was quite low since resource groups aggregate large sets of market players and detailed transmission capacities were not necessary to state to support the analysis of results.

The proposed method was novel to Fingrid, but similar analyses on historical power ramps have been conducted. Also, power ramp restrictions are defined and continuously evaluated for, e.g., the operation of generators (Fingrid Oyj, 2022) and interconnectors (Fingrid Oyj, 2020) in the electricity markets. The limitations are designed to mitigate the resources' ramping impact on the power balance. The 1h power ramp-rates of energy resource groups were seen as somewhat representative metrics for power ramp management challenges of market period shifts, and their urgency was highlighted by the fast installation pace of wind turbines in Finland.

There was also an underlying issue with some power ramp management metrics. They were based on the assumption that flexibility is needed from generators to follow load or residual load, which would lead to the conclusion that flexible generation is necessary. For instance, Lannoye et al. presented the metric *insufficient ramping resource expectation* that describes the power system's lack in matching the power system's generation to the shifts of net load (Lannoye;Flynn;& O'Malley, 2012). However, the metric is not applicable to the available electricity market simulation datasets that, inherently, always have a power balance and adequate ramping resources between market periods due to the simulation logic. Villar et al. referred to definitions of flexibility metrics as ramping adequacy metrics (Villar;Bessa;& Matos, 2018).

The resource group for which the power ramps would be calculated was another worthy discussion. From the TSO flexibility needs' point of view, resource groups with the highest ramp-rates could be considered the most interesting ones since they either cause the largest deviations to the power balance or contribute to restoring the power balance of the whole system. One candidate for the core power ramp contributor is likely IRES generation. Another option is to assess the gross load of the power system, but it is challenging to define which demand resources are flexible and which are not. Thus, a top-down approach to ramp-rate analysis could potentially reveal the main contributors to power ramps on the power system level. After that, the most important contributors could be analyzed and compared to other resources to find correlations in ramping behavior. With these approaches, both the need for power ramp management and the causing and balancing energy resources of power ramps could be deducted to some extent.

5 Quantification methods

This section introduces the 1h power ramp-rate calculations and presents their quantification methods for the resource group categories and resource groups.

5.1 Power ramp calculations

The power ramps are calculated based on the hourly time series of a simulation year. The hourly values are resource groups' average power of grid exchange. An example of the input time series data is presented in Figure 14, which is the total generation of electricity of a simulation year. The benefit of displaying such large datasets is that the general trend and timing of the energy resource's ramping behavior can be seen, but it is tough to draw specific conclusions about detailed power ramp values and timing due to the large dataset compressed into a single figure.

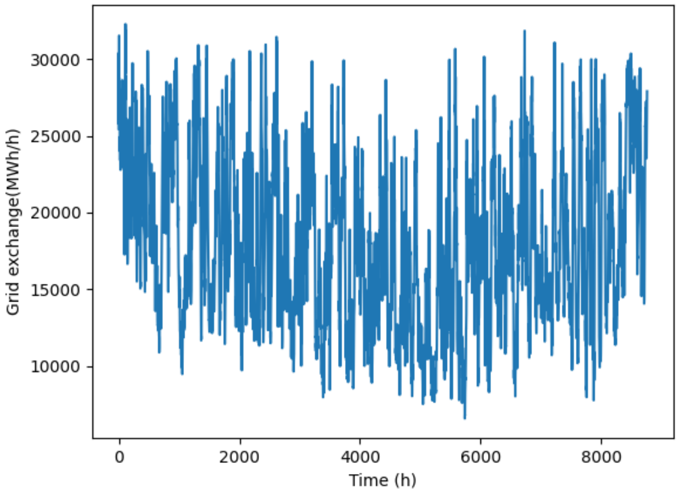


Figure 14: Plotted time series of hourly electricity generation.

To expose the ramping behavior of a resource, 1h power ramp-rates are calculated using (1)

$$R_h = P_h - P_{h-1}, \qquad h \in [2{,}8760], h \in \boldsymbol{N}. \qquad (1)$$

where, h refers to the hour of the simulation year and is limited to natural numbers from 2 to 8760; P_h stands for the resource group's average power of grid exchange at hour h, and P_{h-1} refers to the grid exchange at the hour prior to h; R_h stands for the 1h power ramp at hour h, which means the shift in average power of grid exchange.

The value of grid exchange can be determined differently for different energy resource categories and groups to make power ramp values more intuitive to interpret. If not stated otherwise, the following definitions are applied: For the total generation, generation resource groups, import, and storage, grid exchange is positive when they are supplying energy to the national electricity grid. Storages have negative grid exchange when they withdraw more energy from the grid than they are supplying to the grid. Total system demand, export, and demand resource groups have positive grid exchange when extracting energy from the national power grid. It should be noted that the grid exchange definition is not meant to be based on any common standard but rather the intuition of the author of this thesis.

An example of the resulting ramp-rate values of the total electricity generation is presented in Figure 15. The figure shows the hourly 1h power ramps of total electricity generation. Peak values of power ramps can now be detected, but the detailed distribution of the power ramps is still challenging.

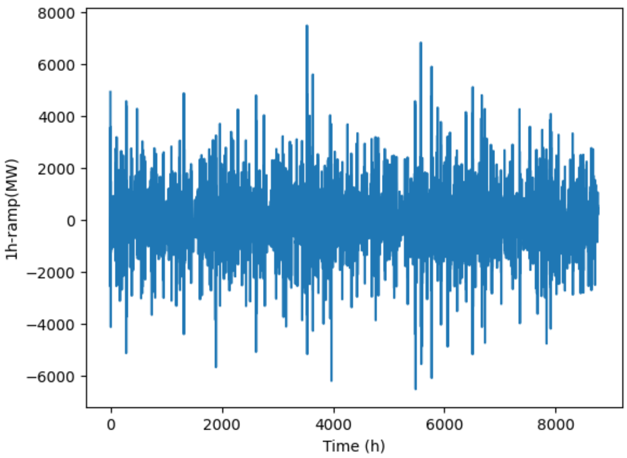


Figure 15: 1h power ramp time series of electricity generation.

To further analyze the distribution of power ramps, duration curves can be used to visualize the distribution of power ramp values. An example is presented in Figure 16. Duration curves are beneficial due to their familarity in the realms of energy business and research, and since they encapsulate extreme ends of the distribution and the general distribution trend. However, their disadvantage is the loss of chronologicality of metric values.

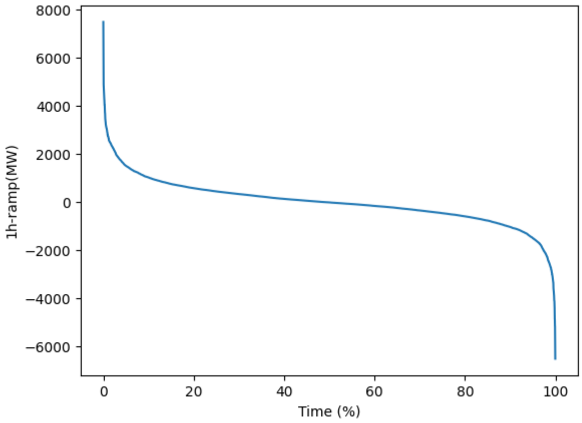


Figure 16: Duration of generation's 1h power ramps.

Another option for 1h power ramp-rate distribution visualization is to plot violin curves that show the shape of distribution but lacks the exact probabilistic values of ramp-rates. An example is shown in Figure 17. Violin curves can ease the interpretation of the values in the middle of the distribution, especially when the values in the middle of the value range are more common. Another advantage of violin curves is to pack the distribution information in a more compressed manner so that the curves do not need to be placed on top of each other. Their disadvantage is likewise the loss of chronologicality of metric values and the more challenging interpretation of extreme fractions and percentiles.

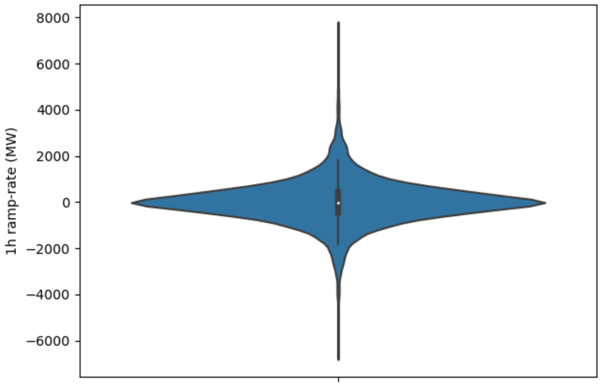


Figure 17: Distribution of electricity generation's 1h power ramps as a violin curve.

5.2 Method 1: Power system's 1h power ramp analysis

A holistic approach is considered to determine the biggest ramp contributors on the power system level. The resulting method was developed to address the bigger picture of power ramps in the electricity market simulations and to assess which energy resource groups would be the most remarkable in the regard of power ramps in the simulation scenarios and thereby require further analyses. Thus, the method would enable easier comparisons of different scenarios and their power ramp dynamics on a power system-level. However, the method would not expose the flexibility needs of power ramp management but rather general ramping behavior of different energy resource categories and groups, which could be a basis for the quantification of the actual needs and resource groups' supply of ramping flexibility. The process followed in the method is presented in Figure 18 where each step is indexed with a number.

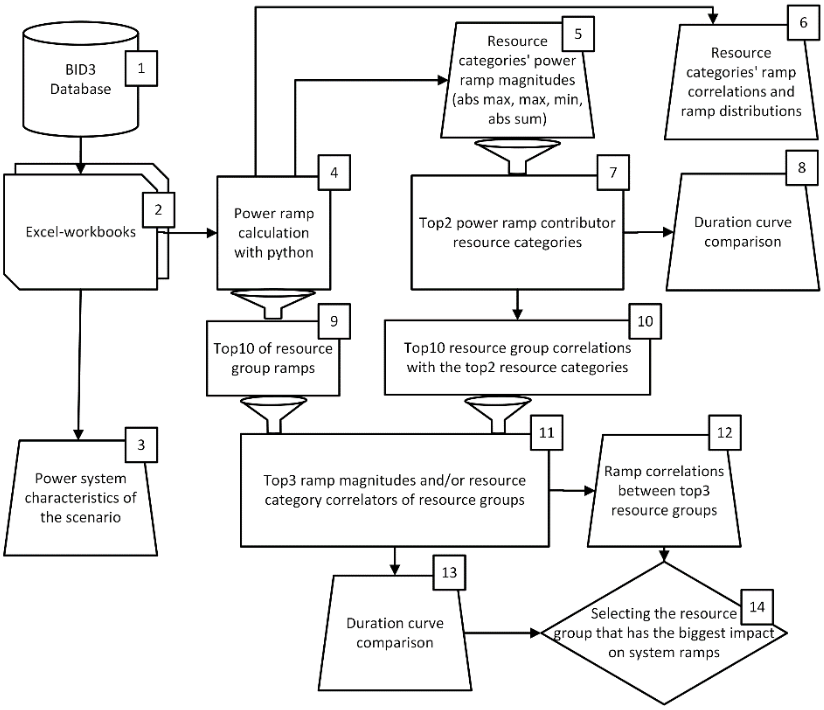


Figure 18: Method process with numbered steps to find the most impactful resource groups contributing to power ramps. Resource categories refer to the power system's total demand, generation, net exchange, and storage. Resource groups stand for aggregated total grid exchange of energy resource types, such as smart EV charging or wind power generation. Own illustration.

First (step 1), electricity market simulations produce data that is stored in the database of BID3 power market modelling suite. The data is then exported as Microsoft Excel-workbooks that represent different resource categories, and stored into file locations (step 2). Then, the Excel-workbooks can be used to form visualizations of power system characteristics, such as installed generation capacity, which helps to indicate differences between scenarios (step 3). The Excel-workbook data is fed into a python script that calculates 1h power ramp values by subtracting grid exchanges of a resource group between consecutive market periods (step 4).

After the power ramp values are calculated, they can be used to plot several illustrations regarding resource categories' power ramps. The resource categories are the power system's total demand, generation, net exchange, and storage. Their ramps' magnitudes, i.e., absolute maximum, maximum, minimum, and absolute sum values are illustrated with heatmaps to address their extreme values and total volume (step 5). Their correlations are presented with correlation heatmaps to expose interrelations (step 6). Their distribution is depicted by violin curvers (step 6), which enhances their comparison. The top two biggest ramp contributor categories are selected based on the biggest absolute values of their ramp-rates (step 7). Their behavior is then presented with duration curves that show a resource categorie's ramp duration and corresponding ramps of another resource category during the same hours of the ramp time series (step 8).

Likewise to the resource categories, the power ramp magnitudes of resource groups are calculated, and ten of the resource groups with the biggest absolute ramps are presented with heatmaps (step 9). For the top two resource categories with largest power ramps, the ten most correlating resource groups' correlations are plotted in a correlation heatmap (step 10). The correlations are calculated for the whole year, 95th percentile, and 5% fraction of the system-level group ramps. Next, the top three resource groups with the greatest ramp magnitudes and system-level correlations are chosen (step 11). The selection is primarily based on the ramp magnitudes, but the chosen resource groups must also be present in the most correlating resource groups of resource category ramps. The top 3 ramp contributors are compared with their power ramps' correlation heat maps (step 12) and duration curve plots (step 13). Finally, the previous steps help to determine the biggest system power ramp contributing resource group (step 14).

5.3 Method 2: 1h power ramps of a resource group

The method was developed with a resource group-specific approach. The idea was to assess the ramping flexibility needs by analyzing the most impactful resource group's power ramps and comparing them to other resource groups. One advantage of the method would be the more focused analysis of a singular resource group that was lacking in the first introduced method. The greater focus would enable more detailed observations of a resource group's interrelations. Another advantage of the method would be that it would help to decide if the resource group was a cause of ramping flexibility needs or a provider of balancing power ramps that were to supply the needs. The process of the method is presented with numbered steps in Figure 19.

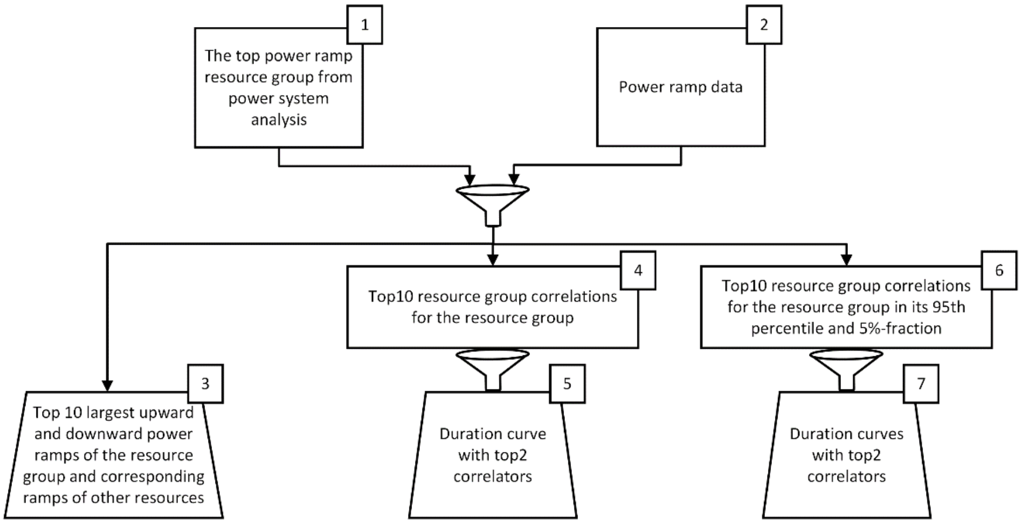


Figure 19: Method process with numbered steps to analyze the most power ramp-wise impactful resource group and its interralations with other resource groups. Own illustration.

First, the most power ramp-wise impactful resource group, henceforth the resource group, has been determined with the method 1 process described in Figure 18 (step 1). The power ramp data is acquired from the same system-level process (step 2). Next, the resource group's top 10 largest upward and downward power ramps are presented with bar plots including other resource groups' ramps (step 3). The barplots help to assess the ramping behavior of all resource groups during the most extreme power ramps of the resource group in focus.

Next, the resource is compared with other resource groups, and the ten most correlating resource groups are displayed with a correlation heatmap (step 4). The correlation heat map helps to identify general interrelations between the resource group and other resource groups. The top two most correlating groups are plotted with the focus resource's duration curve (step 5). The duration curve can consolidate the general interralations indicated by the correlation heatmap.

Similarly, the correlations are calculated and displayed for the 95th percentile and 5% fraction of the resource's ramps with correlation heatmaps (step 6). The correlation heatmaps of percentiles and fractions help to expose trends in extreme ramping conditions. The top two most correlating resource groups' power ramps are plotted alongside the 95th percentile and 5% fraction of the resource group's power ramp duration curve (step 7). The duration curves aid to further examine resource groups interrelated behavior.

It should be noted that the proposed order of the three paths starting from steps 3, 4, and 6 is suggested since the barplots are presumably easier to grasp than the correlation heatmaps and duration curves.

6 Results

In this section, the characteristics of chosen electricity market simulation scenarios are presented in Section 6.1, and the key results are presented for the quantification methods for 1h power ramps for a power system perspective and resource group centered analysis in Section 6.2 and in Section 6.3, respectively.

6.1 Simulation scenario characteristics

Two scenarios were chosen as example input data for the 1h power ramp analyses. These scenarios were *Static* and *EV flex*, whose presumptions were described in Section 4.2.2. The two scenarios were chosen because more scenarios would have been too laborsome to analyze and the only divergent presumption between the scenarios was the charging locig of EVs. The EV charging was a beneficial link to the flexibility potential considerations of distributed DSF resources. It should be noted that the scenarios do not forecast future evolution of the Finnish power system but rather give examples of different trajectories and they could be analyzed with the help of quantification methods. To give context to the analysis of quantification results, the Finnish annual demand and installed generation capacity in the scenarios, i.e., *Static* and *EV Flex*, are presented for resource groups in Figure 20 and Figure 21, respectively.

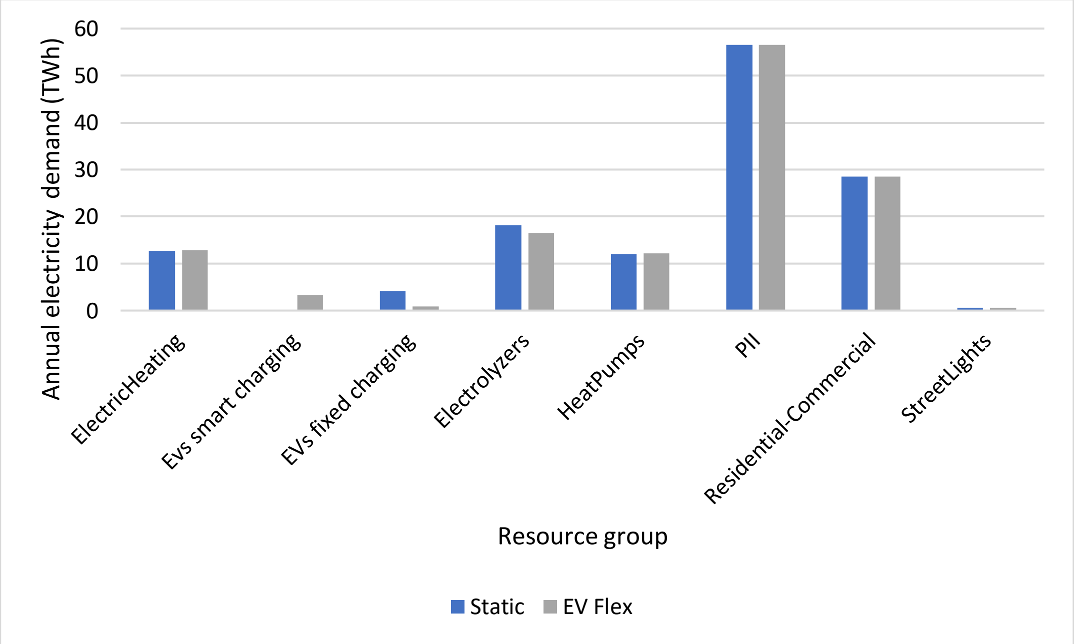


Figure 20: The Finnish annual electricity demand of demand resource groups in the simulation scenarios. The figure contributes to the step 3 of the method 1 process depicted in Figure 18.

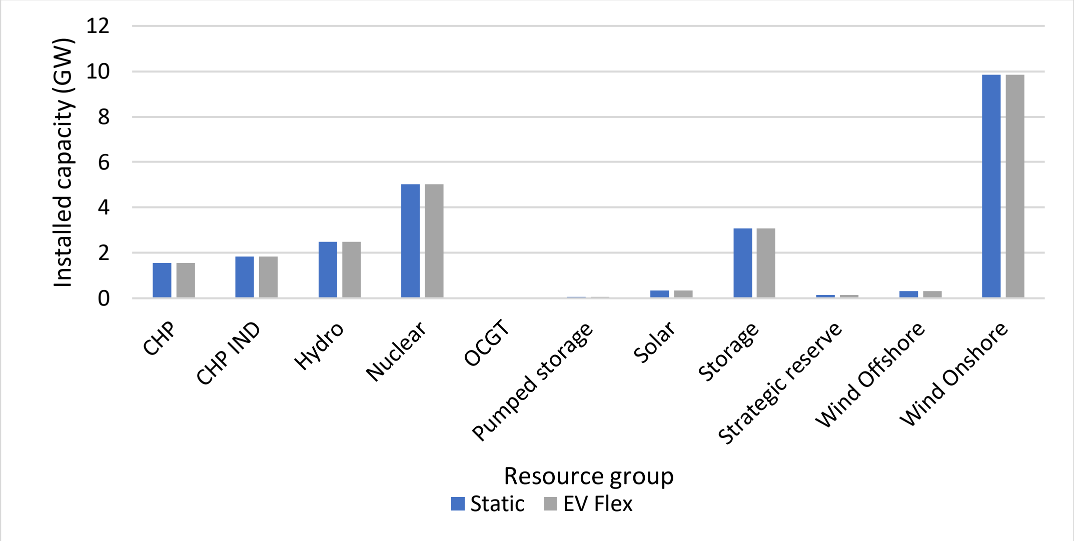


Figure 21: The Finnish total installed generation and storage capacity by resource group in the simulation scenarios. The figure contributes to the step 3 of the method 1 process depicted in Figure 18.

The only remarkable differences between the scenarios were the proportion of EV charging strategies and the annual electricity consumption of electrolysis. The EV charging differences were set as input parameters, but electrolysis capacity was determined by the integrated investment optimization of the simulation software. The difference between the scenarios in electrolysis's annual electricity demand could have been caused by a divergent installed electrolyzer capacity due to investment optimization.

6.2 System analysis of 1h power ramps

This section's analysis of power system's power ramp behavior is conducted with the top-down approach introduced in Section 5.2 and Figure 18. Firstly, the distribution of 1h power ramp-rate values is depicted with violin curves in Section 6.2.1. Secondly, the correlations between resource categories are presented with heatmaps in Section 6.2.2. Thirdly, the magnitudes of resource categories power ramps are presented with heatmaps in Section 6.2.3. Fourthly, the correlations of resource groups with generation are presented with heatmaps in section 6.2.4. Lastly, the selection of the top three most impactful energy resources contributing to system power ramps is presented in section 6.2.5 where their correlations with heatmaps are depicted.

6.2.1 Distribution of resource categories' ramps

Violin curves were used to visualize the distribution of power ramps of the resource group categories demand, generation, net exchange, and storage. They give an indication of how large shifts of power the different categories have in total. By grouping the energy resources into the categories, the power system's energy resources ramping capabilities can be identified on a general level, which helps to decide which types of resources could be the most impactful in terms of power ramp management and thus worthy of further analyses. The distribution of resource group categories' 1h power ramps is presented for scenario *Static* in Figure 22, and for scenario *EV Flex* in Figure 23. It should be noted that all four distribution curves are scaled based on the widest part found in the four curves, and the surface area of each curve is the probability 1. The curves are also smoothened and thus do not detailly represent the actual distribution of values but give a general representation of it.

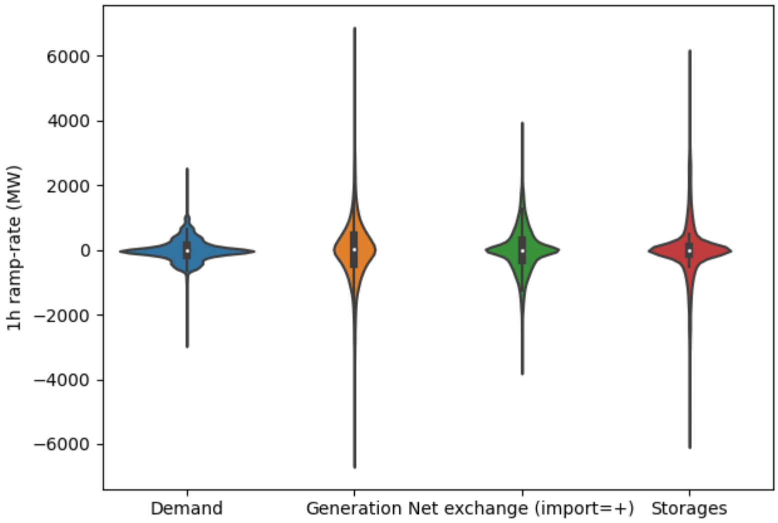


Figure 22: Resource categories' 1h power ramp-rate distribution in scenario *Static*. The figure contributes to the step 6 in the method process of Figure 18.

The scenario *Static* had two resource categories with remarkably higher power ramps than others. The generation had slightly higher ramps than storages and a wider distribution, whereas storages had more values close to zero. The storages had a lower installed capacity which showed in the peak of the ramp values. The demand had the least variation in ramp values, which were centered close to zero. The net exchange had slightly more variation than demand but was probably limited due to the interconnector ramping restrictions. Although, there was no visible clipping of peak values in the distribution of net exchange. In terms of quantification, the violin curves helped to find two noteworthy resource categories for further examination, i.e., generation and storages and indicate that categories demand and net exchange did not contribute in power ramping with such high volumes and magnitudes.

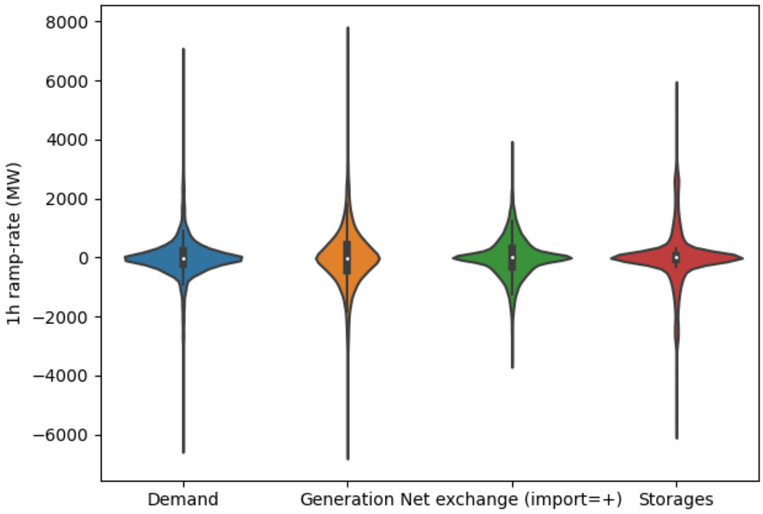


Figure 23: Resource categories' 1h power ramp-rate distribution in scenario *EV Flex*. The figure contributes to the step 6 in the method process of Figure 18.

In scenario *EV Flex*, generation and demand had the largest ramp-rate peaks. Storages had the third-largest power ramps and slightly more even distribution than demand. Generation had the most even distribution with fewer values close to zero than others. It also had the highest peak ramp values. Demand had almost as high peak ramps, but their values were centered closer to zero. Net exchange had the lowest ramp peak values. In terms of quantification, the violin curves provided the general picture of three noteworthy categories, i.e., demand, generation and storages and less significant category net exchange.

When comparing the scenarios, demand and generation ramps were higher in scenario *EV Flex*. Even though, the range of storages was the same in both scenarios, it was spread more within the range of -4 000 and 4 000 in scenario *EV flex*. These changes highlight the advantage of the illustratios with violin curves for interpreting differences in categories' ramp distributions. The differences showcase the impacts of a singular presumption change, i.e., the EV charging logic. Net exchange had a very similar distribution in both scenarios, which shows how the quantification helps to notice similarities between scenarios and narrow down the impacts of presumption differences. The disadvantages of the results were the missing information of the interrelations between the categories' ramps and the temporal occurrence of the ramps, which limited understanding their behavior and thereby relation to flexibility needs.

6.2.2 Correlations between resource categories

Resource category correlations help to detect broad trends of resource types and their interrelations. Positive correlations indicate how strongly the behavior of two resource categories matches in terms of their grid exchanges' shifts. Negative correlations indicate how well the same matching of behavior applies to the values of a resource and the additive inverse values of another resource. Correlations are scaled from -1 to 1 and color-coded with a heatmap where value 1 is colored light yellow, zero values are colored red, and -1 is colored black. Colors between these values are determined by a gradient color scale. The resource categories' correlations of the simulation year's power ramps in the scenarios *Static* and *EV Flex* are presented in Figure 24 and in Figure 25, respectively.

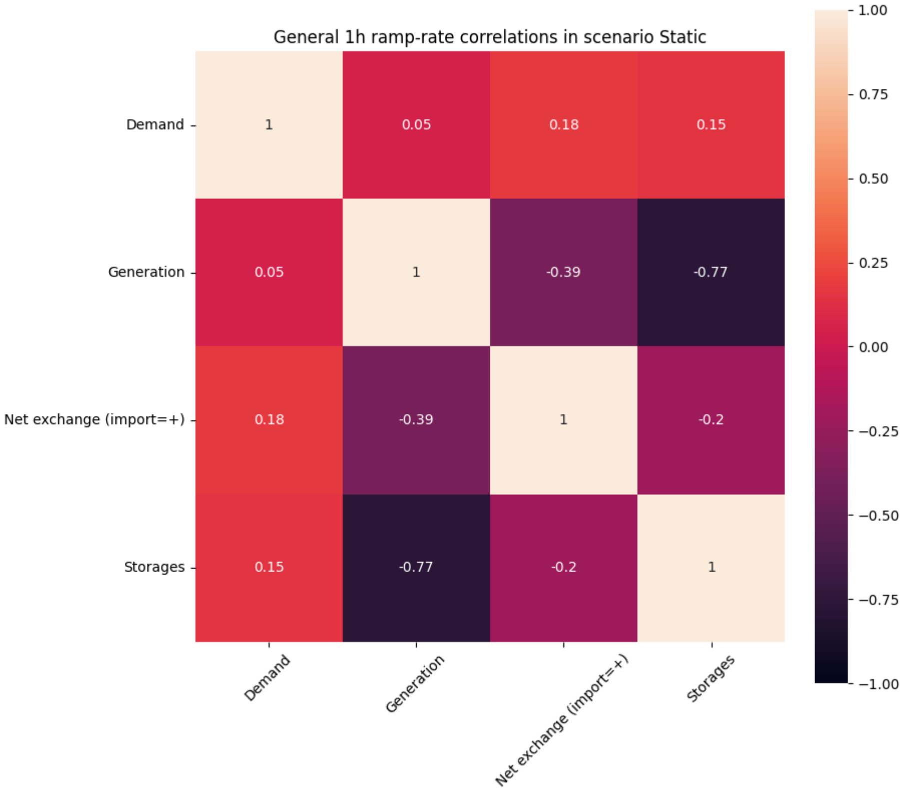


Figure 24: Resource categories' 1h power ramp-rate correlations in the scenario *Static*. The figure stands for the step 5 in the method process introduced in Figure 18.

In the scenario *Static*, generation and storages had strong negative correlations. Since both had positive values when feeding the grid, the negative correlation indicated that they had a balancing relationship in terms of power shifts. Net exchange and generation had apparent negative correlations but not as strong as between generation and storages, which similarly indicates that they had a balancing relationship to some extent. Net exchange and storages also had some negative correlation but were not as significant as the aforementioned resource category pairs. Other correlations were quite weak, which suggests that the dynamics between generation, storages, and net exchange would be the most important categories to assess further. Generation and storages also had the highest 1h power ramp-rates, so they were selected for the remaining ramp analysis of the scenario *Static*. In terms of quantification the correlation heatmap of resource categories helped to define the two most power ramp-wise impactful resource categories, i.e., generation and storages in combination with the violin curves. Also, the weak correlations of other categories helped to dismiss them as behavior with less noticeable trends and focus more on strongly correlating category pairs.

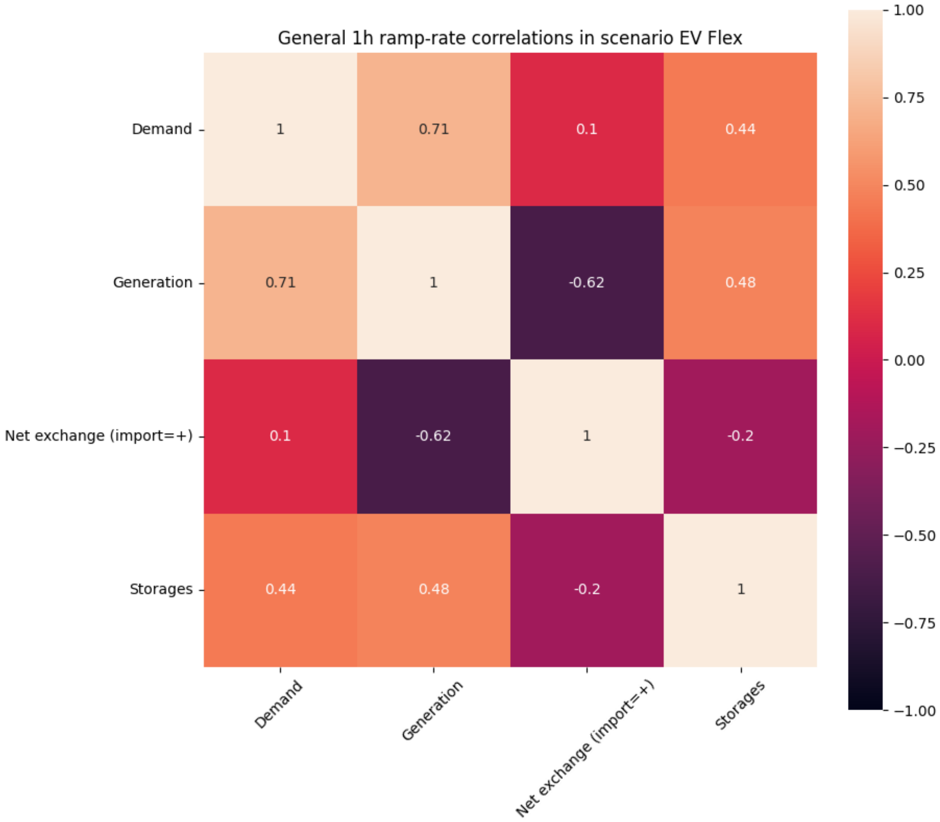


Figure 25: Resource categories' 1h power ramp-rate correlations in the scenario *EV Flex*. The figure stands for the step 5 in the method process introduced in Figure 18.

In the scenario *EV Flex*, the 1h power ramp-rates of generation and demand had a high positive correlation. Since demand and generation had opposite signs regarding grid exchange, their power ramping relationship could be considered balancing. Net exchange and generation had a strong negative correlation, which also indicated a balancing relationship. Storages had a somewhat remarkable positive correlation with both demand and generation, which suggested that storages had a balancing relationship with demand, but a contradictory relationship with generation. Net exchange was the only category with weak correlations that coincided with demand and storages. In terms of quantification, the correlation heatmap helped to expose the most correlating resource category pair, i.e. net exchange and generation. It also showed strong correlations between multiple categories and revealed one category to have the least amount of strong correlations, i.e., net exchange. These observations from the illustration helped to narrow down the most worthwhile categories, i.e. generation, demand, and storages, for further examination combined with information obtained from the violin curves.

Overall, the scenario *EV Flex* had a more dispersed set of strong correlations than the scenario Static. On the same note, demand had very weak correlations in the scenario *Static*, while the scenario *EV Flex* showed strong correlations with generation and storages. The role of the storages was more distributed between demand and generation in the scenario *EV Flex* compared to the strong correlation with generation in the scenario *Static*. Only noteworthy correlations of net exchange were with generation that strengthened in the scenario *EV Flex*. This could have meant that the net exchange was mainly following generation rather than other resource categories. Generation had the strongest correlations in both scenarios, which suggests that it was a central category regarding 1h power ramp behavior of the power system.

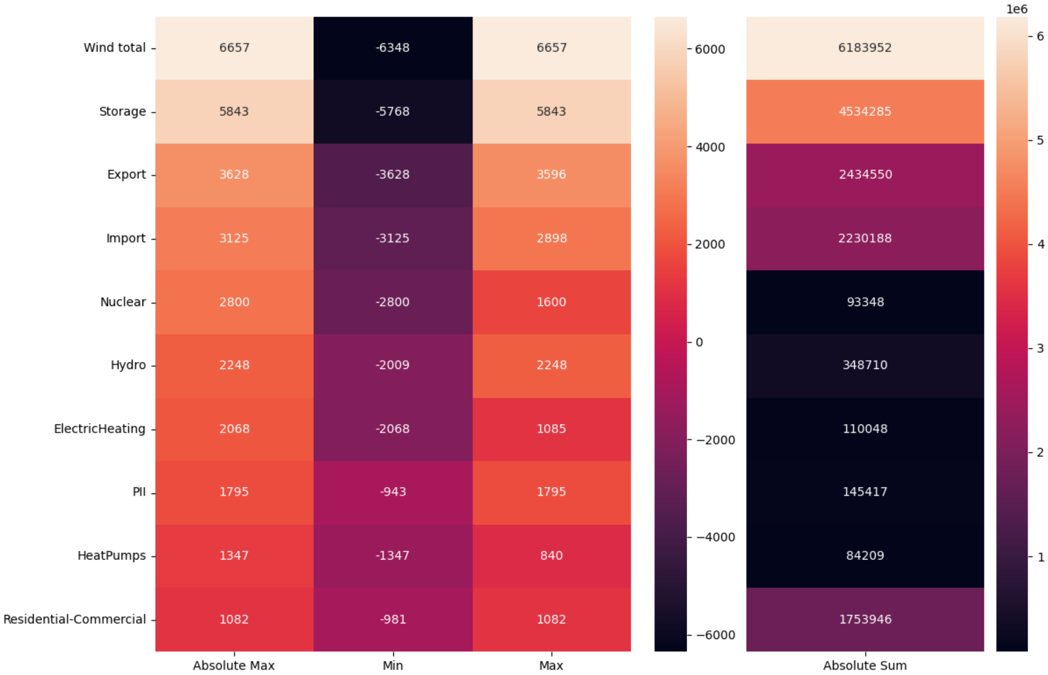
In terms of quantification, the correlation heatmaps helped to compare the interrelation trends of resource categories' power ramps between the two scenarios, which highlighted how a singular presumption difference, i.e., EV charging logic could have impacts on several resource categories' power ramping interralations. In combination with the violin curves, the most impactful resource category, i.e., generation could be determined to concentrate further examinations of resource groups. Also, the correlations could help efforts on the determination of power ramp management flexibility needs based on the interrelationships between different categories.

A disadvantage of the correlation heat map is that strong correlations of the whole year indicated similar behavior overall but might have not reflected the ramping interrelations during the highest ramps, which are the most interesting ones regarding ramping flexibility needs. For instance, if some resources, such as EVs had many hours without any power ramps, they might resemble low ramping resources, such as nuclear generation, even though EVs can also have high power ramps. Thus, conclusions of the correlations should be drawn carefully and more extreme ramping situations should be examined in addition to the annual correlations.

6.2.3 Resource groups' ramp magnitudes

Presenting the largest ramp magnitudes of resource groups with heatmaps would help to reveal the most impactful resource groups in terms of power ramps and thereby groups that either balance or cause power ramps. By revealing these groups the further ramping flexibility need analyses could be concentrated more efficiently. Resource categories' ramp magnitudes were not presented since they had no significant new information in addition to the violin curves that could show the ramp extreme values and volumes in a general level. The violin curves were not used for the resource groups since they would presumably be too general and take more space to illustrate than the heatmaps. The ten largest power ramp-wise resource groups were set as the scope of the illustration to expose the clearly most significant groups and upper range of the rest of the groups.

The ten largest resource groups' ramp magnitudes are presented in Figure 26 for the scenario *Static*. *Absolute Max* refers to the absolute maximum of power ramps, i.e., the largest value of the absolute ramp values. *Min* refers to the minimum value of power ramps, i.e., the largest negative power ramps. *Max* refers to the maximum of power ramp values, i.e., the largest positive power ramps. *The absolute sum* was calculated by summing the absolute values of power ramps. It gives an indication of the yearly volume of power ramps rather than focusing on the extreme points. The ramp peak values are colored as a heatmap ranging between values of ca. -8 000 and 8 000 MW, and colors of black, red, and light yellow. The ramp volumes are colored in another heatmap whose values range ca. between 0 and 10^6 MW, and colors of black, read, and light yellow.



	Absolute Max	Min	Max	Absolute Sum
Wind total	6657	-6348	6657	6183952
Storage	5843	-5768	5843	4534285
Export	3628	-3628	3596	2434550
Import	3125	-3125	2898	2230188
Nuclear	2800	-2800	1600	93348
Hydro	2248	-2009	2248	348710
ElectricHeating	2068	-2068	1085	110048
PII	1795	-943	1795	145417
HeatPumps	1347	-1347	840	84209
Residential-Commercial	1082	-981	1082	1753946

Figure 26: Resource groups' 1h power ramp-rate magnitudes in MW sorted by the absolute maximum values in the scenario *Static*. Ten resource groups with the largest absolute ramp-rate peaks are presented. The figure stands for the step 9 in the method process introduced in Figure 18.

In the scenario *Static*, total wind generation and battery energy storage (BES) had the largest 1h power ramp peaks both downward and upward. They also had the largest absolute sum of ramp values, which indicated their superiority in ramping volume. Below BES, export and import were both very similar in terms of ramp peaks and volume. The rest of the top 10 resource group list showed a gradual decline in ramping peaks and volumes, which highlights the significance of the total wind generation's and BES's power ramps' impact on the system, while the rest of the resource groups had a more distributed role in the power ramps of the system. However, there was an irregularity in this trend with the resource group residential-commercial electricity consumption that had larger ramping volumes than the other resource groups below import.

In terms of quantification, the ramp magnitude heatmap helped to expose the most significant power ramping resource groups, i.e., wing generation and BES, by indicating their ramp peaks and volumes and the less significant magnitudes of other resource groups. The determination helped to concentrate the further analyses of power ramping, presumably more efficiently than just analyzing the most significant resource categories. The adjacent presentation of ramp peaks and volumes helped to detect that the sorted order of largest ramps peaks would not necessarily match the sorted order of ramp volumes, which indicated different ramping behavior and possibly roles of different resource groups that should be considered in flexibility need quantification.

The ten largest resource groups' ramp magnitudes are presented in Figure 27 for the scenario *EV Flex*.

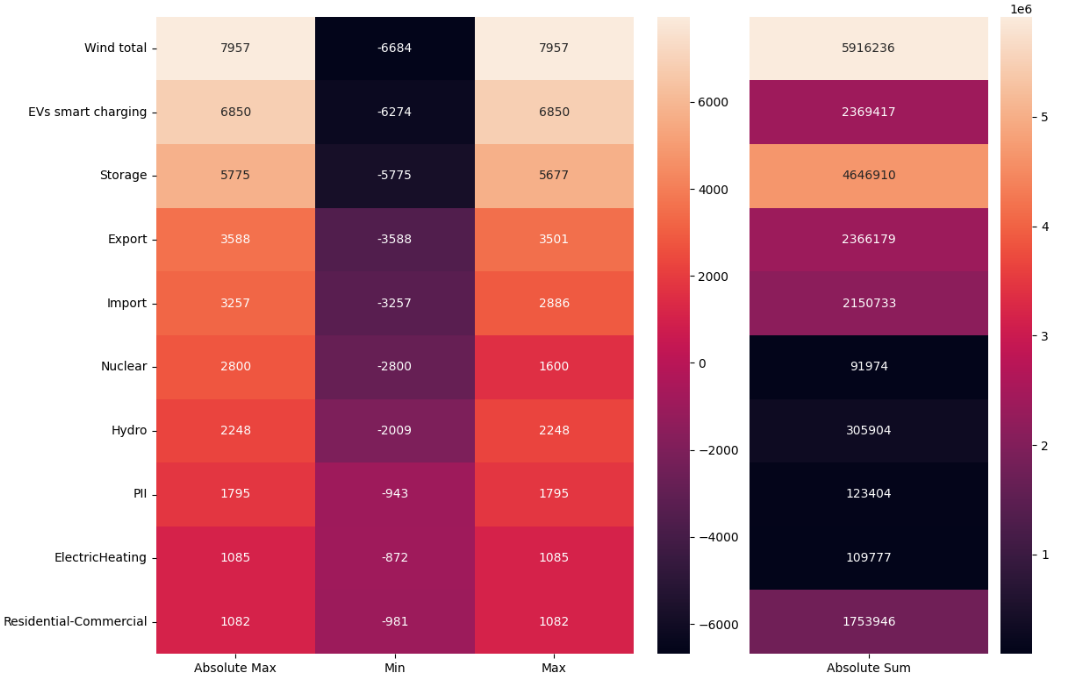


Figure 27: Resource groups' 1h power ramp-rate magnitudes in MW sorted by absolute maximum ramp values in the scenario *EV Flex*. Ten resource groups with the largest absolute ramp-rate peaks are presented. The figure stands for the step 9 in the method process introduced in Figure 18.

In the scenario EV Flex, total wind generation, smart EV charging, and BES clearly had the three largest 1h power ramp peaks in the order of mention, but volumes were not as coherent. Wind had the largest ramp volumes, but EV charging had almost the same volumes as export, which was in the fourth place in terms of ramp peaks. Storages had the second-largest ramp volumes, even though they had the third-largest ramp peaks. Export and import had similar ramp peaks and volumes, but export had slightly larger values. The rest of the resource groups had a gradual decline in absolute ramp peaks and volumes, which highlights the significance of the three largest ramping resource groups. The residential-commercial group had a divergently higher ramp volume than the rest of the resource groups below import that had higher ramp peaks.

In terms of quantification, the magnitude heatmap helped to determine the most significant ramping resource groups, i.e., wind generation, BES, and smart EV charging and highlight the lower significance of other resource groups to focus the further power ramp analyses. The mismatch in the sorted order of ramp peaks and volumes highlighted the complexity of power ramp flexibility needs' quantification with resource group considerations.

Overall, total wind generation had the largest 1h power ramp-rate peaks and volumes in both scenarios. BES had the second-largest ramp volumes in both scenarios. BES had the second largest ramp peaks in the scenario *Static* and the third-largest in the scenario *EV Flex*. EVs had almost half of the ramp volume compared to BES. Export and import had similar ramp peaks and volumes with each other and scenarios in both scenarios, indicating that their ramping capabilities are exploited equally but not necessarily for balancing of same resource groups' ramps. Residential-commercial group had the tenth largest ramp peaks but fifth or sixth-largest ramp volumes in both scenarios, which shows that energy resource groups can have varying importance in the system power ramp landscape in terms of ramp peaks and overall volume of power ramps. However, the general trend was at least for the nine largest absolute ramp peaks that the larger the absolute ramp peaks the more likely they also have larger ramp volumes.

In terms of quantification, the magnitude heatmaps helped to compare the differences of power ramp behavior between two scenarios with a singular presumption change, i.e., EV charging logic. They also helped to detect noteworthy resource groups and trends between ramp peaks and volumes. However, they lacked the interrelations between resource groups to determine if they were causing or balancing power ramping flexibility needs. Another disadvange was the loss of temporal disposition of the power ramps, which could have helped the assessment of flexibility needs and interrelations.

6.2.4 Correlations with generation

To concentrate the further power ramping flexibility need analyses, the most impactful resource categorie's correlations would be explored. Total generation was chosen as the most impactful ramping resource category for both scenarios since it had the largest ramp magnitudes and correlations. Storages would have been the second most impactful ramping resource category of scenario Static, and demand would have been that for the scenario EV Flex, but their top correlations were left out due to the already extensive set of figures in the thesis results. To assess resource groups' effects on the total generation's 1h power ramps, the top ten correlations are presented for the whole year, 99th percentile and 1% fraction. The 99th percentile and 5% fraction were chosen since they represent the extreme ends of generation's power ramps that are very challenging sets of reference points for the ramping flexibility needs with reasonable number of data points.

Correlations of total generation's ramps in the scenario *Static* are presented for three correlation sets in Figure 28 for the entire simulation year, Figure 29 for the 99th percentile, and Figure 30 for the 1% fraction. It should be noted that the wholesale price of electricity was included in the correlation analysis, even though it is not an energy resource group, but rather an attribute of the whole power system.

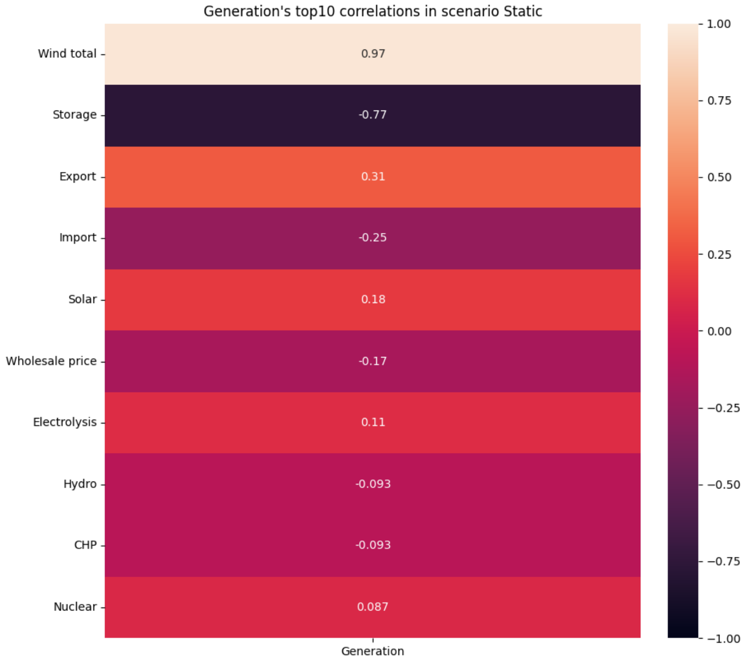


Figure 28: The top 10 largest absolute correlators with total generation's 1h power ramps in the scenario *Static*. The figure corresponds to the step 10 in Figure 18.

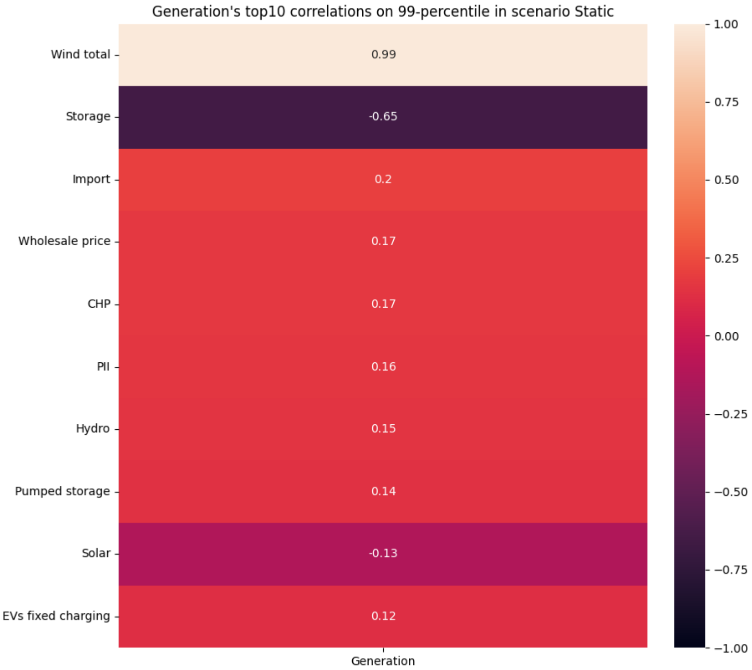


Figure 29: The top 10 largest absolute correlations with the 99th percentile of total generation's 1h power ramps in the scenario *Static*. The figure corresponds to the step 10 in Figure 18.

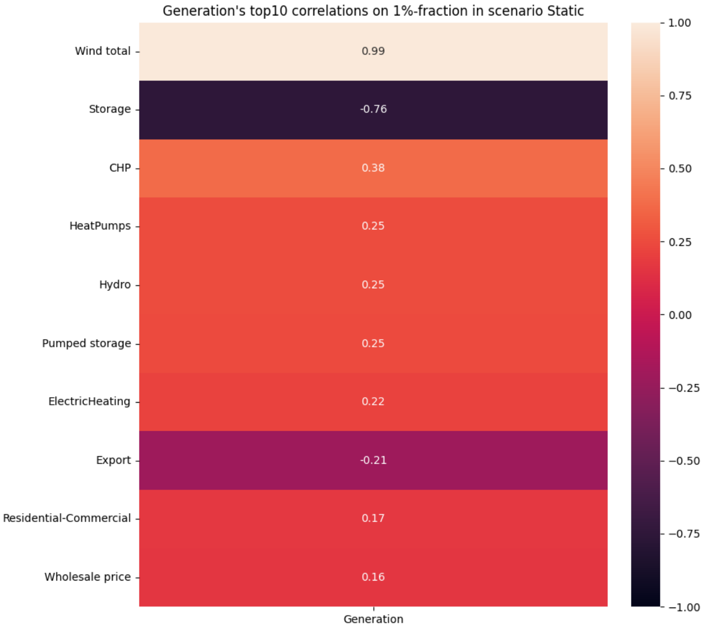


Figure 30: The top 10 largest absolute correlations with the 1% fraction of total generation's 1h power ramps in the scenario *Static*. The figure corresponds to the step 10 in the Figure 18.

In the scenario *Static*, there were two clear resource groups correlating with the resource category generation in terms of 1h power ramps. Firstly, the total wind generation had very high positive correlations with generation for the whole simulation year, in the 99th percentile, and 1% fraction, which entails that wind generation was the major cause of the generation power ramps. The correlation was stronger in the 99th percentile and the 1% fraction, highlighting the role of wind generation as the most impactful ramp contributor for generation and for the whole system. Secondly, BES also had strong correlations with the generation, but its correlations were negative. Thus, BES could be seen as a major balancing resource group for generation.

Other resource groups had weaker and less coherent correlations in all three correlation sets compared to wind and BES. In the set of the entire simulation year, most of the remaining resource groups had a balancing effect on the generation power ramps, excluding solar and nuclear generation that had only minor correlations with generation. Out of the remaining resource groups import and export had the most significant correlations in the annual correlation set. In the 99th percentile correlation set, all correlations, excluding wind and BES, had equal or below 0.2 absolute correlations. In the correlation set, all the most correlating generation groups had, on average, an increasing effect on the generation ramps except solar generation. For the set, demand resource groups had a balancing effect on the generation ramps. In the 1% fraction correlation set of generation, i.e., largest downward generation ramps, the resource groups excluding wind and BES had slightly larger absolute correlations than for the year correlation set. Again, generation groups had an increasing effect and demand groups had a balancing effect on generation ramps. On a final note, on the generation correlations in the scenario *Static*, the shifts in the wholesale price of electricity were among the top 10 correlations in all three correlation sets, most notably in the 99th percentile. Even though, the wholesale price's shifts' correlations were quite weak, their inter-relation should be examined more thoroughly in future analyses.

In terms of quantification, the correlation heatmaps helped to detect the most interrelated resource groups on annual level and in the extreme ends of the generation's ramps. These observations would help to concentrate the analyses of resource groups to expose ramping flexibility needs. They also showed that correlations could differ in different correlation sets significantly, which highlighted the complex dynamics of ramping behavior that could complicate the determination of flexibility needs.

Correlations of total generation's 1h power ramps in the scenario *EV Flex* are presented for three correlation sets in Figure 31 for the entire simulation year, Figure 32 for the 99th percentile, and Figure 33 for the 1% fraction.

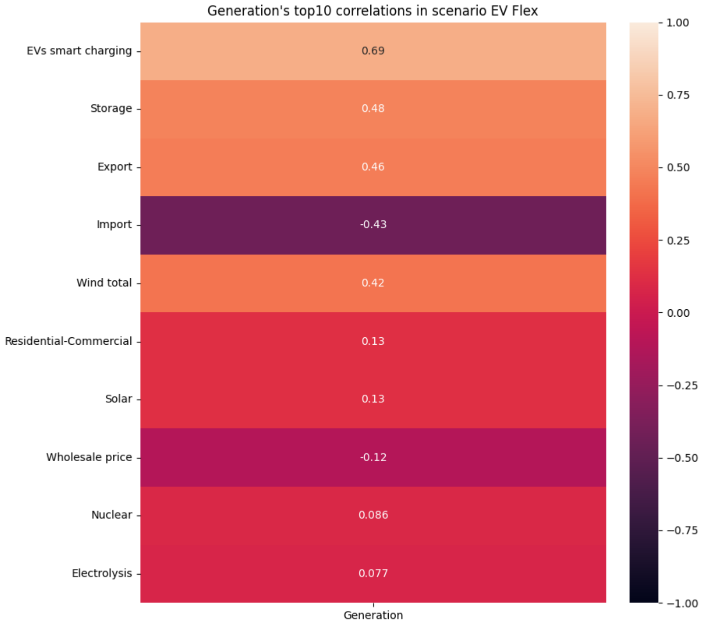


Figure 31: The top 10 largest absolute correlations with total generation's 1h power ramps in the scenario *EV Flex*. The figure corresponds to the step 10 in Figure 18.

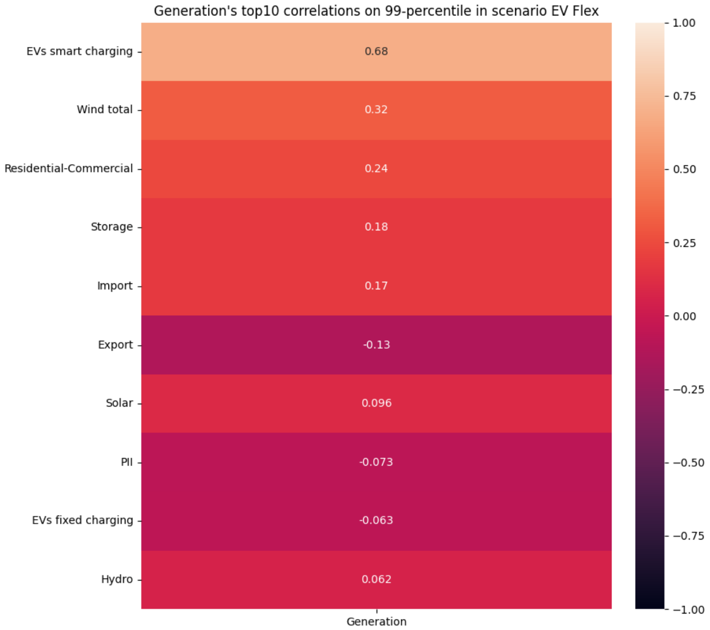


Figure 32: The top 10 largest absolute correlations with the 99th percentile of total generation's 1h power ramps in the scenario *EV Flex*. The figure corresponds to the step 10 in Figure 18.

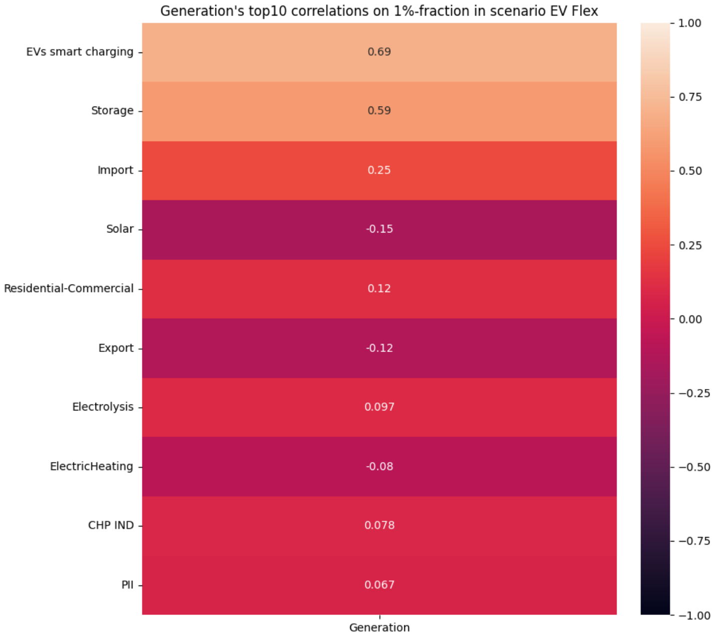


Figure 33: The top 10 largest absolute correlations with the 1% fraction of total generation's 1h power ramps in the scenario *EV Flex*. The figure corresponds to the step 10 in the Figure 18.

In the scenario *EV Flex*, the smart charging of EVs correlates strongly with total generation in all the correlation sets. They had a positive correlation that indicates a balancing relationship since they are a pair of demand and generation that have opposing signs of grid exchange values. In the year set, BES, export, import, and total wind generation have only minor differences in their correlations with generation. However, they had weaker correlations than smart EV charging. Out of the aforementioned resource groups, BES and wind had an increasing effect, and import and export had a balancing effect on the generation. The non-balancing relationship of BES with the generation was surprising and could indicate that BES operates primarily based on other signals than generation balancing. The rest of the resource group correlations were insignificantly weak. A noteworthy observation was that the wind generation was not among the top four correlators in the annual correlation set of generation ramps.

In the 99th percentile correlation set, in addition to the clear role of the smart charging of EVs, total wind generation had a somewhat remarkable increasing effect on generation. Residential-commercial group had some positive correlations indicating a weak balancing relationship. The rest of the resource groups had only negligible correlations. In the 1% fraction correlation set, wind was not present in generation's 1% fraction's top 10 largest absolute correlations. This could entail that wind generation was not consistently responsible for the largest downward ramps of generation. On the other hand, BES had almost as strong correlation as EV smart charging in the correlation set, which could have led to enforced balancing effects with generation. It could also be argued that generation groups balance other resources such as EV smart charging since IRES was not strongly correlating with the largest downward generation ramps. In fact, solar generation had a weak negative correlation with generation during the 1% fraction, which supports the argument of the total generation that follows other resources rather than most of the resources to be balancing IRES generation. On a final note, on the generation correlations in the scenario *EV Flex*, the wholesale price was not present in the top 10 absolute correlations of 1h shifts with generation, which suggest that other resources are more responsible for the price shifts than generation groups in the scenario.

In terms of quantification, the correlation heat maps helped to detect the most correlating resource groups with generation's power ramps. Those observations helped to determine the most significant ramping resource groups by the regard of their system impact. The differences in different correlation sets exposed the differences in ramping behavior of resource groups, which highlighted the complexity of determining the flexibility needs of power ramp management.

Overall, the scenario *Static* had more centralized ramp contributors while *EV Flex* had a more dispersed distribution of strong absolute correlations with generation. Wind ramps were less correlative with generation ramps in *EV flex* than in *Static*. The wholesale price's shifts' correlations were not as apparent in *EV Flex* as in *Static*. Limitation to non-negative wholesale electricity prices could also explain the weak correlations of wholesale price shifts and generation ramps, if IRES curtailment was the cause of the largest ramps when the prices were forced to zero or above. The curtailment issue is further discussed in Section 7.

In terms of quantification, the correlation heatmaps of the resource category generation helped to compare the differences in the interrelations of resource group's ramps between two scenarios diverging in a singular presumption, i.e. the EV charging logic. They helped to make observations of the most significant resource groups' interrelation with the most significant resource category to concentrate the further analyses with the help of magnitude heatmaps. They also exposed divergent interrelation trends in different correlation sets, which highlighted the versatile nature of power ramp management flexibility needs. The disadvantage of the illustrations was the focus on a singlular resource category that could cause a bias in the interpretations of the most significant resource groups. The illustrations also lacked the magnitudes of the resource groups power ramps that could emphasize the meaning of strong correlations. However, this would be executed by also assessing the magnitude heatmaps containing the resource groups.

6.2.5 Top three ramping resources and their correlations

Determining the top three resource groups in terms of power ramp impact would help to concentrate the further analysis efforts of singular resource groups and thus form basis for power ramping flexibility needs' quantification. The top three ramp contributors of the scenario *Static* were total wind generation, BES, and export. All three resource groups were in the top four in the ramp magnitude ranking. They were present in most of the top resource category correlation listings, notably for the correlation sets of generation. Wind and BES were clear contributors to generation ramps in terms of ramp magnitudes and correlations. Out of the two, the total wind generation was the cause of the generation ramps, while the BES was responsible for balancing the generation ramps to some extent. The third most impactful system ramp contributor for the scenario *Static* was export which had slightly larger absolute ramp peaks and was slightly more apparent in generation correlations than import, even though they had similar ramp volumes. Correlations between the top three ramp contributor resource groups of scenario *Static*, i.e., total wind generation, BES, and export, are presented in Figure 34. The correlations are expressed for the entire year, 1% fraction of each resource group, and the 99th percentile of each resource group.

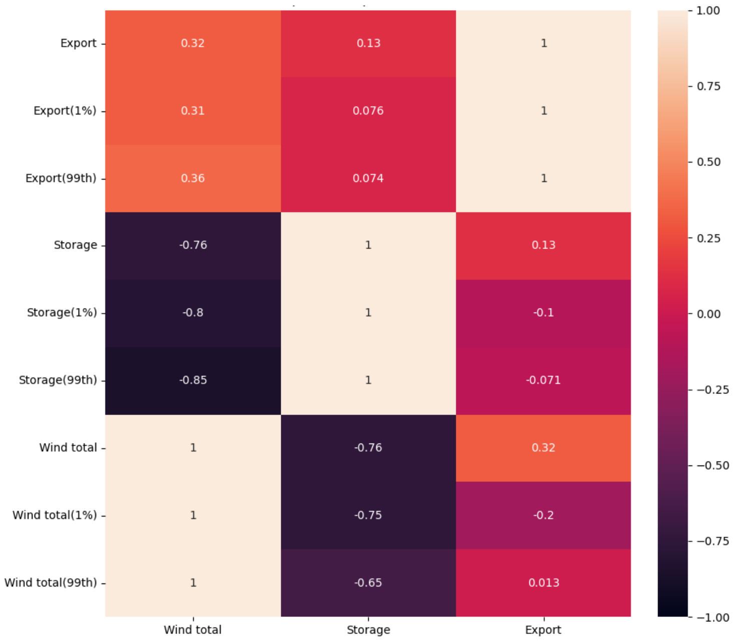


Figure 34: Collection of power ramp correlations between the top 3 system power ramp contributors in scenario Static. The figure corresponds to the step 12 in Figure 18.

In the scenario *Static*, wind and BES had strong correlations for the entire year and in their extreme ends. This enforced the balancing relationship of the categories generation and storages in the scenario. Export has mixed correlations with others' extremes, but others balanced export ramps coherently, even though the correlations were quite weak. This could entail that export ramps do not balance other resource groups but rather are balanced by others. As wind generation had the largest ramp magnitudes and the strongest correlations with generation, it was chosen as the most impactful ramping resource group of the scenario *Static*.

In terms of quantification, the correlation heatmap of the top three resource groups helped to detect more detailed interrelations and decide which group would be the most beneficial to be analyzed further in combination with the previous observations.

The top three ramp contributors of scenario *EV Flex* were wind generation, smart EV charging, and BES. The three resource groups were the clear top three of ramp magnitude ranking and present in most of the generation correlations. Wind generation had substantially larger ramp magnitude volumes than smart EV charging, even though smart EV charging had stronger correlations with generation correlation sets. Correlations between the top three ramp contributor resource groups of scenario *EV Flex*, i.e., total wind generation, smart EV charging, and BES, are presented in Figure 35. The correlations are expressed for the entire year, 1% fraction of each resource group, and the 99th percentile of each resource group.

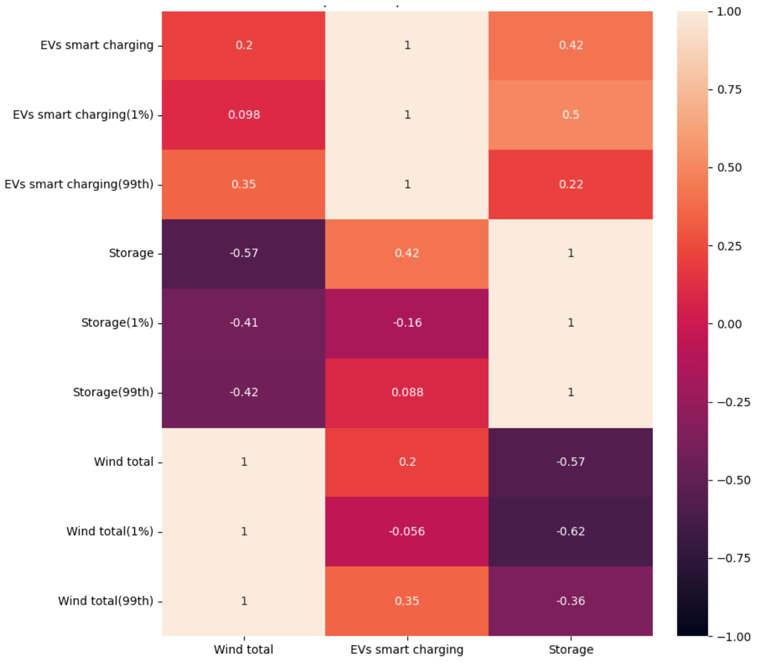


Figure 35: Collection of power ramp correlations between the top 3 system power ramp contributors in scenario EV Flex. The figure corresponds to the step 12 in Figure 18.

In the scenario *EV flex*, storage and wind were a strong correlation pair. Smart EV charging had mixed correlations in other resources' extremes but coherent positive correlations in its own extremes, which could indicate that other resources adapted to EV behavior rather than EV adapting to other resource groups' extremes. Wind generation and upward smart EV charging ramps had a quite strong positive correlation suggesting a balancing relationship. BES balanced downward EV ramps based on a relatively high positive correlation. The most impactful resource group of scenario *EV Flex* in terms of system ramps was chosen to be wind generation, even though it did not have as strong correlations with generation as in scenario *Static*. Smart EV charging could have been another candidate, but it had lower peak power ramps and volumes. Due to the smart charging profile, versatile generation affected its behavior through price optimization, which could explain the better correlation with total generation compared to wind generation.

In terms of quantification, the correlation heatmap of the top three resource groups helped to detect more detailed interrelations and decide which group would be the most beneficial to be analyzed further in combination with the previous observations. The incoherencies among different correlation sets of a resource group with another resource group revealed ramping behavior to be complex even with singular resource group pairs.

Overall, wind generation was surprisingly not equally strong in both scenarios in terms of generation correlations. Differences in EV charging behavior resulted in broad effects on system dynamics. Thus, sensitivity analyses on EV charging logic's impact on system dynamics should be conducted to better understand, prepare for, and affect their role in the future power system. It could also be beneficial to conduct the resource group power ramp analysis for smart EV charging in addition to wind generation to expose other interrelations not found in the top-down approach. However, in this thesis, the resource group analysis is limited to wind generation, so that both scenarios can also be better compared with each other. The results and analysis of the 1h power ramps method for wind generation is presented in the following section 6.3.

In terms of quantification, the heatmaps of top three ramping resources helped to determine the most impactful resource group in combination with the previous illustrations of the top-down approach. They also revealed several differences caused by a singular presumption difference, i.e., EV charging logic. However, they lacked the magnitudes of the resource groups' ramps, which makes it more challenging to deduct any conclusions of ramping flexibility needs. Another disadvantage is the large amount of information in a singular illustration that hampers the interpretation of the results.

6.3 1h power ramps of wind generation

IRES generation was hypothetically the most impactful resource group to create ramping flexibility needs. Wind generation was selected for the resource group level power ramp analysis since it had the biggest share of installed capacity of the IRESs, the largest power ramp peaks and volumes, and it significantly correlated with generation in both simulation scenarios. The process that resulted in the choice of wind generation was presented in Section 6.2. The results of the method, that was introduced in Figure 19 and

Section 5.3, are presented in this Section. First, the ten largest upward and downward 1h power ramp hours of wind generation are presented with the rest of the resource groups' power ramps during the corresponding hours in section 6.3.1. Lastly, the other resource groups' correlations with wind generation are presented for the scenario *EV Flex* on three correlation sets, and the two most correlating resource groups' ramps are plotted with wind generation's ramp duration in Section 6.3.2.

6.3.1 The ten largest upward and downward ramps of wind

To expose the most supposedly challenging situations of power ramp management flexibility needs, the top ten largest upward and downward wind ramps are presented with other resource groups ramps. This illustration would help to detect the temporal disposition of the challenging situations and the resource groups contributing to the power ramps during those hours. To present all system resources' 1h power ramps in the same figure, some alterations to the energy resources signs are needed. To unify the power ramp values, the sign of the ramp rate values indicates, if they are upregulation or downregulation. Negative power ramps are downregulation and positive power ramps are upregulation. Upregulation means that the net sum of the grid exchange of a resource group increases. In other words, the resources of the group supply more or they take less electricity from the grid in total. On the other hand, downregulation means that the net sum of the grid exchange of a resource group decreases. In other words, the resources of the group supply less or withdraw more electricity from the grid in total.

The ten largest upward and downward ramps of wind generation are present for the scenario *Static* in Figure 36 and Figure 37. The hours when the power ramps occurred are indicated by the horizontal axis labels.

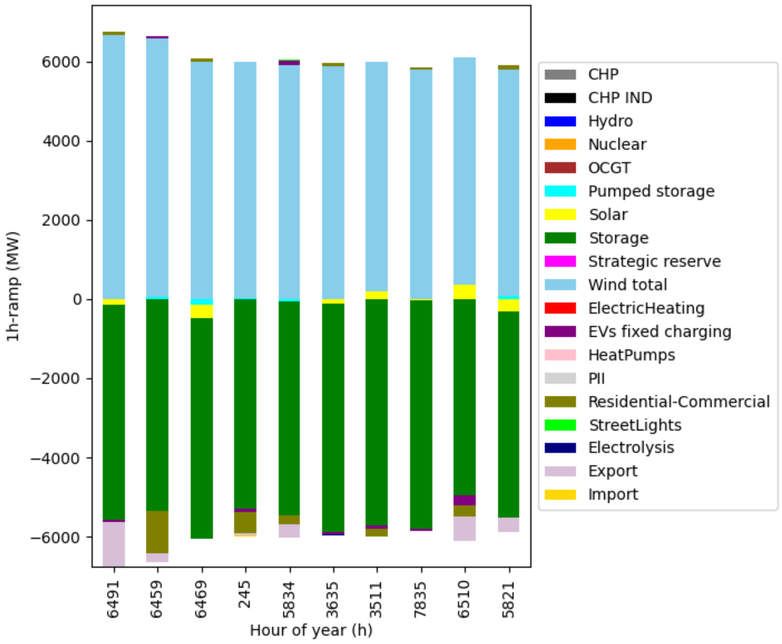


Figure 36: The ten largest upward 1h power ramps of wind generation in the scenario *Static* with other resource groups' ramps. Positive ramps stand for upregulation and negative ramps for downregulation. The horizontal axis states the hours of the simulation year when the ramps occurred. The figure corresponds to the step 3 in Figure 19.

In the scenario *Static*, the top ten largest upward 1h power ramps of wind generation coincided with large downregulations of BES. This enforced the strong behavioral link between the two resource groups found in Section 6.2.5. Export and residential-commercial resource groups showed other noticeable downregulating ramps. Their effects were minor compared to the BES downregulation. The solar generation had a mixed relationship with the largest wind generation ramps, which suggests that combined IRES ramps could occur in different hours than the ten largest wind ramps, or at least in a different order. When it comes to the hours of the simulation year when the ramps occurred, no subsequent hours were present in the top ten, but there were four ramps within the range of hours 6450 and 6510. This could entail a challenging week in terms of power ramp management. It should also be noted that the majority of the top ten ramps occurred in the latter half of the simulation year.

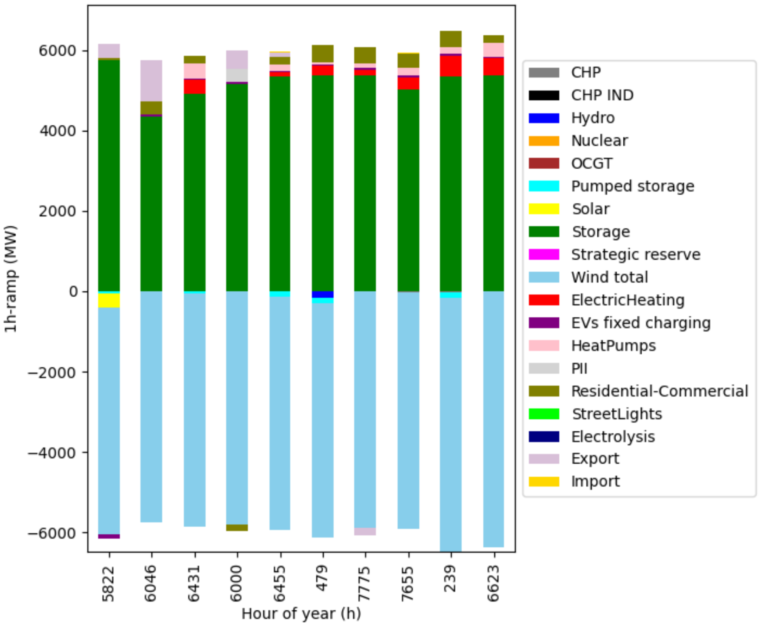


Figure 37: The ten largest downward 1h power ramps of wind generation in the scenario *Static* with other resource groups' ramps. Positive ramps stand for upregulation and negative ramps for downregulation. The horizontal axis states the hours of the simulation year when the ramps occurred. The figure corresponds to the step 3 in Figure 19.

In the scenario *Static*, the top ten largest downward 1h power ramps of wind generation coincided with large upregulations of BES. This was again a strengthening sign of the strong balancing relationship between BES and wind generation in the scenario. However, the other resources had a slightly greater role in the balancing behavior of downward wind ramps compared to the upward wind ramps. Export and residential-commercial resource groups had a similar magnitude in their ramps as during the upward wind generation ramps. Notably, the electric heating and heat pumps had a visible share of the upregulation during the downregulating wind power ramps. Similar to the upward wind ramps, the 10-hour set had hours mainly from the latter half of the simulation year between the range of hours 5 800 and 7 800. However, the hours were not within as close proximity to each other as in the upward ramp top ten sets. Although, both top ten-hour sets fall mainly on the same range of hours, which could entail a long period of challenging ramping conditions in both upward and downward directions.

The ten largest upward and downward ramps of wind generation are present for the scenario *EV Flex* are presented in Figure 38 and Figure 39.

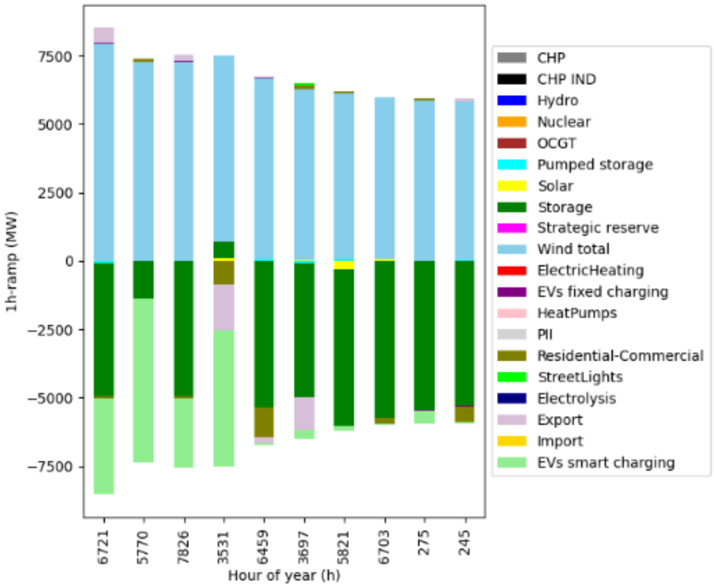


Figure 38: The ten largest upward 1h power ramps of wind generation in the scenario *EV Flex* with other resource groups' ramps. Positive ramps stand for upregulation and negative ramps for downregulation. The horizontal axis states the hours of the simulation year when the ramps occurred. The figure corresponds to the step 3 in Figure 19.

In the scenario *EV Flex*, the ten largest upward wind generation's 1h power ramps did not have a singular coherent balancing resource. The balancing resource groups BES and smart EV charging had the largest volumes of power ramps in the ten-hour set with varying proportions. Smart EV charging was strongly present in the top 4 wind ramp hours, whereas BES balanced most of the wind ramps in the rest of the hours. Other remarkable ramping resource groups were export and residential-commercial that provided balancing ramps for wind generation on a couple of occasions. It should be noted that the BES and export showed, respectively, once and twice minor upregulation behavior during the top ten-hour set of upward wind ramps, which highlighted the complex relationships of power ramping behavior of the energy resources.

When it comes to the hours of the simulation year, the latter half of the year had a slight majority in the top ten-hour set of wind power ramps. No dense cluster of hours was found, but a notable group of power ramps was situated between the hours 5 700 and 7 900. There also were two close pairs of ramp hours around the hours 3600 and 260.

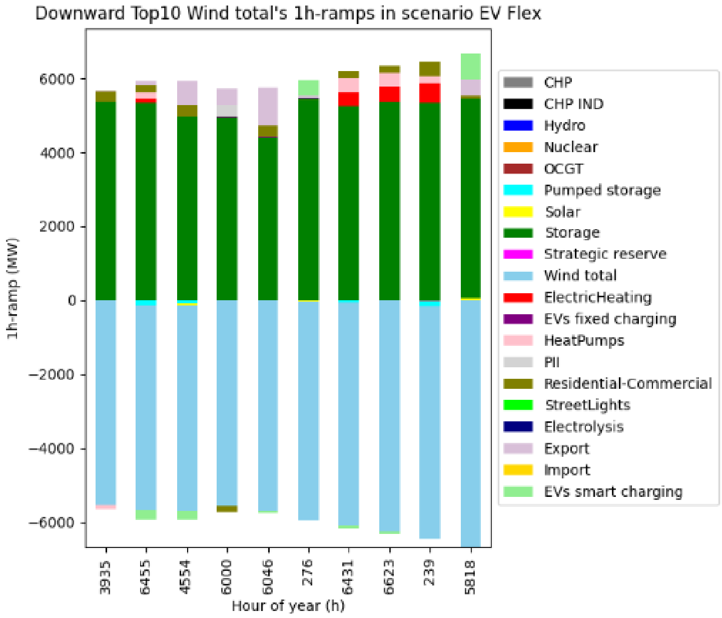


Figure 39: The ten largest downward ramps of wind generation in the scenario *EV Flex* with other resource groups' ramps. Positive ramps stand for upregulation and negative ramps for downregulation. The horizontal axis states the hours of the simulation year when the ramps occurred. The figure corresponds to the step 3 in Figure 19.

In the scenario *EV Flex*, the top ten largest downward 1h power ramps of wind generation coinsided with strong upregulation of BES, which again emphasizes their balancing relationship. Among the top ten-hour set, export had four noticeable upward ramps, which could entail some balancing relationship with wind ramps. Electric heating and heat pumps had three noticeable upward ramps in the top 4 of downward wind ramps, which shows some interrelation with wind ramps. The residential-commercial resource group had noticeable power ramps in most of the top ten set of hours. All of their ramps in the set were upregulation except during hour 6 000, when they had a relatively small downregulation ramp. Smart EV charging had two noticeable upregulation ramps in the set and several minor downregulation ramps, which shows that the wind geration ramps did not have a coherent relationship with smart EV charging. Overall in the top ten set of hours, the balancing upregulation of other resources followed the wind downregulations with almost unchanged BES share and varying combination of other resource groups.

When it comes to the temporal distribution of the top ten set of downward wind ramp hours, half of the hours were between the hours 6 000 and 6 630, which could entail a challenging period in terms of ramp management. Most of the hours situated in the later half of the year. Notably, the hours of the simulation year, when the ten biggest wind ramps occurred, situated in similar range around the hours 6 000 and 7 000. Also the both had two hours around the hours 200 and 300. Wind ramps even had two consecutive hours 275 (downward) and 276 (upward). These similarities could entail that downregulation and upregulation of wind generatation had an interrelation at least close to the largest ramps.

Overall, both of the simulation scenarios had strong presence of balancing BES ramps during the ten largest 1h power ramps of wind generation, although, there was some hours with exceptions on that regard. The residential-commercial resource group was present in most of the largest wind ramps as balancing ramping resource in both scenarios but their volume was small compared to the BES ramps. Electric heating and heat pumps had a role in balancing the downward wind ramps in both scenarios. EV charging had a greater role in wind ramp balancing in the scenario *EV Flex* compared to the scenario *Static*, but not in a coherent manner. Export ramps had some noticeable balancing effects on the largest wind ramps in both scenarios. Both scenarios had minor regulations of ramps in the same direction as wind ramps, which showed that wind was not the only cause of ramping.

For all top ten sets of hours, the wholesale price that the ramps ended on were found to be zero. The zero values of wholesale price were the minimum price threshold in the simulation that did not allow prices to be negative. This could suggest that the downward ramps of wind generation could be, at least partly, caused by curtailment and the upward ramps could be caused by so called rebounds[7] of curtailment events.

Regarding the temporal distribution of the largest 1h power ramps of wind generation, it was clear that most of the largest ramps occurred in the later half of the simulation year and clustered around the range between the hours 5 000 and 7 000. Some of simulation year hours were among the largest wind ramping hours in both scenarios. Upward wind ramps had three out of ten common hours of the simulation year which were 245, 6 459, and 5 821. Downward wind ramps had six out of ten common hours of the simulation year which were 6046, 6431, 6 000, 6 455, 239, and 6 623. The larger number of common downregulation ramps could mean that the curtailment of wind generation had a role in the largest downward wind ramps, since the rebound effect could variate more in terms of delay from the curtailment and its magnitude than the initial start of curtailment. The similarities in temporal location of the largest wind ramps between scenarios could suggest that some climate factors, such as wind speed conditions, affected the behavior of the power system and its energy resources.

In terms of quantification, the bar plots of the largest wind ramps succeeded in describing the temporal disposition of the supposedly most

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[7] In this context the expression 'rebound' refers to the upregulation of wind power after a curtailment event in a case were more wind generation could have been produced but the market simulation curtailed the generation in order to reach non-negative wholesale price as a market solution.

challenging ramping conditions of the power system and how different resource groups' ramps behave then. However, a comprehensive determination of ramping flexibility needs could not be deducted since the illustrations only provided a narrow sample of the power ramps. Also, the lack of context, such as curtailment information would lead to incomplete quantification of uncontrolled ramping of wind generation that would be supposedly a key causing resource group of ramping flexibility needs.

6.3.2 The resource group interrelations of wind ramps

Correlations in 1h power ramps of resource groups with wind generation help to expose general trends of their behavioral interrelations and thereby form a basis for determining flexibility needs of power ramp management. By plotting different fractions of most correlating resource groups with wind generation's 1h power ramps, the relations can be explored in more detail. A more detailed assessment can be more challenging to draw conclusions from since there are more datapoints than in correlation heatmaps. Thus, in addition to the interrelations, the distribution of wind ramps can also be explored from the duration curves if the other values do not interfere with the wind ramps' curve line. The figures of wind ramp analysis are only presented for the scenario *EV Flex* due to the limited space of the thesis report.

First, the top ten most correlating ramping resource groups with 1h power ramps of wind generation for the entire simulation year are in the scenario *EV Flex* presented in Figure 40.

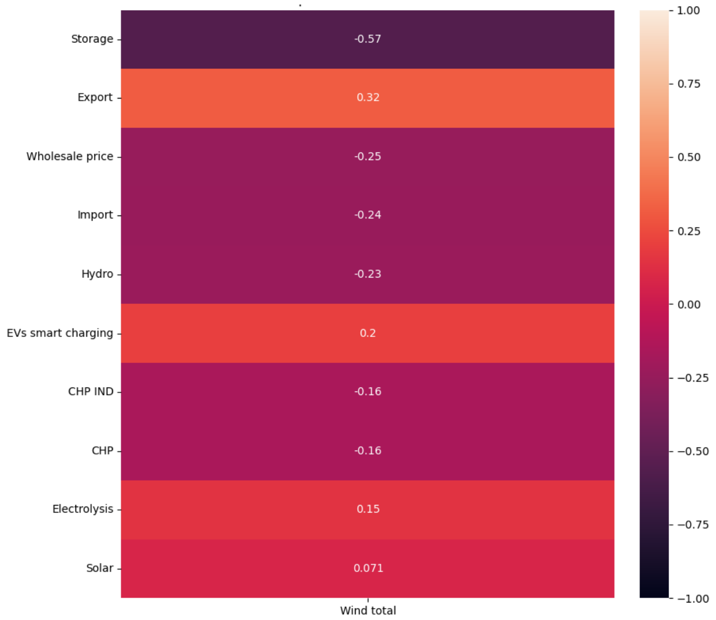

Figure 40: Heatmap of top 10 correlations with wind generation's 1 h power ramps in the scenario *EV Flex*. The figure corresponds to the step 4 in Figure 19.

In the scenario *EV Flex*, storage had a strong negative correlation with wind generation in their 1h power ramps, which suggests a balancing relationship that was also found in the largest wind ramps presented in Section 6.3.1. Export ramps had a weaker but still noticeable positive correlation, which suggests a balancing relationship with wind ramps. The shifts in wholesale price had a noticeable but weak negative correlation with wind ramps, which suggests that the electricity prices rose while wind generation decreased and vice versa. The interrelation is logical due to the large volume of wind generation that has low marginal costs. Import and hydro ramps had the next strongest correlations. The rest of the resources had a gradually decreasing strength of correlations with wind ramps. The weakness of correlations other than BES and export emphasized the balancing role of the top two most correlating resources.

Next, the two most correlating resource groups' ramps in the scenario *EV Flex* are plotted with corresponding hours of the 1h power ramps of wind generation, which was sorted into a duration curve, and presented in Figure 41.

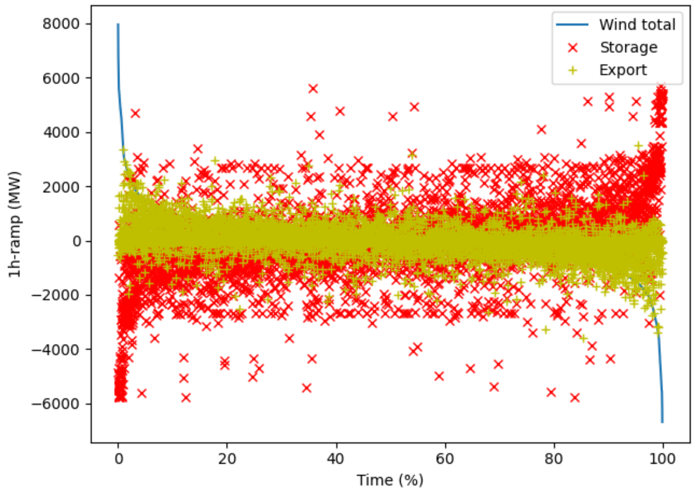

Figure 41: Wind generation's 1h power ramps' duration with corresponding power ramp values of BES and export in the scenario *EV Flex*. The figure corresponds to the step 5 in Figure 19.

In the scenario *EV Flex*, BES had a clear trend of balancing 1h power ramps of wind generation, but some incoherences could be seen. Export did not have as large power ramps as BES, but it had a noticeable interrelation with wind ramps. The distribution of export values was more challenging to comprehend than the ones of BES, which had larger ramp magnitudes. The extremes of wind ramps could be seen, but the middle of the duration curve was covered by the BES and export ramp values' marks.

The top ten most correlating ramping resource groups with 95th percentile of 1h power ramps of wind generation in the scenario *EV Flex* are presented in Figure 42.

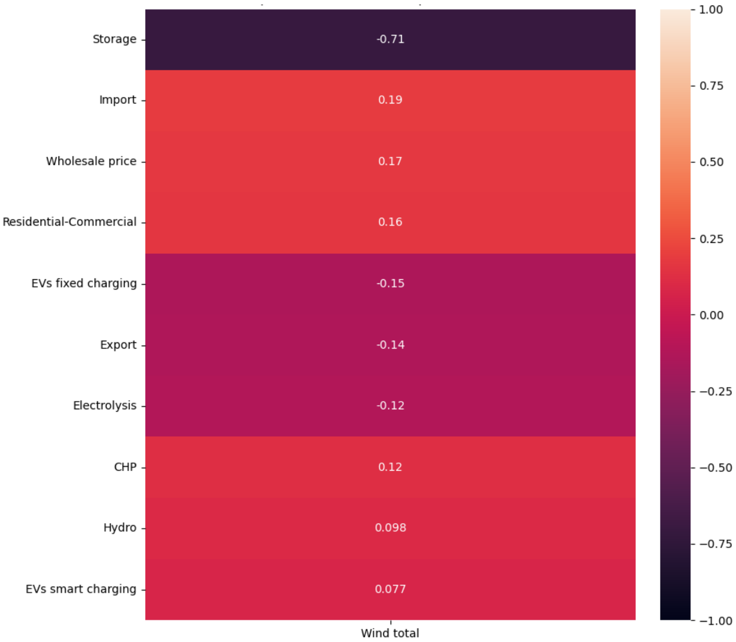

Figure 42: Heatmap of the top 10 correlations with wind generation's 1h power ramps' 95th percentile in the scenario *EV Flex*. The figure corresponds to the step 6 in Figure 19.

In the scenario EV Flex, the 95th percentile of 1h power ramps of wind generation correlated mostly with BES as a balancing relationship. Import ramps had a weak positive correlation with wind ramps, which could suggest a non-balancing relationship or that import ramps could be caused by the same initial factors as wind ramps or divergent factors. The rest of the correlation-wise top ten resource groups have weak correlations with wind ramps that decrease gradually. Similar to the import ramps, export ramps could have a non-balancing relationship with wind ramps because their correlation is negative. Although the correlations are weak, conclusions of the relationships' balancing nature were not clear. The shifts in wholesale price had a weak positive correlation with wind ramps, which is not intuitive in conditions of unconstrained price formation. However, the non-negativity constraint of wholesale price could have limited the price to zero during the curtailment periods. As the prices were to rise again, also the curtailment could have ended up causing upward wind ramps and thus a positive correlation between wind ramps and wholesale price shifts.

Next, the two most correlating resource groups' ramps in the scenario *EV Flex* are plotted with corresponding hours of the of 95th percentile of 1h power ramps of wind generation, which was sorted into a duration curve, and presented in Figure 43.

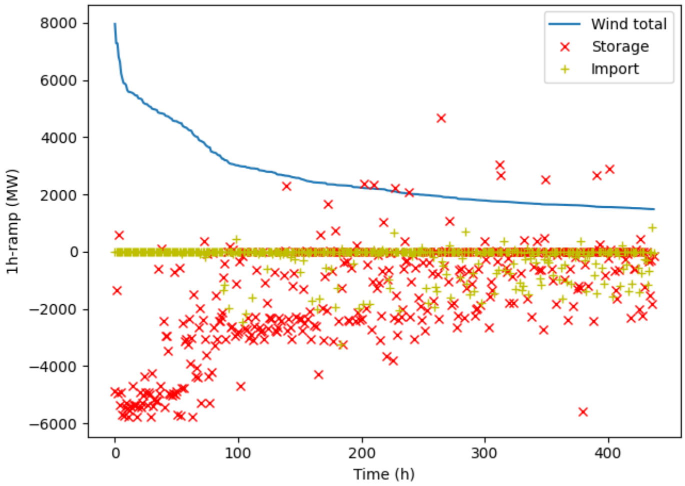

Figure 43: Wind generation's 1h power ramp duration's 95th percentile with corresponding power ramp values of battery storage and system import in the scenario *EV Flex*. The figure corresponds to the step 7 in Figure 19.

In the scenario *EV Flex*, BES was a clear balancer of the wind generation's 1h power ramps' 95th percentile. The general trend of BES is almost symmetrical by the horizontal axis with wind ramps, with few exceptions. Import had mostly a balancing impact even though the correlation was positive. Although, the ramps are relatively low. The unintuitive correlation of import ramps could be caused by their absence during the largest wind ramps, which forms its general slope to resemble the one of wind generation ramps. The absence of import ramps during the largest wind ramps could be caused by an excess of power generation during the largest wind generation that leads to the export rather than the import. The larger the wind generation's magnitude, the more there would be curtailment possibilities that could result in the largest upward wind ramps as curtailment periods end.

The top ten most correlating ramping resource groups with 5% fraction of 1h power ramps of wind generation in the scenario *EV Flex*, are presented in Figure 44.

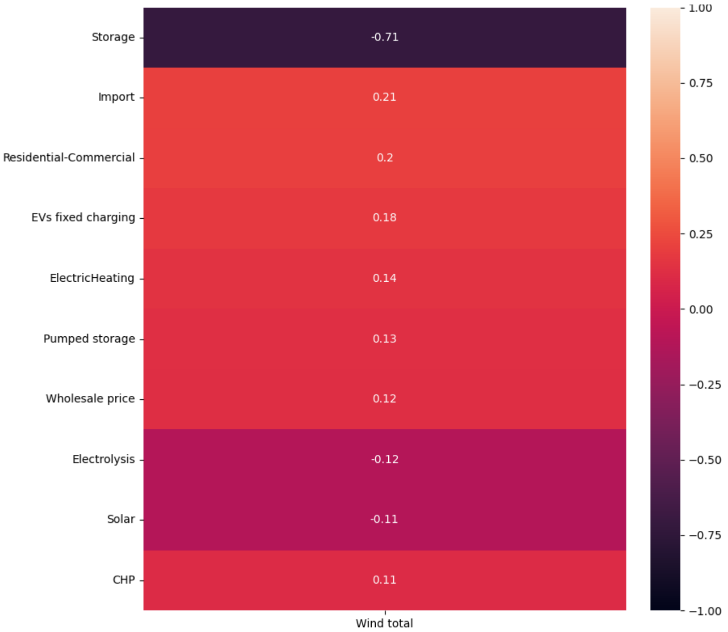

Figure 44: Heatmap of the top 10 correlations with wind generation's 1h power ramps' 5% fraction in the scenario *EV Flex*. The figure corresponds to the step 6 in Figure 19.

In the scenario *EV Flex*, the 5% fraction of 1h power ramps of wind generation correlated mostly with BES as a balancing relationship. Import and residential-commercial had very similar correlation values. The rest of the resource groups had gradually declining correlations. BES had such a big role in balancing the downward wind ramps that there was no clear second resource group in terms of wind ramp correlations. Import ramps had a slightly stronger correlation than residential-commercial ramps. Import ramps had a positive correlation, which suggests that they could have a non-balancing relationship with wind ramps. However, as seen in Figure 42 and Figure 43, a weak correlation of import ramps could mislead the interpretation of their relationship with wind ramps. Compared to the upward wind ramp correlation in Figure 42, the wholesale price shifts had a weaker correlation. The wholesale price shifts also had a positive correlation with wind ramps, which is unintuitive, but could be explained by the constraint dynamics of the wholesale price that can lead to curtailment of wind generation.

Next, the two most correlating resource groups' ramps in the scenario *EV Flex* are plotted with corresponding hours of the 5% fraction of 1h power ramps of wind generation, which was sorted into a duration curve, and presented in Figure 45.

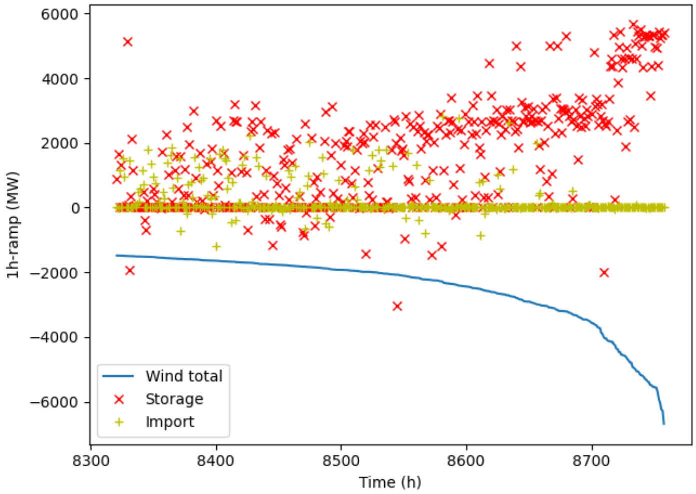

Figure 45: The 5% fraction of wind generation's 1h power ramps' duration with corresponding ramp values of BES and system import in the scenario *EV Flex*. The figure corresponds to the step 7 in Figure 19.

In the scenario *EV Flex*, BES was a clear balancer of 1h wind generation's 5% fraction. Import ramps were not present during the largest downward wind ramps, and they had more balancing than same direction ramps during the rest of the 5% fraction. Thus, the positive correlation of import ramps could again be explained by the absence of import ramps during the largest downward wind ramps rather than a non-balancing relationship.

Overall, BES ramps dominated both the correlations and the balancing of wind ramps in the scenario *EV Flex*. Import ramps were not present in the largest upward and downward wind ramps. The top ten strongest correlations with wind ramps were not necessarily indicating balancing relationships, but the ramp figures showed that the correlations could mislead the interpretations in cases of weak correlations. The effect was present, at least, in the 95th percentile and 5% fraction that had smaller datasets than the entire year. The interpretation of correlations should thus be explored beyond the notion of balancing and non-balancing relationships to avoid false conclusions about the behavioral relationships of energy resources' power ramps. Another finding was the unintuitive correlation of wholesale price shifts with wind ramps' 5% fraction and 95th percentile. This phenomenon should be explored in more detail in future research.

7 Discussion

This part of the thesis discusses the credibility and implications of the quantification results in Section 7.1**Error! Reference source not found.**, the needed development of the 1h power ramp quantification methods in Section 7.2.1, general research and development needs of flexibility in Section 7.2.2, proposed modifications of electricity market modelling in Section 7.2.3, and proposed research related to distributed DSF resources' flexibility potential 7.2.4.

7.1 Results' conclusiveness

The quantification results presented in Section 6 were based on two arbitrary data sets obtained with electricity market simulations that were based on ideal minimization of generation cost without regarding suboptimal behavior of electricity market players. The sets of data were derived for only one weather year representing average weather conditions, limiting wholesale electricity prices to non-negative values, and modelling only the DA electricity market. This straightforward approach was chosen because of the fact that the scope of this thesis was not in the analysis of the market modelling results but developing and analyzing the quantification methods. Thus, the results presented should not be taken as forecasts of future development but rather as arbitrary examples of describing Finnish electrical power system's evolution.

The flexibility needs of power ramp management were not explicitly depicted by the results, but they provided a basis for the prioritization of further analysis and method development. Firstly, the ramps of wind generation would be, in reality, mostly based on the changes in wind conditions at generation sites rather than the exact shifts of power between market periods. However, the power ramps that are based on market period differences of average power can capture some of the general ramping trends that require attention or even possible acquisitions of flexibility in the future. It should be noted that wind generation curtailment was not assessed, which could have exposed some of the wind ramps to be controlled ramping, i.e., curtailment. Although, the curtailment would not have been executed to balance ramping but rather the energy balance of the power system and keeping the wholesale price non-negative.

7.2 Proposed follow up research and development

7.2.1 Aspects related to applicating the 1h power ramp methods

The analyses of two arbitrary data sets provided concrete examples of how the 1h power ramp methods could be applied and which kind of information they could provide about the flexibility need of power ramp management. The two methods introduced in Section 5 could benefit from several modifications that would enhance their results' clarity and interpretability, and they should also be tested with different data sets.

First, the upward and downward regulation logic applied for the top ten hours of wind generation's 1h power ramps in Section 6.3.1, should be applied to the other figures as well, i.e., duration curves, ramp magnitudes, and correlation heat maps. This would unify the power ramp behavior of different energy resources in relation to the electricity grid, which would ease the interpretation of relations between energy resources and their power ramp impacts. Easier interpretability would help to present the results more efficiently and provide a more coherent basis for discussion. An important addition to the figures, i.e., bar plots and duration curves, would be the wholesale price of electricity, which would expose the significance of the price in relation to 1h power ramps. Alternatively, the wholesale price or its hourly shifts could be analyzed similarly to the wind power ramps to find interrelations of energy resources' power ramps and the price.

Several new perspectives could be introduced to the developed methods. Firstly, in addition to the assessment of total wind generation's power ramps, other noteworthy aggregated energy resource groups would be the total IRES generation and the power system's residual load. Assessing their power ramps with this thesis' methods would provide a broader context of the power system's uncontrolled ramping behavior and even the need for ramping flexibility. However, there is a challenge in determining what are the values used for IRES generation and residual load due to possible IRES generation curtailment and DSF. One option would be to separate available IRES generation as one resource group and curtailed generation's as its own imaginary resource group for the power ramp methods' application. Similarly, demand resource groups could be divided into input demand and DSF to better assess the initial power ramps of loads that could require balancing. The residual load could be derived from the combination of the available IRES generation and input demand. It should be noted that both of the divisions would require additional data treatment to be applied to the formed methods of this thesis. However, the advantage of the approach would be the inclusion of curtailment and DSF into the same figures. Another option would be to assess curtailment and DSF information separately from the method analysis, which would require more data acquisition, but less data treatment and running of code. The disadvantage of the approach would be that the information on power ramps, IRES curtailment, and DSF would be located on separate figures.

Secondly, analyzing the temporal distribution of 1h power ramps could provide important knowledge of the temporal disposition of challenging periods of ramping or even ramping flexibility needs. The temporal aggregation of power ramps could be conducted in, e.g., months or hours of the day. Thirdly, the hours of the top ten largest 1h power ramps of wind generation could be examined with snapshots of the power curves in their vicinity to provide more context for the ramping behavior of energy resources and its possible causalities. Fourthly, assessment of the most impactful ramping resources in addition to wind generation, i.e., smart EV charging and BES could expose new interrelations. Also, changing their parametrization with sensitivity analyses of the power ramp method results could reveal, how impactful they are in terms of the power ramp dynamics of the power system.

Finally, the methods should be applied with more extensive sets of simulation data if the target is to gain more comprehensive understanding about the nature of future flexibility needs. Firstly, conducting the power ramp analysis on several different energy resource portfolios could provide more versatile results of the power ramps or highlight the role of certain resource groups in terms of their power ramps' impacts. Secondly, an assessment of multiple simulation years could describe more continuous trajectories of power ramp evolution and provide a dataset for detecting tipping points when the behavior would change remarkably. Thirdly, simulating multiple weather years with the same presumptions would expose variations and more extreme values of power ramps that could help to prepare for more diverse sets of ramping conditions. Lastly, conducting the power ramp methods for different power system areas could expose spatial differences in power ramping that could affect the adequacy of flexibility for location-dependent flexibility needs, such as congestion management.

7.2.2 Other quantification methods for the demand of flexibility

The dispersed research field of flexibility needs and their quantification requires both comprehensive analyses of flexibility needs and detailed method development of singular flexibility needs. A learning outcome of this thesis was that conducting both the systematic evaluation of quantification methods for different flexibility needs and developing a quantification method for a singular flexibility need can be a laborsome set of tasks. Thus, flexibility need classification and quantification method development should be conducted more separately. For instance, the development of a singular flexibility need and its quantification methods should be conducted without mapping all other needs. However, some references of other needs' quantification methods could help the development. In the case of concetrated method development efforts, the research field would benefit from closer collaboration between TSOs and academia and even from an established practice for determining flexibility needs and their representative metrics. As many of the quantification methods are still in incumbent stages, common practices could be challenging to form in the near future, but they should be explored and tested to give a basis for extensive future determinations. The collaboration would also aid the extensive mapping of established methods that could expose gaps in the domain of flexibility needs' quantification and call for research on those deficits. A possible intermediator for the collaboration could be ENTSO-E that has already established EU-wide collaboration between TSOs in various subjects, such as resource adequacy assessment (ENTSO-E, 2020) and sharing knowledge of research, development, and innovation efforts (ENTSO-E, 2022).

A natural continuation for the 1h power ramps' quantification would be to modify the methods for power shifts of longer periods, such as three or eight hours. They could expose challenging periods in terms of power ramps and be connected to power adequacy considerations (ENTSO-E, 2021). The quantification tools, e.g., correlation heatmaps applied to power ramps could possibly be applied to the assessment of transmission needs and, thereby, congestion management flexibility needs.

Overall, the different flexibility needs should be quantified in the same power system conditions to give a basis for methods that assess their frequency and overlapping. Even two flexibility needs' quantification methods could provide sufficient data for the creation and development of such methods. For instance, the methods of this thesis could be applied to the same data sets as in Summanen's congestion management flexibility need assessment (Summanen, 2021) to compare the occurrence of two different flexibility needs. These methods could be combined with the assessment of flexibility resources providing the flexibility in the simulations. Thereby, the flexibility resources' impacts could be assessed more comprehensively.

7.2.3 Electricity market modelling modifications

The electricity market modelling could be modified to yield more representative results of power system behavior and to provide more suitable data for quantification methods of different flexibility needs. Sensitivity analyses of the modifications' impacts should be conducted to assess if they change the simulation outcomes significantly. The sensitivity analyses could be executed by analysing the simulation outcomes of singular modification with the same methods, such as the ones developed in this thesis. The resulting differences of modifications should be reflected in the additional labor required by the modifications to determine if the modifications are worthwhile to put more effort into.

Firstly, modelling other electricity market places than DA markets, i.e., reserve and ID markets, would enable more suitable datasets for assessing imbalance management and system reliability flexibility needs. This modification would require the determination of imbalance probabilities of different energy resource groups that could be deducted from historical data. A useful reference for the modelling of different market places and imbalances is the technical report from Elia (Elia, 2019).

Secondly, the shortening of the market period length from one hour to fifteen minutes would increase the electricity market simulations' resemblance under future power system conditions after implementating the NBM (Nordic Balancing Model, 2022) introduced in Section 2.3.2. Two approaches could be taken to test the higher temporal resolution. One option would be to simulate the power system with the same input data for both resolutions and analyze if it has a significant impact on the power system behavior, e.g. in terms of 1h power ramps. Another approach would entail more detailed weather data and electricity demand profiles that could result in very different flexibility quantification results than the original presumptions. It should be noted that increasing the temporal resolution of electricity market simulations' input data would require the acquisition of new data and more computational effort. Thus, sensitivity analyses of changes should be conducted thoroughly to avoid unnecessary labor.

Thirdly, several modifications could be enforced to the parametrization of distributed DSF resources to examine their role in both their behavior and broader system impacts, such as 1h power ramp dynamics. One re-parametrization could be made by either limiting the maximum power of some loads, such as smart EV charging, or simulating distribution tariffs of loads, such as electric heating. These modifications would give an indication of how other drivers of DSF than minimization of electric energy costs change their behavior. Another approach would be to variate demand profiles of DSF resources more with randomized variations and multiple cyclic frequencies, such as weekday-specific and seasonal variations. These modifications would make the simulation more detailed and thereby possibly reveal a more versatile range of power system dynamics, such as 1h power ramps. However, the modifications would not necessarily be more representative of future behavior, and they would require more effort in data acquisition, formation of presumptions, computation of simulations, and the interpretation of quantification results.

7.2.4 Distributed DSF resources' flexibility potential

As discussed in Section 3.3, the flexibility potential of distributed DSF resources and their evolution could have both positive and negative impacts on the electrical power system. Thus, it is important to research the evolution from different perspectives. Also, the benefits of flexibility participation should be communicated more to enhance, e.g. the commercial potential of distributed DSF resources.

Firstly, the flexibility potential should be assessed more based on resource types or industry fields to better detect the drivers and barriers to their flexibility's utilization. For instance, greenhouses were researched specifically to expose their flexibility potential in the reserve markets of Fingrid, and now they have become established flexibility resources in the electricity markets (Fingrid Oyj, 2019). Another valuable approach would be to assess the implications of energy policy and energy business model design on the DSF participation (Kubli;Loock;& Wüstenhagen, 2018).

Secondly, the results acquired from the quantification of flexibility needs should be communicated clearly to incentivize investments into technologies that provide flexibility, such as smart control devices. Also, the analyses of the financial benefits of flexibility should be conducted and informed to the owners of DER. For instance, Forsman, et al. provided estimations of average energy cost savings of flexible EV charging compared to inflexible EV charging (Forsman, et al., 2021). The other two important research topics are the value chain analysis and the emission reduction potential of DSF that would, respectively, emphasize the financial and environmental benefits of flexibility participation and thus accelerate the growth of commercial flexibility potential.

Thirdly, topical events and phenomena should be analyzed to validate the factors described in Section 3.2 and better estimate short-term developments of the flexibility potential of distributed DSF resources. For instance, at the time, record high DA wholesale market prices in Finland and the Nordics in the fourth quarter of 2021 (Statistics Finland, 2022) could have significantly impacted the flexibility potential evolution. One hypothesis could be that high electricity prices would have incentivized flexibility participation. Alternatively, high prices could have resulted in the replacement of spot-based retail contracts with fixed retail pricing to avoid risks. Other topical events, such as the Russian invasion of Ukraine in 2022 (Mišík, 2022) led to a suspension of electricity imports from Russia to Finland (Fingrid Oyj, 2022) and a suspension of natural gas imports from Russia to Finland (Gasum Oy, 2022). These events will probably cascade to electricity prices and hence affect the flexibility potential of distributed DSF resources.

8 Conclusions

The background for this thesis was that climate change mitigation efforts include an energy transition that shapes the electrical power systems by, e.g. replacing flexible fuel-based generation with IRES generation and introducing a high number of new electrical loads, such as electric vehicle chargers and electrical heating. The changes challenge the basic principles of electrical power systems' operation and their demand for flexibility. Thus, analyses of both energy resources providing flexibility and the needs for flexibility in different trajectories of power system evolution are needed. Quantification methods for flexibility needs are the key enablers of interpreting the impacts of different future developments, e.g. energy resource portfolio changes, on an electrical power system.

The first key literature finding was that flexibility could be defined in various ways, but a consistent definition was derived to support the scope of this thesis. Another finding was that flexibility needs have dispersed classifications that can be encapsulated in five need categories as follows: frequency management, energy balance management, resource adequacy, power transfer management, and non-frequency ancillary services. Each of the categories consisted of one or more flexibility needs. The existing quantification methods for the flexibility needs had a varying degree of applicability for electricity market simulation data. It should be noted that some of the flexibility need quantification methods, such as resource adequacy assessment, were already very well established.

When it comes to the flexibility potential of distributed DSF resources, it had sparse estimates of future evolution in the literature. However, the factors that affect its future evolution were mapped successfully, revealing many important barriers, such as too long payback times of smart control device investments and broad value chains, and drivers, such as predictable flexibility needs, requirements, and design of flexibility markets. The importance of flexibility needs' predictability highlighted the demand for flexibility needs' quantification. Also, the possible outcomes of different developments of theoretical, technical, and commercial flexibility potential layers were presented, which emphasized the importance of researching the concept of flexibility potential.

The results from the first introduced method, i.e., the system-level approach to 1h power ramps, showed that the methods could determine the most significant resource categories and resource groups in terms of the power ramps of electricity market simulations' electrical power systems and expose differences between simulation scenarios formed with a singular diverging presumption, i.e., EV charging logic. The illustrations of the method lacked information to quantify ramping flexibility needs individually, but could be observed together to concentrate further development of the quantification. Wind generation's 1h power ramps were analyzed in the second introduced method. The results of the method showed that singular resource groups ramps and their interrelations can indicate their role as ramping flexibility causing or balancing resources, but the illustrations were found to be misleading individually at times. Also, the illustrations did not manage to fully quantify the flexibility needs of power ramp management.

Due to the simplicity of the electricity market simulations and their presumptions, the results of the 1h power ramp quantification methods should not be taken as forecasts of the future Finnish power system's behavior, but rather as examples of how its power ramp management flexibility needs could be quantified and analyzed. The results also lacked some possibly critical information on IRES generation curtailment that should be considered in future analyses. To reach more definitive results of power system behavior and power ramp management flexibility needs, greater number of datasets should be used.

The proposed follow-up research and development could be classified into four categories. Firstly, the developed 1h power ramp quantification methods would benefit from the unification of the signs of ramp values and the inclusion of curtailment and DSF information. Secondly, other quantification methods require more extensive mapping of TSOs flexibility needs and separate development of singular flexibility needs' quantification methodology. The research field would benefit from an increased level of collaboration and standardization. Thirdly, the electricity market modelling could be modified by both systematic changes, such as adding different marketplaces and higher temporal resolution into the simulations, and more detailed re-parametrizations of energy resources, such as introducing electricity distribution constraints and more variations to demand profiles. It is imperative to analyze the impacts of the proposed changes in order to prove their usefulness compared to the additional effort they require. Fourthly, the flexibility potential of distributed DSF should be researched more from the stand-points of resource types and industrial sectors, and the impacts of regulatory changes should also be assessed. In addition to increased communication of future flexibility needs, the financial benefits of flexibility participation should also be explored and addressed. Finally, topical events, such as the increase of wholesale electricity prices of DA markets that affects distributed DSF resources' flexibility potential, should be examined closely to test, do the proposed factors of flexibility potential evolution tally.

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A. Appendix Description of Interviews

This appendix consists of interviews' scope and general description of the interviewees. Ten interviews were conducted via online video calls. Interviewees were company representatives that have experience with distributed DSF resources. The pool of companies included market players that provide smart control devices and software for electricity consumers and players that provide flexibility services of aggregated flexibility resources. Some of the companies had both roles.

The general scope of the interviews was on the distributed DSF resources, their flexibility potential, and key factors affecting the potential development. Each interviewee chose the scope of flexibility resources discussed from the distributed DSF resource domain. Mainly chosen scopes focused on buildings and their flexibility resources such as electric heating, EV charging, and utilization of on-site PV generation. EV charging was chosen as a discussed resource group by one interviewee. Another interviewee focused on energy storages, UPSs, data centers, and reserve power generators. Also, one interviewee decided to discuss distributed DSF resources on a general level.

List of questions

- Which flexibility resources are discussed?
- Have you formed any scenarios for their flexibility potential?
- What is the most important flexibility need for flexibility resource owners?
- Do resources participate in flexibility activity more based on electricity price or external signals in the future?
- Which factors accelerate the growth of flexibility potential in general?
    - Which factors could paralyze the growth?
- Which factors contribute to the growth of technical potential?
    - Which are the hindering factors?
- Which factors contribute to the growth of commercial potential?
    - Which are the hindering factors?
- Are there remarkable differences in the investment and market environments between Finland and other countries?
- What could Fingrid do to enhance the utilization of the distributed DSF resources? Could Fingrid generate and communicate useful information to enhance the development?

B. Appendix Deriving an EV charging profile

Pareshi, et al. conducted a study of how well simulations of EV charging match empirical data. They provided figures of empirical charging data that was utilized in the parametrization of inflexible EV charging in this thesis's electricity market simulations. The profiles presented by Pareshi, et al. were derived from The North East's "Switch EV" electric vehicle trial conducted in the United Kingdom, which was described in (Neaimeh, ym., 2015). The EV charging profiles derived from the figures of Pareschi, et al. are presented for three charging place types: *Home* in Figure 46, *Public* in Figure 47, and *Work* in Figure 48. (Pareschi;Küng;Georges;& Boulouchos, 2020)

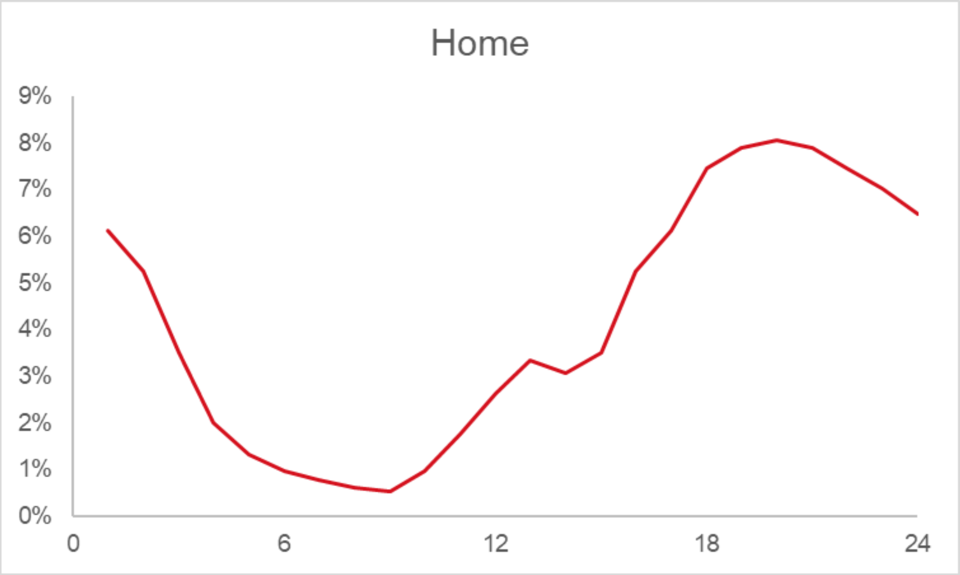

Figure 46: EV charging profile at place type *Home*. Own illustration based on (Pareschi;Küng;Georges;& Boulouchos, 2020).

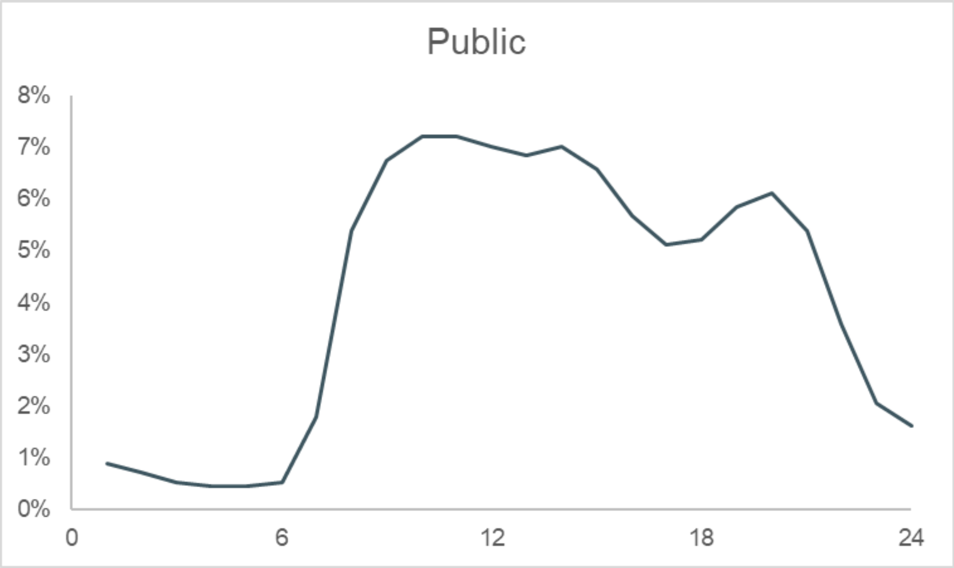

Figure 47: EV charging profile at place type *Public*. Own illustration based on (Pareschi;Küng;Georges;& Boulouchos, 2020)

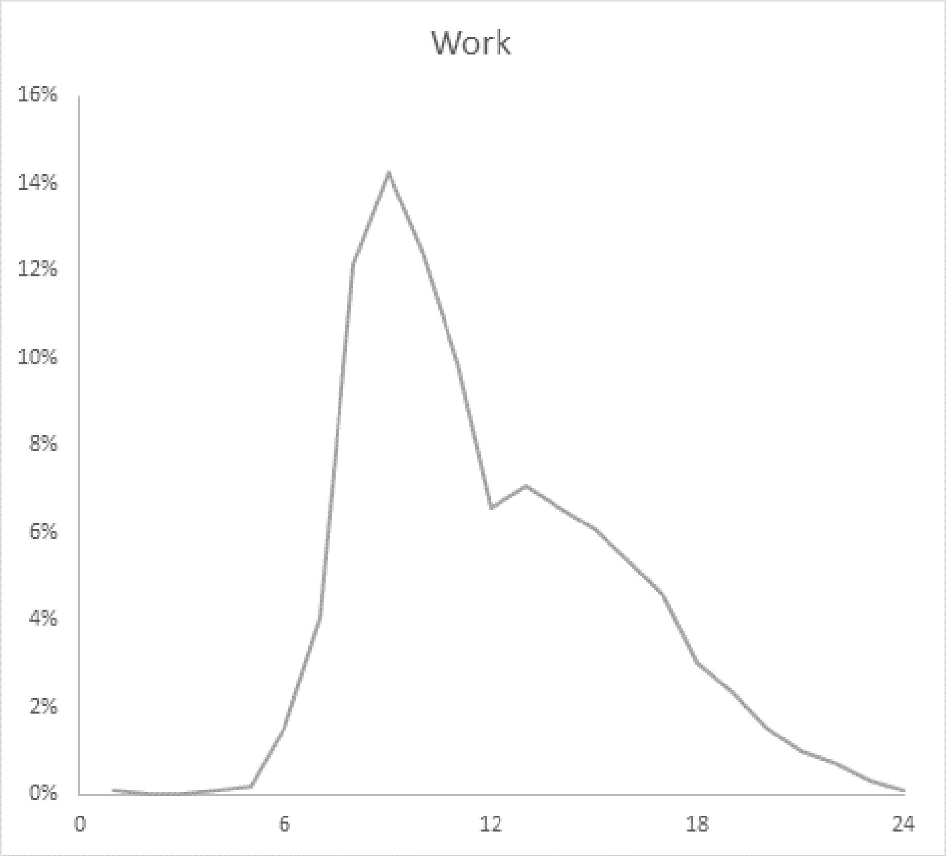

Figure 48: EV charging profile at place type *Work*. Own illustration based on (Pareschi;Küng;Georges;& Boulouchos, 2020).

When the profiles were combined in equal proportions, the total charging profile was retrieved. The average charging profile of EVs and the place type profiles are presented in Figure 49.

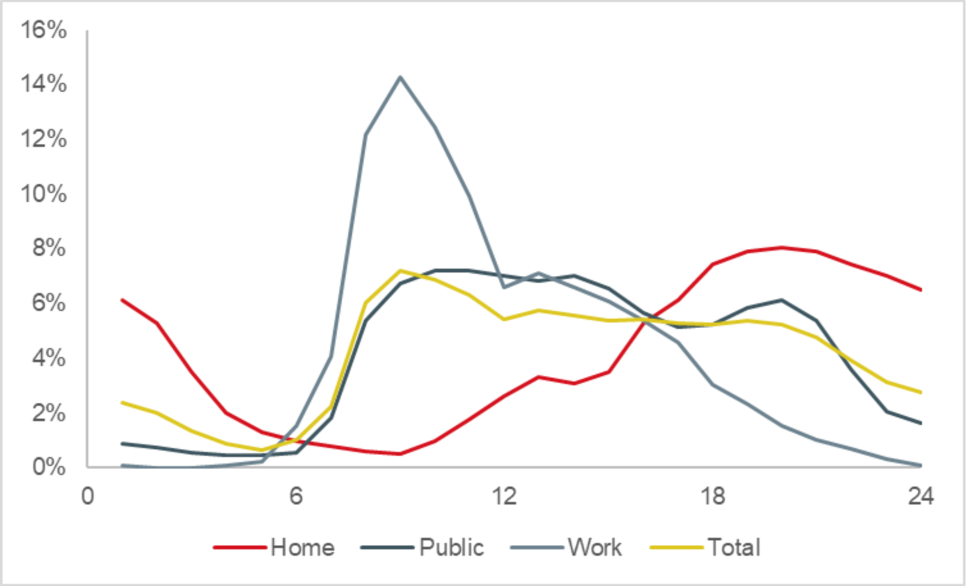

Figure 49: Total charging profile of EVs with place type profiles. Own illustration based on (Pareschi;Küng;Georges;& Boulouchos, 2020).

The charging profiles were weighed with the factors 0.65 for *Home*, 0.1 for *Public*, and 0.25 for *Work*. The weighing was based on the assumption that most of the smart chargers are located in *Public* and *Work* place types, and thus the inflexible charging profile would mostly follow the profile of place type *Home*. It should be noted that the public charging of EVs could also be inflexible due to the need for fast charging during short stops of mobility. The weighed total profile of EV charging is presented in Figure 50.

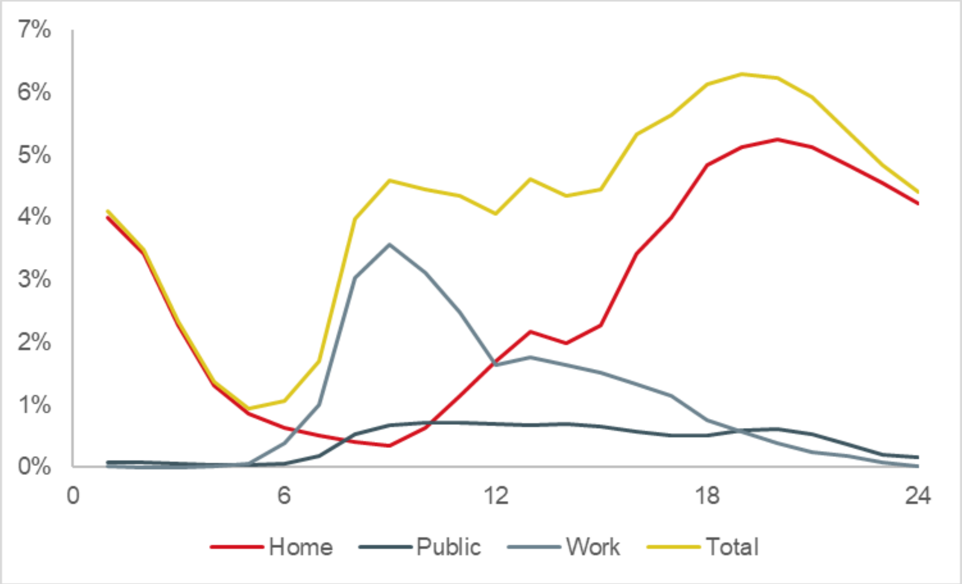

Figure 50: Total charging pforile of EVs based on weighed place type profiles. Own illustration based on (Pareschi;Küng;Georges;& Boulouchos, 2020).

The weighed profile was chosen for the electricity market simulations as a parameter for inflexible EV charging. It should be noted that the goal of the charging profile formation was not for it to be as realistic as possible but rather to have a fixed charging profile that varies hourly and is based on assumptions.

C. Appendix Flexibility need metrics

This section consists of the found metrics that describe different TSO flexibility needs. The flexibility needs, their metrics and the references of the metric definitions are presented in Table 5.

Table 5: TSO flexibility needs, their representative metrics, and references for the metric definitions.

NEED	METRIC	REFERENCES
POWER RAMP MANAGEMENT	1hour net or residual load ramps	(ENTSO-E, 2021), (Loutan;Zhou;& Motley, 2019), (EirGrid, 2021), (North American Electric Reliability Corporation, 2018), (Heggarty;Bourmaud;Girard;& Kariniotakis, 2020),
	Insufficient ramping resource expectation (IRRE)	(Lannoye;Flynn;& O'Malley, 2012)
	Expected Unserved Ramping	-
STABILITY MANAGEMENT	System inertia	(North American Electric Reliability Corporation, 2018), (EirGrid, 2021), (Ørum, ym., 2018), (Ørum, ym., 2018)
	N-1 inertia	(North American Electric Reliability Corporation, 2018), (EirGrid, 2021), (Ørum, ym., 2018), (Ørum, ym., 2018)
	N-1 RoCoF	(North American Electric Reliability Corporation, 2018), (EirGrid, 2021), (Ørum, ym., 2018), (Ørum, ym., 2018)
	Synchoronous inertial response (SIR)	(North American Electric Reliability Corporation, 2018),
	N-1 Frequency drop level	(North American Electric Reliability Corporation, 2018),
	Frequency response performance	(North American Electric Reliability Corporation, 2018),
	N-1 Frequency drop time	(North American Electric Reliability Corporation, 2018),

	N-1 fault frequency deviation magnitude	(North American Electric Reliability Corporation, 2018), (Elia, 2019)
SYSTEM RELIABILITY	N-0 expected power deviations	(North American Electric Reliability Corporation, 2018), (Elia, 2019)
	Average number of unexpected outage events	(Elia, 2019)
	N-1 fault probability/duration	(Elia, 2019)
	Reserve requirements	(EirGrid, 2021)
	Reserve margin	(North American Electric Reliability Corporation, 2018),
	Energy balancing flexibility needs	(Heggarty;Bourmaud;Girard;& Kariniotakis, 2020)
ELECTRICITY TRADING	-	-
IMBALANCE MANAGEMENT	Residual load	(ENTSO-E, 2021), (Heggarty;Bourmaud;Girard;& Kariniotakis, 2020)
	DA-ID forecast error	(Elia, 2019)
	ID-real-time forecast error	(Elia, 2019)
RESOURCE ADEQUACY	Expected energy not served (EENS)	(ENTSO-E, 2021), (ENTSO-E, 2020)
	Expected unserved energy (EUE)	(North American Electric Reliability Corporation, 2018),
	Loss of load hours (LOLH)	(North American Electric Reliability Corporation, 2018),
	Loss of load expected (LOLE)	(ENTSO-E, 2021) , (ENTSO-E, 2020)
	Loss of load duration (LLD)	(ENTSO-E, 2021), (ENTSO-E, 2020)
	3hour residual load ramps	(ENTSO-E, 2021), California ISO, (EirGrid, 2021), (North American Electric Reliability Corporation, 2018),

	8hour power ramps	(ENTSO-E, 2021), (EirGrid, 2021)
	Curtailed surplus energy during 95-percentile	(ENTSO-E, 2021)
	Forced outage rate/duration	(ENTSO-E, 2021), (Elia, 2019)
FLOW RAMP MANAGEMENT	Ramping constraints of HVDC inter-connectors	-
CONGESTION MANAGEMENT	Transmission capacity	-
	Transmission needs	-
	Congestion	-
VOLTAGE & REACTIVE POWER MANAGEMENT	N-0 voltage limit violations	-
	N-1 voltage limit violations	-
	Reactive power need	(EirGrid, 2021)
	N-1 post transient voltage limit violations	
	Power angle	
BLACK START CAPABILITY	Required black start capacity	(EirGrid, 2021)
SHORT-CIRCUIT POWER ADEQUACY	Short-circuit power adequacy	-