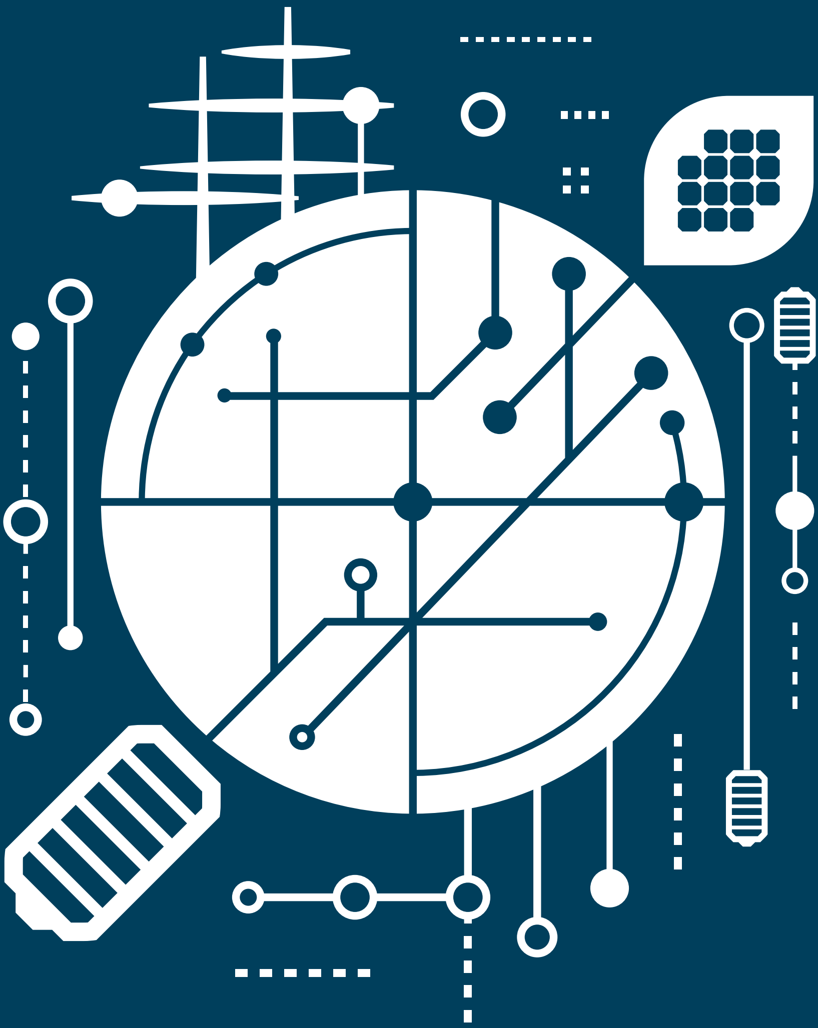
Master's Thesis Sustainable Energy Technology

The Effects of the Distribution of Energy Storage Systems in Dutch Low-Voltage Grids

J.B.J. Kienhuis



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Faculty of Electrical Engineering, Mathematics and Computer Science (EEMCS)

Master Graduation Assignment for the Master's Programme
Sustainable Energy Technology

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Abstract

Grid congestion is an ever-growing problem in the Netherlands. Rising energy prices and growing climate ambitions are accelerating the electrification of heating, transportation and industrial processes. This increased electricity demand, coupled with the integration of more and more intermittent renewable energy sources (RES) causes synchronized peak loads and grid congestion issues forcing system operators to reinforce the grid. However, the demand for electricity transport capacity outpaces these grid reinforcement efforts, hindering the construction of essential infrastructure, RES integration and electrification of industry. Energy storage systems (ESSs) could reduce the need for grid reinforcement, but the effects of ESS distribution remain unclear.

This thesis investigates the impact of ESS distribution on Dutch low-voltage grids and their reinforcement requirements. Various scenarios with different siting and sizing of ESSs, controlled to reduce grid stress, were simulated in both consumption-dominated and generation-dominated cases. Furthermore, the thesis assesses the different placement and ownership scenarios of ESSs from the perspective of energy justice.

For almost all placement and sizing scenarios, simulations show that ESSs reduce voltage deviation, line loading and transformer loading, reducing the need for cable and transformer reinforcements to varying extents. ESSs placed near prosumer households show superior overall results. ESSs also offer the ability to match electricity production and consumption which is not offered by traditional grid reinforcement.

Beyond the technical aspects, socio-economic analysis shows that without ESS, the financial burden of grid upgrades would fall on all users, potentially leading to an unfair distribution of costs. Home-ESS, especially when financed by overproducers of photovoltaic (PV) energy, can distribute costs more fairly. Phasing out the Dutch net-metering policy could encourage prosumers to invest in home-ESS to enhance self-consumption.

Samenvatting

Netcongestie is een steeds groter wordend probleem in Nederland. Stijgende energieprijzen en groeiende klimaatambities versnellen de elektrificatie van verwarming, transport en industrie. De toenemende vraag naar elektriciteit en de integratie van steeds meer variërende hernieuwbare energieopwekking veroorzaken piekbelastingen op het stroomnet. Netbeheerders proberen het net beter bestand te maken tegen deze piekbelasting door het net te verzwaren. Echter groeit de vraag naar transportcapaciteit sneller dan de mate waarin netbeheerders het net kunnen verzwaren, waardoor verduurzamingsprojecten en bouwprojecten voor essentiële infrastructuur op een wachtlijst komen te staan. Energie opslagsystemen (ESS's) zouden de behoefte aan netversterking kunnen reduceren maar de effecten van de verdeling van deze opslagsystemen zijn nog onduidelijk.

Deze scriptie onderzoekt de impact van de verdeling van ESS's op Nederlandse laagspanningsnetten en het effect op de behoefte aan meer transportcapaciteit op deze netten. Verschillende scenario's met variërende verdelingen van ESS's, aangestuurd met het doel om netbelasting te reduceren, werden gesimuleerd in zowel consumptie-gedomineerde als opwek-gedomineerde scenario's. Daarnaast worden de verschillende verspreidings- en eigendomsscenario's beschouwd vanuit een socio-economisch perspectief.

De resultaten laten zien dat ESS's spanningsafwijkingen, kabelbelasting en transformatorbelasting in verschillende mate kunnen afzwakken en daarmee vraag voor netverzwaring kunnen verminderen. Daarnaast bieden ESS's ook de mogelijkheid om opwek en consumptie op elkaar af te stemmen. Iets dat traditionele netverzwaring niet kan bieden. Thuisbatterijen, vooral wanneer die bij huishoudens met zonnepanelen worden geplaatst, laten de meest gunstige resultaten zien.

Naast de technische aspecten laat de socio-economische beschouwing zien dat, zonder de uitrol van ESS's, de financiële lasten van netverzwaring bij alle net-gebruikers komen te liggen. Dit kan leiden tot een onrechtvaardige verdeling van de kosten. Thuisbatterijen, vooral wanneer deze gefinancierd worden door prosumenten met zonnepanelen, kunnen zorgen voor een rechtvaardigere verdeling van de kosten. Afschaffing van de Nederlandse salderingsregeling zou deze prosumenten kunnen aansporen hun zelf-consumptie te vergroten met een thuisbatterij en zo bij te dragen aan een rechtvaardige verdeling van de kosten van netverzwaring.

Dankwoord

Bijna zeven jaar geleden begon voor mij een spannende maar vooral ontzettend fijne periode als student aan de UT. Na een intensieve zes maanden komt er met deze scriptie nu een einde aan mijn studententijd.

Graag maak ik van deze gelegenheid gebruik om mijn dank uit te spreken aan de mensen die mij gedurende dit traject hebben ondersteund en geholpen. Allereerst wil ik mijn dagelijkse begeleiders, Gerwin Hoogsteen en Edmund Schaefer, hartelijk bedanken voor de deskundige begeleiding, waardevolle feedback en interessante discussies tijdens het afgelopen half jaar. Jullie kennis en inzicht hebben een onmisbare bijdrage geleverd aan de totstandkoming van deze scriptie. Ik waardeer de tijd en moeite die jullie staken in het begeleiden en (tussentijds) lezen van mijn stukken.

Ook gaat mijn dank uit naar mijn huisgenoten met wie ik veel productieve (en late) uren heb mogen doorbrengen in onze heuse *kantoortuin*. Menig woord in deze scriptie is in jullie gezelschap door het toetsenbord gegaan. Om maar niet te spreken over de mooie discussies tijdens onze rondjes wandelen. Dank voor het (willen) aanhoren van mijn tirades over de energiesector.

Daarnaast wil ik mijn ouders, zusje en vriendin bedanken voor hun onvoorwaardelijke steun en geduld tijdens mijn gehele studie.

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Veel leesplezier.

Jim

Contents

1

Introduction

Grid congestion is an ever-growing problem in the Netherlands. Rising energy prices and growing climate ambitions are accelerating the transition towards the electrification of heating and transportation. Currently, the Netherlands has 500,000 electric vehicle (EV) charging stations, a number projected to grow to 2 million by 2030 [52]. Also, (industrial) companies are rapidly electrifying and need more and larger power capacity connections to the electricity grid. These developments not only increase the average electricity demand but also increase the risks of synchronised peak loads when many grid users consume a lot of electricity simultaneously [4].

As the integration of intermittent renewable energy sources (RES) progresses, electricity will be increasingly generated by fluctuating energy sources such as photovoltaic (PV) and wind energy [78]. The mismatch between (peak) loads and intermittent (peak) generation could lead to capacity and congestion problems in distribution grids [26] such as over-/under-voltage deviations [76], light flickering [10], cable and transformer overloading [49] and phase and voltage imbalance due to single-phase generation (such as PV) or single phase electric loads [3, 38].

Currently, distribution system operators (DSOs) are addressing these issues by enhancing the grid's transport capacity through the addition of cables and replacement of transformers, a process known as grid reinforcement. However, the increase in demand for transport capacity is outpacing the rate at which network operators can expand the grid. This lag is slowing down construction projects of housing and crucial infrastructure such as schools and hospitals [52]. Also, the lack of transport capacity slows down the energy transition as new RES projects can not be connected to the grid and companies that need a bigger connection for electrification are put on a waiting list. Therefore, alternative solutions, such as energy storage systems (ESSs) and intelligent load control for EVs, should be explored.

1.1 Problem Statement

According to Netbeheer Nederland, the Dutch grid operators plan to invest over 8 billion euros per year to reinforce the grid from 2025 [51, 53]. This involves installing over 100,000 kilometres of (underground) cables and the construction of new transformer stations equivalent to 800 football pitches in urban areas [51]. Although it is beyond dispute that the electricity grid will be reinforced [51, 53], it is not necessarily clear if it needs to be reinforced as much as DSOs are advocating for, when considering other flexibility options such as ESSs.

Additionally, the effects of the distribution of ESSs remain unclear. Specifically, the effects of spreading out ESSs over houses compared to more centralized storage solutions (e.g., neighbourhood batteries) need to be examined. Furthermore, questions about the ownership of ESSs and how the costs and benefits are distributed across different layers of society are still unanswered. How the ESSs are physically distributed and who owns these storage systems, whether it be private companies, local communities, or the DSOs, can significantly affect the accessibility, affordability and acceptance of these technologies. The effects of deploying ESS distribution on the division of costs and benefits need to be evaluated to assess the effects of ESS deployment on energy justice.

1.2 Research Questions

The main research question directly addresses the core problem of determining how different configurations of ESS placement and sizing (distribution) affect the Dutch low-voltage grids:

What is the impact of the distribution of electricity storage systems in Dutch low-voltage grids?

To answer this main research question, several specific sub-questions need to be addressed. The first sub-question contributes to the main research question by establishing an understanding of the Dutch low-voltage grids as a foundation for further analysis.

1: What are the characteristics and topology of Dutch low-voltage grids?

The second sub-question involves reviewing related work on optimization techniques for ESS placement and sizing. It also aims to adapt and apply these findings to the context of Dutch low-voltage grids to identify any general trends in the optimal position and size of ESSs in grids.

2: How can ESS placement and sizing be optimized?

The third sub-question examines the impacts of ESS distribution on grid reinforcement. It discusses how different ESS placements and sizes could influence the requirements for grid reinforcement based on the findings of the simulations of this thesis.

3: What are the effects of the distribution of ESSs on grid reinforcement?

The fourth sub-question addresses the broader impacts of ESS distribution on society. It includes a discussion on energy justice and how the costs and benefits of ESSs could be fairly shared. By examining socio-economic effects, this research aims to provide a broader view of the implications of ESS distribution, contributing to the main research question.

4: What are the socio-economic effects of ESS distribution in Dutch low-voltage grids?

1.3 Approach and Thesis Outline

This thesis addresses the research questions through a structured approach. First, to answer the first sub-question, a literature study will establish the characteristics and topology of Dutch low-voltage grids, providing insights into their operational and topology characteristics in Chapter 2. This chapter will also cover the background of congestion-related problems in low-voltage grids and the necessary background for modelling power flow in electricity grids.

Also in Chapter 2, (section 2.4), this thesis will discuss related work on the role of ESSs in low voltage grids and optimization methodologies for ESS placement and sizing to answer the second sub-question.

The core of this thesis is a Python-based simulation model of a low-voltage grid that allows for simulating ESS behaviour and its effects on the grid. This model will simulate two ESS control methods, evaluate different placement scenarios and analyze diverse load cases to assess how ESS distribution impacts the grid and its reinforcement needs. The working of the model and the methodology for the simulations are covered in Chapter 3. The simulation scenarios and the results of these simulations will be evaluated in Chapter 4. Also, the effects of the ESS distribution on grid reinforcement based on the simulations are discussed in this chapter.

The socio-economic effects and the effects of ESS distribution on energy justice are covered in Chapter 5 by observing literature on energy justice in smart grid pilots in the Netherlands and combining these observations with the results from Chapter 4. Finally, the main research question is answered by synthesising the answers to the sub-questions in Chapter 6 together with the recommendations for future work.

2

Background

This chapter provides an examination of the fundamental aspects of electricity grids, with an emphasis on their structure, operational principles and regulatory framework in the Netherlands. It covers the hierarchical levels of the grid, the roles and responsibilities of grid operators and the network structures that ensure efficient and reliable electricity distribution. Furthermore, this chapter addresses the causes and effects of grid congestion in Dutch low-voltage grids and presents potential solutions to mitigate these issues. Various types of ESSs are analyzed and the concept of load flow analysis is introduced. Additionally, this chapter features related work, providing an evaluation of relevant existing research in the field of ESSs in Dutch electricity grids and ESS placement and sizing optimization.

2.1 The Electricity Grid

Electricity grids have been the backbone of modern civilization for over a century. The main purpose of electricity grids is to electrical energy from generators to consumers in a reliable and (cost)efficient manner. Security of supply is considered essential as a constant supply is of great social importance [59]. Although absolute security of supply is impossible due to unforeseen failure of equipment or human error, an acceptable level of grid security in established by incorporating sufficient reserves, despite the additional costs involved [59].

According to the Dutch electricity law, the term *grid* refers to one or more connections for the transmission of electricity and the associated equipment, excluding the connections and equipment that are located within the installation of a producer or consumer [57] [57]. In the Netherlands, as in many other countries, the electricity grid is structured into hierarchical levels, each designed to handle different voltage levels and fulfil different roles. This hierarchical approach ensures that electricity is transported efficiently across various distances, from national and international transmission lines to local distribution networks that serve homes and commercial activities. To cope with this wide range of transportation, the Dutch electricity grid comprises four hierarchical levels: The synchronous grid, the transmission grid, the regional distribution grid and the local distribution grid [59]. Figure 2.1 shows a schematic of the voltage levels with types of connected generators and consumers.

The basic design of these levels is determined by the amount of electricity and the distance over which it has to be transported [68]. A higher voltage level allows for the transportation of the same power with less current and therefore fewer losses. On the other hand, higher voltage levels require larger equipment and more safety precautions making it impractical and unsafe to operate very high voltages in the built environment. The larger the distance and the amount of power that needs to be transported, the higher the voltage level. Vice versa, the closer to the end consumer of the electricity, the lower the voltage levels.

The majority of electricity transportation happens through synchronous and transmission grids. The Dutch electricity system has multiple connections with Germany, Belgium, the United Kingdom, Denmark and Norway to allow for international energy exchange and enhance system reliability [75].

The distribution grid distributes electricity from the higher voltage levels to consumers [59]. The voltage levels are transformed towards the desired level for consumption. Traditionally, the distribution grid was a ‘one-way road’ that distributed electricity from central generation facilities to consumers. Today, decentralised generation by wind turbines, combined heat and power (CHP) and PV can now lead to electricity being fed back into the distribution network, resulting in a bi-directional distribution network [59].

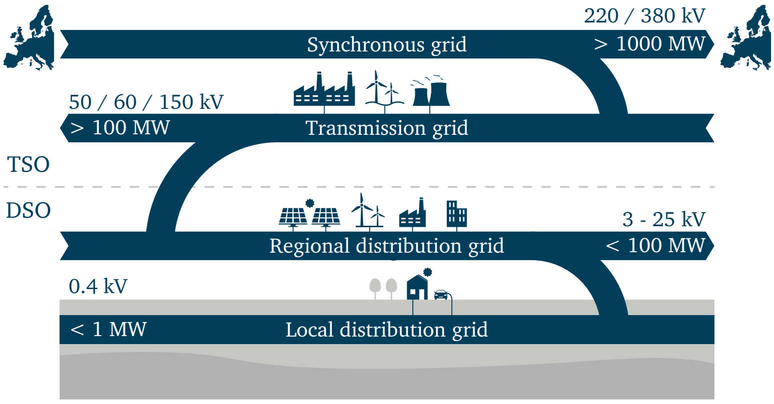

Fig. 2.1.: Overview of the hierarchical levels of the electricity grid (adapted from [59, 33]).

2.1.1 System Operators

System operators, or grid operators are responsible for managing and maintaining the electricity grid. Their role in the energy system has evolved over the years. The Dutch electricity market was liberalized in 1998 with the introduction of the Electricity Act [75]. The act aimed to give individual electricity consumers and suppliers more freedom in buying and selling electricity while ensuring reliability, sustainability and efficiency in the market. To handle the act, a new entity called TenneT was created to manage and maintain the high-voltage (HV) grid (220 kV and 380 kV). Later, in 2008, the Dutch government decided to separate the distribution of electricity from commercial activities completely. Grid operators could no longer be part of a holding with a commercial interest in the energy sector such as production or supply [56]. With this separation, the Netherlands needed a new entity that owns and operates the low-voltage (LV) (<1 kV) and medium-voltage (MV) grids (<50 kV): the DSO.

Today, the Dutch transmission and distribution networks are operated by one transmission system operator (TSO) and six DSOs respectively. The TSO, TenneT, is owned by the Dutch state and is responsible for managing, maintaining, exploiting and constructing the high-voltage transmission grid (≥50kV) [30]. TenneT also has the final responsibility for the balance between generation and consumption of electricity on the grid. Together with other (connected) European TSOs, they cooperate to harmonise the European electricity markets, provide international system balance and the prevention of congestion in the Netherlands [30].

2.1.2 The Role of the Distribution System Operator

DSOs are owned by (local) governments and commit to serving the public interest [50]. The DSOs are responsible for managing, maintaining, exploiting and constructing the distribution grid (<50kV) with a focus on safety and preventing failures/interruptions (transport security) [30, 50, 19]. DSOs are obliged by law to offer a connection to any producer or consumer that requests access to the electricity grid and must ensure non-discriminatory access to the grid. Also, it is the DSO's responsibility to measure the consumption of (small) consumers and report this to electricity suppliers and the TSO. Also, the logging, management and exchanging of data for market players fall under the responsibility of the DSOs [50].

The non-discriminatory principle works well when there is sufficient capacity, but in cases of grid congestion, it can lead to undesirable societal outcomes [5]. Grid connections for crucial infrastructure such as schools or hospitals must wait in the same line as infrastructure that is considered less critical. Also, parties that, for example, can contribute to mitigating congestion problems may then have to wait for grid access. Therefore, as of 2023, the Netherlands Authority for Consumers and Markets (ACM) allows grid operators to prioritize projects that solve or mitigate congestion issues. Additionally, ACM aims to allow prioritization of other projects with a societal function, such as housing construction, security services, healthcare or schools. This means that in congestion-affected areas, grid operators may deviate from the non-discriminatory principle of 'first come, first served' when granting a connection to the grid. If grid operators can justify the need for prioritization, the ACM will not penalize them for exceeding their regulatory bounds [5].

As natural monopolies, DSOs have their tariffs overseen and regulated by the ACM. Each of the six DSOs is responsible for managing one or more distribution grids within the Dutch system. Also, the performance of the DSOs is subject to evaluation by the ACM [54]. This regulation focuses on setting maximum tariffs for DSOs and ensuring the quality of services provided to network users. It aims to prevent excessive tariffs while also encouraging operators to operate as efficiently as possible. Targets for tariffs and quality are set through a so-called 'yardstick regulation', meaning that targets are based on the average performance of all DSOs and their revenues are influenced by their deviation from the group average [54].

2.1.3 Network Structures

Apart from the different voltage levels discussed in section 2.1, different levels within the grid hierarchy have different structural characteristics too [68]. The structures can be distinguished in 'single-point feeding' and 'multiple-point feeding'. A single-point feeding network can have three layouts: radial, looped and multi-looped. The three layouts are shown in Figure 2.2. As visualised in Figure 2.2b and Figure 2.2c, the looped and multi-looped grids are equipped with switches that allow the grid operator to create openings in the grid. These openings allow the grid operator to operate a (multi)looped network as a radial network. In case a failure occurs in one of the feeders of the radial network, switches can be opened and closed strategically to change the configuration of the network, bypassing the failure. This option makes a (multi)looped network more reliable than a radial network. However, the added cables, switches and increased complexity of operation make them more costly.

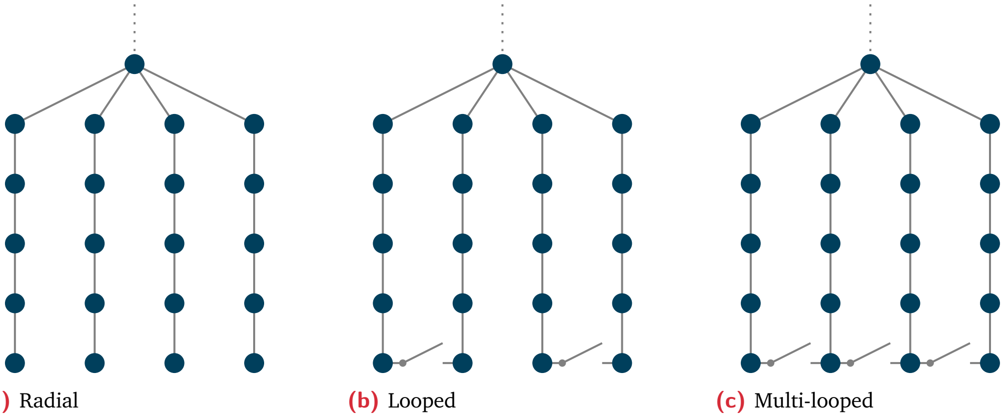
(a) Radial **(b)** Looped **(c)** Multi-looped

Fig. 2.2.: Schematic illustrations of a radial, looped and multi-looped grid (adapted from [68]).

2.1.4 Dutch Low-Voltage Grids

Although the overall structure of electricity as presented in section 2.1 is roughly the same all over the world, details might differ per country or even per region (e.g. urban versus rural).

In Europe, single-phase loads are connected to one of the three phases of the three-phase grid. Uneven distribution of the loads between phases can cause an imbalance between the phases. It is therefore that DSOs are aiming to evenly spread new grid connections over the phases [40]. Unlike this European structure, United States distribution grids for example have three-phase primary feeders and single-phase branches that cover a specific zone [60]. Because of this, phase imbalance in the US is mainly caused by the design of the grid's layout and not by the distribution of loads along a feeder [40]. As a result, the same grid-related problems (voltage imbalance in this case) might have a completely different cause and therefore a completely different solution in another country.

The typical European LV grid is a radial network that consists of one MV/LV transformer with several three-phase cables (feeders) spanning from the secondary side of the transformer to the final consumer connected to that feeder [25]. Also, a typical European LV network can be seen as an alternating current (AC), three-phase, four-wire system [37]. Figure 2.3 shows a schematic of a three-phase, four-wire feeder.

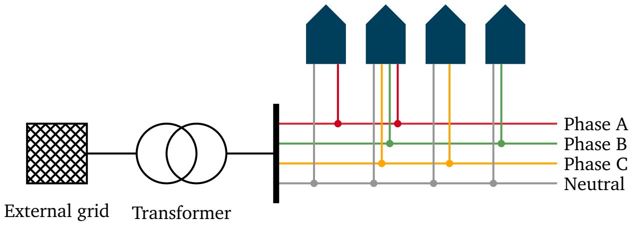

Fig. 2.3.: Schematic of a three-phase low-voltage feeder with connected houses. The second house from the left has a three-phase connection.

2.1.5 Power Quality in Low-Voltage Grids

As discussed in section 2.1, the grid consists of connections for the transmission of electricity, excluding the connections and equipment that are located within the installation of a producer or consumer. Whereas the grid belongs to the grid operator, it is directly connected to the equipment of the grid user via a connection point. This connection point is the interface between the system of the grid operator with the system of the grid user, leading to a mutual influence between the grid and the grid user. Short circuits or sudden peaks in demand on the consumer side can lead to disruptions within the grid and, vice versa, fluctuations as a result of short circuits or switching actions caused by the grid operator can influence the functioning of the connected party's equipment. It is therefore important that grid operators and grid users agree upon the same grid requirements regarding design and operation. In the Netherlands, this is stated in the *Netcode*. The Netcode contains regulations regarding the functioning of the grid, the connection of (new) grid users and the transportation of electricity through the grid [6].

The term *power quality* is used to define how well the power characteristics meet the system requirements. It includes various factors related to the voltage, frequency and waveform of the electricity that is supplied. Common power quality issues are [59, 55]:

Long-term Voltage Drops or Swells

According to the Netcode, the voltage in grids up to 35kV, the 10-minute average of the voltage must be within U_{nom} ± for 95% of the time during a week. Furthermore, the 10-minute average of the voltage must always be within U_{nom} + 10% and U_{nom} - 15%. For low voltage grids, $U_{nom} = 230$V.

Voltage Dips

A voltage dip is a sudden drop in the voltage level between 1% and 90% of the nominal voltage level.

Flicker

Flicker refers to repetitive voltage variations that cause annoying flickering of lighting. These voltage variations can be less than 10% from the nominal voltage.

Unbalanced Phases

In an ideal situation, all three phases of a three-phase system have the same voltage amplitude with a 120-degree phase shift. If the phases are not loaded evenly, phases become asymmetric and unbalanced.

Harmonic Distortion

In an ideal situation, the voltage and current waveforms are sinusoidal at a single fundamental frequency of 50Hz. However, nonlinear loads draw current in a non-sinusoidal manner and can introduce harmonic currents into the grid, causing harmonic distortion.

Other than ensuring power characteristics meet the system requirements, grid operators must also prevent the overloading of grid equipment. Cables, for example, have a maximum loading which is the maximum current that can flow through a cable continuously without it being damaged. It depends on the heat generation within the cable and its ability to dissipate this heat to the environment [59]. Also, transformers have a maximum loading which is the maximum apparent power (in VA) that the transformer can handle. Overloading transformers can lead to undesirable voltage drops, insulation issues and reduced efficiency. Also, the overloading of transformers and cables increases the probability of the sudden failure of these assets, decreasing the overall reliability of the grid.

2.1.6 Voltage Regulation

As discussed in section 2.1.5, voltage levels in low voltage grids must be always lower than 253V (230 + 10%), always higher than 196V (230 - 15%) and higher than 207V (230 - 10%) during 95% of the time. Grid operators have various techniques to keep voltage levels between these limits. Voltage variations on the higher-level HV grid can be large. However, thanks to the voltage regulation capabilities of the HV/MV transformer, the influence of these voltage fluctuations on lower levels is smaller [59]. Still, voltage variations in the distribution exist depending on the amount of transported power, the components in the network, the current network configuration and the margin in the HV/MV transformer regulation [59].

Despite the voltage regulation activities of the grid operator, there will always be voltage loss across the impedance of a loaded cable in the grid, leading to inevitable voltage drops or swells along a feeder. The extent of the voltage drop depends on the cable's impedance and the amount of power flowing through it. As shown in Equation 2.1, the voltage drop over a line can be expressed in the active power P and reactive power Q transported over that line and impedance R and reactance X of that line.

$$\Delta V = \left|\underline{V_2} - \underline{V_1}\right| \cong \frac{R \cdot P + X \cdot Q}{V_1} \tag{2.1}$$

From Equation 2.1, it is clear that the influence that the values of P and Q have on the voltage drop depends on the values of R and X. Or, to be more precise, the ratio between R and X, known as the R/X ratio.

Tab. 2.1.: Typical X/R ratio values for different types of lines in high voltage, medium voltage and low voltage grids [59].

Voltage-level	Type	R/X	Main influence
High-voltage	Aerial line	< 0.5	Q
Medium-voltage	Cable $> 150\text{mm}^2$	0.5 ... 2	P and Q
Medium-voltage	Cable $\leq 150\text{mm}^2$	> 2	P
Low-voltage	Low voltage cable	> 2	P

Table 2.1 shows typical R/X ratio values for different types of grid levels. It can be seen that for a high-voltage transmission line, X is larger than R and therefore Q is of greater influence on the voltage drop than P. For low voltage grids, however, R is larger than X and thus P has a greater influence on the voltage drop than Q.

2.1.7 Grid Congestion

As briefly covered in Chapter 1, grid congestion is becoming an ever-growing problem in the Netherlands. At the time of the design and construction of the current distribution grids, grid operators did not anticipate the extensive electrification of transportation and heating.

Also, the deployment of decentralised intermittent generation by renewable energy sources (mainly PV and wind power) can overload the grid during synchronised generation. Grid congestion occurs when the DSO expects that the future load on the electricity grid will exceed or is likely to exceed the capacity of the grid. This is when the power quality and grid asset loading requirements discussed in the previous section can no longer be guaranteed by the DSO. As a result, plans such as the construction of schools, houses and hospitals may be put on hold. Also, grid congestion can hinder sustainability efforts in a wide range of sectors. For instance, residential heating can not be electrified and new residential areas can not be connected to the electricity grid. Congestion can be due to either 'Levering Door Netbeheerder' (supply by grid operator) to the end-user (LDN congestion) or 'Opname Door de Netbeheerder' (intake by grid operator) (ODN congestion) [30].

LDN congestion can occur during times when, for instance, too many EVs are being charged at the same time or when many heat pumps are operating simultaneously in winter. Figure 2.5 shows the rapid increase of EVs in the Netherlands from 2019 to 2023. When LDN congestion occurs, the grid operator will not allow new (high-consumption) connections. ODN congestion can occur when large amounts of electricity are being fed into the grid by PV or wind power assets during periods of high irradiation or wind. Figure 2.4 shows the increase in total installed PV installations on households in the Netherlands from 2019 to 2023. When ODN congestion occurs, households, for example, cannot export their generated electricity to the grid, resulting in (economic) losses for PV asset owners. The degree of losses for households with PV installations depends on multiple factors, such as the location of the household's connection to the feeder, PV penetration in the neighbourhood, the capacity of the grid and the type of inverter (active or passive) [30]. Households at the end of the feeder (further from the transformer) encounter issues with feeding solar power into the grid more often. Especially rural areas or older grids suffer from congestion problems caused by PV generation [30].

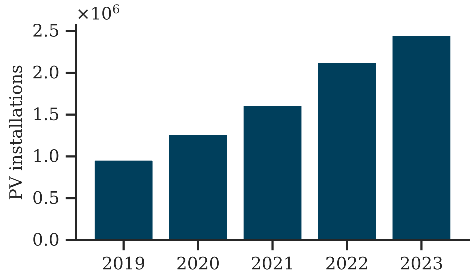

Fig. 2.4.: The number of PV installations on houses in the Netherlands from 2019 to 2023 [13].

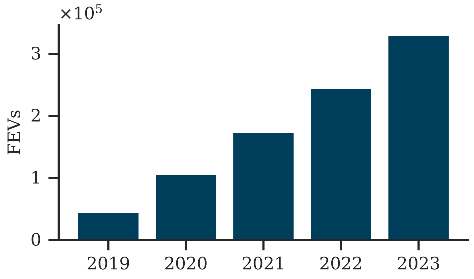

Fig. 2.5.: The number of fully electricity vehicles (FEVs) in the Netherlands from 2019 to 2023 [12].

The grid has traditionally been designed to transport electricity from central generation locations (large power plants) to end-users (e.g. households in neighbourhoods). This implies that all electricity flows outwards from the substations or transformers toward the end of the feeders [69]. When decentralised generation is connected directly to the distribution grid, the assumption that the distribution grid is a one-way system with the substation as the only power source no longer holds true [69]. The issue with this so-called reverse power flow is that it has undesirable interactions with the voltage regulation techniques discussed in section 2.1.6. Under the assumption that a low-voltage feeder is a one-way connection, the current can be measured at the regulator terminal and the downstream voltage drop along the line can be calculated. The voltage at the transformer can be adjusted to compensate and ensure an acceptable voltage profile over the feeder. Suppose a generator (e.g. PV installation) injects a significant current into the feeder just after the regulator terminal. In that case, the PV will also feed the loads downstream and mask this current for the regulator. This leads to inadequate voltage regulation by the tap-changing transformer which can result in a too-large voltage drop over the feeder [41]. When a significant amount of current is injected into the end of the feeder, this can lead to an undesirable voltage rise over the feeder. The reverse current injected at the end now creates a voltage over the impedance of the feeder that adds up to the voltage set by the regulator at the beginning of the feeder [41].

Grid congestion can be prevented or mitigated in multiple ways. In this thesis, flexible demand, optimizing the existing grid, grid reinforcement and storage solutions are discussed.

Flexible supply and demand

Flexible demand can be used to reduce demand peaks by spreading the load on the grid over time. Reducing peaks can have several advantages such as reducing grid losses improving power quality and reducing the need for peak generation [23]. The total amount of energy supplied by the electricity grid may remain the same through the use of flexible demand, but it is more evenly distributed throughout the day. Additionally, RES can be ‘curtailed’ to reduce the stress on the grid. Curtailment refers to the reduction in output of renewable energy sources, such as wind or solar power, that occurs when their production exceeds the grid’s capacity to transport it or when demand is too low.

Improved utilization of the existing grid

Grid operators generally maintain wide margins to accommodate unforeseen spikes in consumption or generation [30]. To free up more capacity for connections, the grid operator can explore whether the existing network can safely handle heavier loads. The grid components can be deliberately subjected to heavier loads if research indicates that this is a safe and effective solution. For example, dynamic line rating (DLR) can be used to free up more transport capacity on the grid. As discussed in section 2.1.5, the capacity of a cable depends on the heat generation within the cable and its ability to dissipate this heat to the environment. The ability to dissipate heat to the environment, however, depends on weather conditions such as (ground) temperature or windspeed (for aerial lines). DLR revers to continuously assessing the capacity of the equipment in real-time instead of using a static capacity that is based on the worst case [32].

Grid reinforcement

The most straightforward solution is to upgrade the existing network, for example, by installing new cables or larger transformers with more capacity. According to DSO Liander, this is the preferred solution for the long term, especially where congestion problems are significant [30]. Over the past three years, grid operators have doubled their investments. In the coming years, there will be even more investment in cables, stations and high-voltage lines to further expand the capacity of the electricity grid. The total investments for all grid operators are expected to reach €8 billion per year in the coming years [53].

Storage

ESSs can be used to solve congestion problems caused by decentralised generation and peak demand. As the focus of this thesis is on storage in distribution grids, ESS in low-voltage Grids are discussed in more detail in the next section.

2.2 ESSs in Distribution Grids

By installing a (battery) ESS in the power grid, congestion problems caused by decentralized renewable generation and peak demand *could* be reduced. The most common version of this solution is a home ESS system [79]. However, also community batteries or neighbourhood batteries exist. The definitions of a home ESS and a neighbourhood ESS are adapted from [11].

2.2.1 Home ESS

The home ESS is an ESS typically installed in households or small businesses. Home batteries are placed behind the electricity meter meaning they are part of the electricity system of the building where it is placed and share the connection to the grid with the other devices in that household. A home ESS can be used for various purposes: storing excess solar electricity, trading on energy markets or reducing peak load on the electricity grid.

Depending on the regulations, storing excess solar electricity can reduce energy costs for the household, as less energy needs to be purchased from the energy supplier. In addition, consumers with a dynamic energy contract (where electricity prices fluctuate throughout the day) can purchase electricity during low-price periods and store it, so that electricity does not have to be purchased during periods with higher prices. It should be mentioned that these objectives can conflict. Multiple home batteries in a neighbourhood that react on the same price signal, for example, can increase the stress on the grid: When many households neighborhood have a home ESS, they might all attempt to charge or discharge their ESSs simultaneously based on the same dynamic energy prices that are based on (inter)national electricity supply and demand. For example, if the electricity price drops significantly, all these ESSs may start charging simultaneously to take advantage of the low prices. Vice versa, if the price rises, they might all discharge their stored energy simultaneously to avoid buying expensive electricity. This simultaneous action can lead to a sudden increase in electricity demand (when charging) or a sudden increase in electricity supply (when discharging), which puts additional stress on the local electricity grid.

2.2.2 Community ESS

A community ESS is an ESS system primarily designed and controlled to create local benefits such as storing solar energy or mitigating local grid congestion problems. A community ESS is a 'stand-alone' system, meaning that it does not share its connection to the grid with other installations or users. In other words, the community ESS has its own connection with its own electricity meter. This is in contrast to a home ESS, which is connected behind the electricity meter as part of a building's electricity system and shares the grid connection with all other appliances in the building.

2.3 Power Flow Analysis

Power flow analysis (or load flow analysis) plays an important role in the planning and operation of power systems. It aims to evaluate the network's state during normal operation and exceptional situations, such as failure and maintenance scenarios. Voltages, currents and power distribution are calculated iteratively during the load flow analysis process to give insight into the steady-state behaviour of the power system [68]. In this thesis, load flow analysis is used to calculate currents and voltages in a grid to simulate and compare the behaviour of ESS distributions.

For a load flow analysis, an electricity grid is modelled as a network of buses (or nodes/vertices) in set $\mathscr{N}$ and lines (or branches/edges) in set $\mathscr{E}$. Each bus represents a point in the network where elements, such as generators or loads are connected. A line, or multiple lines, connects a bus with other buses in the network.

Four variables are associated with each bus: active power, reactive power voltage phasor magnitude and voltage phasor angle. For a given bus, two of these four variables are known while the other two unknowns are obtained by solving the system equations iteratively until convergence is achieved. Which parameters are known or unknown depends on the type of bus. Within load flow analysis, three types of buses can be distinguished: slack buses, PQ buses and PV buses.

Slack bus

Voltage magnitudes and angles must always be expressed relative to something else. The slack bus (or swing bus/reference bus) serves as the reference for the rest of the system such that voltages and angles can be calculated relative to the slack bus. Also, the slack bus ensures power balance by absorbing a surplus and supplying shortages of electricity (including grid losses). A network model under power flow analysis must contain at least one slack bus. Usually, the largest generator in the system is modelled as the slack bus. For LV grid, the transformer is usually modded as the slack bus [29].

PQ bus

A PQ bus, or load bus, is a bus with specified active and reactive power. Despite the name, a load bus can be used for representing both load and generator elements in a grid model [29]. As RES and ESS in a distribution grid must be synchronised to the grid voltage at the bus they are connected to, RES and ESS are often represented by PQ buses in load flow calculations.

PV bus

PV buses (or generator buses) have a specified active power and root-mean-square (RMS) output voltage magnitude. Usually, synchronous generators are represented by PV buses [29]. Note that, in this context, PV refers to 'Power Voltage' and not 'photovoltaic' as in prior sections of this thesis. Table 2.2 shows the three types of buses with their known and unknown parameters.

The unknown variables are obtained by using the standard power flow equations as given in Equation 2.2 and Equation 2.3. Here, i and j represent bus numbers within a system with n buses and P_i, Q_i, $|V_i|$, δ_i, Y_{ij} and θ_{ij} represent active power, reactive power, bus voltage magnitude, voltage angle, line admittance magnitude and impedance angle respectively.

Tab. 2.2.: Types of buses in a load flow analysis and corresponding known and unknown parameters.

Bus types	Known	Unknown
Slack bus	$\lvert V_i\rvert$, δ_i	P_i, Q_i
PQ	P_i, Q_i	$\lvert V_i\rvert$, δ_i
PV	P_i, $\lvert V_i\rvert$	Q_i, δ_i

$$P_i = \sum_{j=1}^{n} |V_i| \left|V_j\right| \left|Y_{ij}\right| \cos(\theta_{ij} - \delta_i + \delta_j) \tag{2.2}$$

$$Q_i = -\sum_{j=1}^{n} |V_i| \left|V_j\right| \left|Y_{ij}\right| \sin(\theta_{ij} - \delta_i + \delta_j) \tag{2.3}$$

The nonlinear power flow equations are linearized around an initial guess of the voltage magnitudes and phase angles at each node. Numerical methods, such as the Gauss-Seidel method or Newton-Raphson method are commonly used to solve these equations iteratively until a solution converges. The linearization step involves computing the Jacobian matrix $\mathbf{J}$ that contains the partial derivatives of the power flow equations with respect to the voltage magnitudes and phase angles as shown in Equation 2.4.

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \underbrace{\begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V} \end{bmatrix}}_{\mathbf{J}} \cdot \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} \tag{2.4}$$

For PV buses, only partial derivatives $\frac{\partial P}{\partial \delta}$ and $\frac{\partial Q}{\partial \delta}$ are calculated [67]. For a PQ bus, partial derivatives $\frac{\partial P}{\partial \delta}$, $\frac{\partial P}{\partial V}$, $\frac{\partial Q}{\partial \delta}$ and $\frac{\partial Q}{\partial V}$ are calculated for each iteration. Thus, for a network with only PQ buses, as in this thesis: $\mathbf{J} \in \mathbb{R}^{2n \times 2n}$.

2.3.1 Notation

In AC grids, voltage is represented as a sinusoidal wave that varies over time. This voltage can be described using two key components: magnitude $|V|$ and angle δ. The magnitude is the peak value or amplitude of the voltage wave. It represents the maximum voltage level reached during each cycle or, in other words, the length of the voltage vector in the complex plane.

Angle δ, also known as the phase angle indicates the position of the voltage wave relative to a reference point in time. The phase angle is measured in degrees or radians and shows how much the wave is shifted horizontally. Together, the magnitude and angle provide a complete description of the AC voltage at any given moment. This is often represented using phasor notation, where the voltage is depicted as a vector in a complex plane, with the length of the vector representing the magnitude and the angle representing the phase.

Per unit [p.u.] values are a normalized system of measurement used to express electrical quantities such as voltage, current, power and impedance. The per-unit system expresses quantities as fractions of a defined base or reference value. Essentially, a per unit value is the ratio of a given quantity to its base value. For example, in a system with a base value $U_{nom} = 230$ V, a voltage value of 253 V is presented as $\frac{253V}{230V} = 1.1$ p.u.. Per-unit values are used for modelling voltage magnitudes in this thesis. In this thesis $U_{nom} = 230$ V so 230 V = 1.0 p.u..

2.4 Related Work

As discussed in section 2.1.7, increasing integration of renewable energy sources, particularly PV systems and increasing EV adoption pose significant challenges to the stability and efficiency of low-voltage grids. To address these challenges, extensive research has been conducted on various energy storage solutions and their impacts on grid performance. This section covers the related work on the role of ESS in (congestion-constrained) low-voltage grids. Additionally, related work on the optimization of siting and sizing of ESS is discussed.

2.4.1 The Role of ESS in Low-Voltage Grids

In [27], the implications of increased EV charging on low-voltage grids are discussed and the potential of using battery storage as a temporary solution during periods of grid reinforcement is examined. One of the primary issues identified is voltage sag, caused by EV charging, particularly with single-phase or two-phase charging systems that create voltage imbalance. The research indicates that traditional grid reinforcement is a lengthy process, whereas battery storage systems can be deployed to manage these issues temporarily. Battery storage can help maintain grid stability and allow for continued EV charging without immediate grid expansion. The positioning of the battery within the grid, whether at individual households or a central location, significantly impacts the required power capacity.

Some studies go beyond seeing ESS as a temporary solution and instead view it as a permanent asset in modern grids. For example, [66] discusses the potential of energy storage systems to increase grid flexibility when charging an EV fleet, showing that when deploying ESS, the required microgrid's external grid connection can be reduced to up to 85%. Positioning ESSs as a permanent component in (micro)grids rather than just a temporary measure during grid reinforcement.

The operational and economic benefits of decentralized home storage systems versus centralized large-scale battery storage systems in low-voltage grids with high PV penetration were investigated in [84]. The study finds that centralized (e.g. neighbourhood-level) storage systems offer superior operational efficiency and economic viability compared to decentralized (home-level) systems. Centralized systems can use aggregated load profiles for better predictability and efficiency, resulting in lower financial losses and higher grid stability. These systems also provide significant advantages in voltage regulation due to optimal placement within the grid, unlike decentralized systems, which are less predictable and harder to manage. However, the current regulatory and economic frameworks are not favourable to large-scale systems, necessitating further research into viable business models and regulatory adjustments to fully realize the potential of neighbourhood batteries.

Authors address the challenge of voltage unbalance caused by high PV penetration in low-voltage networks in [15]. They propose using ESS to mitigate these imbalances. The study shows that ESS can effectively balance the voltage by storing excess energy during peak solar generation times and releasing it during low generation periods. This not only improves voltage stability but also enhances the overall reliability of the grid. The implementation of ESS in PV-rich areas is shown to significantly reduce the occurrence of voltage sags and swells.

In [80], the focus is on the use of community batteries to mitigate congestion in low-voltage power grids. The focus of the paper is on the design principles and control strategies for community battery deployment. Experiments show that community batteries can significantly reduce grid congestion by storing surplus energy during low-demand periods and supplying it during high-demand times. This approach not only helps in balancing the load but also improves voltage stability and reduces the need for grid reinforcements. The study underscores the importance of strategic placement and intelligent control of community batteries to maximize their benefits.

The potential of different flexibility options for managing congestion in distribution networks was investigated in [20]. The paper evaluates various technologies, including battery storage, to determine their effectiveness in mitigating grid congestion. The findings indicate that battery storage, in particular, offers significant benefits due to its ability to provide immediate and reliable flexibility. The study also discusses the economic implications of deploying these technologies and suggests that a combination of flexibility options is necessary to address the diverse challenges faced by modern distribution grids.

Lastly, in [36], the economic and operational value of storage devices in distribution networks constrained by congestion are investigated. The study analyses the impact of deploying storage devices at strategic locations within the network to manage load flow and reduce congestion. The results demonstrate that storage devices can effectively mitigate congestion, improve load balancing and enhance overall grid reliability. The paper also highlights the cost-benefit analysis of storage deployment. However, since the paper is from 2004, this cost-benefit analysis is considered outdated.

2.4.2 Optimizing ESS Siting and Sizing

Various methodologies have been proposed in the literature to determine the optimal placement and sizing of ESS within distribution grids. In general, ESS placement optimization problems can be solved analytically, mathematically and by using (meta)heuristics [81, 1, 62, 8].

Analytical Methods

For an analytical approach, no specific mathematical programming is involved [87]. Instead, an objective function is determined and predefined sets of variables that meet system constraints are tested against their objective value. The set that yields the most satisfactory results is chosen as the optimal solution [81]. Analytical approaches are suitable for providing accurate results very quickly for small and simple systems [17] but are not suitable for larger complex systems [62].

Several papers used analytical methods for cost-benefit analysis on only ESS sizing for voltage support to minimize grid costs [83, 82, 39]. In [24], a sensitivity analysis was used to optimize ESS size and placement to minimize the total storage size and line losses in a randomly generated radial network. In [70], a similar sensitivity analysis is performed to identify the most sensitive buses to power injections or withdrawals. This analysis helps in determining promising bus locations for large-scale energy storage or demand response to reduce grid congestion. The results highlight the buses that show the highest sensitivity to power injections or withdrawals, thereby suggesting optimal locations for ESS.

Mathematical Methods

In a mathematical approach, numerical methods are used to find the optimal solution for the optimisation problem. The advantage of a mathematical approach is that it offers the optimal solution instead of approaching an optimal solution. One of the major drawbacks is that computational time can increase drastically when optimisation problems become larger [81].

Linear programming (LP) was used in [21] to optimize size and placement for ESS for power loss reduction. The LP minimized storage costs in the European CIGRE LV benchmark grid model. In [58], a three-stage mixed integer linear program (MILP) was used to mitigate grid congestions by minimizing the sum of the generation costs in the IEEE Reliability Test System from 1996. ESS placement and sizing were optimized in [74] by mathematically analysing the structural properties of the optimal solution in a scenario in which all loads have the same shape. In [24], ESS size was optimized for minimal ESS costs and network losses by using a multi-period optimal power flow in the IEEE 34-bus networks, Italian 17-bus test networks and 200 randomly generated networks. For ESS placement, a heuristic strategy based on voltage sensitivity analysis was used.

Heuristics

Heuristics can find solutions more quickly when mathematical methods are too slow to find the exact optimal solution, making heuristics better suited for efficiently solving large optimization problems. Most heuristics are inspired by nature [17, 48, 47] and offer an (almost) optimal solution efficiently by trading optimality for speed. Also, heuristics are known for their ability to escape local optima [48, 47].

In [65], sizing and placement are optimized using a modified particle swarm optimization (PSO) algorithm. The ESS objective was to maximize DSO revenue by providing network support in a radial 30 and a 69 bus test grid. A PSO was also proposed in [35] A PSO algorithm was used for sizing ESSs in a distribution network in Ontario. A loss sensitivity-based algorithm was used for optimizing the placement of ESSs. Simulated annealing (SA) was used for allocation of ESS as an emergency backup in [22]. SA is suitable for finding the global optimum in large discrete solution spaces. It escapes local optima by also allowing non-improving moves during the early stages of the calculation [18].

2.4.3 Conclusion and Literature Gap

In conclusion, the reviewed literature underscores the potential role of ESS in addressing the complexities of modern low-voltage grids, particularly with the rising integration of RES and the increasing adoption of EVs. ESS has proven to be essential in mitigating voltage instability and grid congestion, offering both immediate and long-term solutions. Centralized storage systems, such as community batteries, show better efficiency and economic viability compared to decentralized home storage systems, primarily due to their ability to use aggregated load profiles for better predictability and efficiency. However, these centralized systems face challenges due to current regulatory and economic frameworks.

Regarding the optimization of siting and sizing ESS, most optimization efforts involve minimizing or maximizing specific key performance indicators (KPIs). These KPIs often need to be translated into the same unit or weighted to define what is considered ‘optimal’. This approach, however, may not be suitable for the broad assessment aimed at in this thesis. Instead, sensitivity analysis appears more appropriate as it can assess how sensitive grid variables are to ESS placement and sizing, allowing for a broader perspective on the results.

Despite these insights, there are gaps in the literature. The effect of ESS placement and sizing on grid reinforcement remains unknown. Additionally, the socio-economic impacts of ESS distribution and deploying ESS versus not deploying ESS on grid reinforcement have not yet been analyzed.

3

Methodology

This chapter outlines the methodology employed to assess the impact of ESS distribution on their effects on low-voltage grids. Including the description of the used model, data collection methods, ESS control algorithms and experiment design. The model used for the simulations is described by outlining its structure, sets, elements and their associated parameters. Also, the modelling assumptions and limitations of the model are addressed. Following this, the data collection process is discussed. This includes an overview of the parameters used for the artificial load profiles and the allocation of these load profiles to the grid elements for both the static and the time-series simulations. Finally, the experiment design and KPIs are presented. This section outlines the experimental setup and the metrics used to quantify the impact on grid congestion.

3.1 Modelling ESS in Electricity Grids

Researching the effects of ESS distribution requires a model that accurately represents the characteristics and dynamics of low-voltage grids. This section introduces the model developed to study how different configurations of ESS influence the low-voltage grids. The purpose of this model is to simulate various scenarios, allowing for the analysis of the impacts of different ESS configurations on the local grid.

3.1.1 Model Overview

The model's foundation is an electricity grid model, representing the physical layout of the buses, lines and transformers in a grid. To analyze the power flow in this grid, the power flow analysis method, discussed in section 2.3, was used. Each line has a specific impedance $R + jX$ based on the length and physical characteristics of the cable. The impedance values of the lines in the grid are used to compute admittance $Y_{i,j}$ as utilized in Equation 2.2 and Equation 2.3 of the load flow analysis.

At each node, power can be either positive, negative or zero, meaning that power can be fed in or drawn from the grid at a bus. Supplying or consuming power can be done by three types of assets: generators, loads and ESSs. In this model, the power signage for ESSs is the same as that of the load. Therefore, positive power means importing power from the grid, i.e., charging. Vice versa, negative ESS power means discharging. Figure 3.1 shows a schematic of a generator, load and ESS at two buses connected by a line. In the model, each grid element belongs to an associated set. Table 3.1 shows the sets of the model.

As discussed in section 2.1, low-voltage grids do not stand on their own. They are almost always part of a larger grid structure. The superior grid or 'external grid' is represented by a

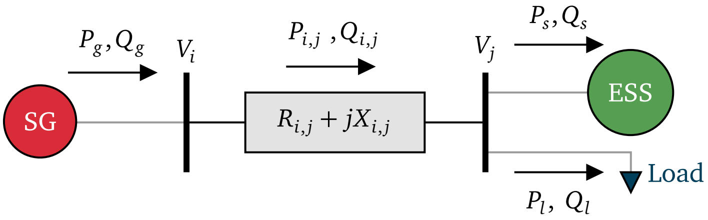

Fig. 3.1.: Schematic of two buses i and j with voltages V_i and V_j respectively connected by a branch with impedance $R + jX$. An ESS with power P_s is connected to bus i and a static generator (SG) with power P_g and a load with power P_l are connected to bus j.

slack bus. When the total consumption in a local grid is larger than the generation in that local grid, the required supplementary power needed to supply the loads is supplied at the external grid bus. Vice versa, when the total generation in the local grid is larger than the total consumption, the external grid bus draws the excess power to restore balance.

Tab. 3.1.: Sets in the model.

Symbol	Description
$\mathscr{N}$	Set containing all buses in the grid model
$\mathscr{L}$	Set containing all loads in the grid model
$\mathscr{G}$	Set containing all generators in the grid model
$\mathscr{E}$	Set containing all lines in the grid model
$\mathscr{S}$	Set containing all ESSs in the grid model
$\mathscr{T}$	Set containing all transformers in the grid model

Once the values P_s, P_l and P_g at each bus are specified, the load flow algorithm is used to compute voltage magnitude $|V_i|$ at each bus and the currents through each line and power through each transformer. These values are now translated to line loading by Equation 3.1 for each line. Here, line loading L_e is the fraction (in percentage) of the current I through line e and its maximum current I_{max}.

The transformer loading L_t for transformer t as a function of the power through each (often one) transformer is computed by Equation 3.2. Here, the maximum value of the loading at the primary and secondary sides is chosen as transformer loading L_t. For both sides, the transformer loading is based on the current I through that transformer. Current I at that side is translated to apparent power by multiplying with rated voltage V_{rated} at that side of the transformer. Now, transformer loading L_t is the fraction (in percentage) of the apparent power and its rated apparent power S_{rated}.

$$L_e = \frac{I}{I_{max}} \cdot 100\% \tag{3.1}$$

$$L_t = \max\left(\frac{I_{primary} \cdot V_{rated,primary}}{S_{rated}}, \frac{I_{secondary} \cdot V_{rated,secondary}}{S_{rated}}\right) \cdot 100\% \tag{3.2}$$

Finally, each input and output variable of the model is listed in Table 3.2.

The methodology presented in this chapter was implemented by using the Python package `pandapower` [77]. `pandapower` provides an open-source framework for element-based modelling of electricity networks, allowing for implementing the methods used in this

Tab. 3.2.: Input and output variables with their unit and associated set.

Symbol	Associated set	Description	Unit	Type
P_g	$\forall g \in \mathscr{G}$	Active power of generator g	kW	Input
P_l	$\forall l \in \mathscr{L}$	Active power of load l	kW	Input
P_s	$\forall s \in \mathscr{S}$	Active power of ESS s	kW	Input
E_s	$\forall s \in \mathscr{S}$	Stored energy in ESS s	kWh	Input/output
SoC_s	$\forall s \in \mathscr{S}$	State of charge of ESS s	%	Input/output
$\lvert V_i \rvert$	$\forall i \in \mathscr{N}$	Voltage magnitude at bus i	p.u.	Output
L_e	$\forall e \in \mathscr{E}$	Loading of line e	%	Output
L_t	$\forall t \in \mathscr{T}$	Loading of transformer t	%	Output

thesis. Additionally, the control methods utilize the Python package `scipy.optimize` for optimization.

3.1.2 Time-Series

The model discussed above is a *static* model, meaning that it only considers a snapshot of the grid at a specific point in time. To also capture the dynamic behaviour of the grid and the impact of ESS over time, a time series model is incorporated. The time-series model is a so-called *quasi-stati* model. This means that a time-series simulation consists of a sequence of static load flow models over a given period. Each load flow calculation represents a timestep in the time-series simulation. Load and generation profiles can be implemented by assigning the power values from the corresponding timestep to the loads and generators in the grid model.

At $t = 0$, E_s is equal to the initial state of charge of ESS s: $SoC_{s,init}$ (e.g. 50%). After each timestep, the stored values of the ESS are updated. The stored energy $E_{s,t}$ of ESS s at timestep t is computed by adding the (dis)charged energy during a timestep t to the state of charge values of timestep $t-1$. The (dis)charged energy is computed by assuming that ESS power $P_{s,t}$ at timestep t is the average power over the entire time increment Δt (e.g. 60 seconds). The values for P_s are bound by P_s^{min} and P_s^{max} to represent the maximum discharging power and the maximum charging power respectively. The calculation of the stored energy is shown in equation Equation 3.3.

$$E_{s,t} = E_{s,t-1} + P_{s,t-1} \cdot \frac{\Delta t}{3600} \tag{3.3}$$

The values for E_s are bound by E_s^{min} and E_s^{max} to represent the maximum and maximum amount of energy that can be stored by ESS s. Finally, the state of charge is expressed as the stored energy relative to the maximum energy that can be stored by the ESS as shown in Equation 3.4.

$$SoC_s = \frac{E_s}{E_s^{max}} \cdot 100\% \tag{3.4}$$

The values for SoC_s are bound by SoC_s^{min} and SoC_s^{max} to represent the maximum and maximum state of charge of ESS s (e.g. 0% - 100%). The output of the SoC computed for timestep t serves as an input for the consecutive timestep to prevent the ESS from theoretically overcharging when it is full and, vice versa, to prevent it from further discharging when it is already empty. The three cases for battery power P_s are shown in Equation 3.5.

$$P_{s,t} = \begin{cases} P_s^{min} \leq P_{s,t} \leq 0 & \text{if } SoC_{s,t} = SoC_s^{max} \\ 0 \leq P_{s,t} \leq P_s^{max} & \text{if } SoC_{s,t} = SoC_s^{min} \\ P_s^{min} \leq P_{s,t} \leq P_s^{max} & \text{otherwise} \end{cases} \tag{3.5}$$

3.1.3 Modelling Assumptions and Limitations

The discussed model operates under certain limitations and assumptions to simplify and focus the analysis. First, the model assumes that all phases are perfectly balanced. This implies that the power load and generation are evenly distributed across all three phases, neglecting the voltage imbalance introduced in section 2.1.4.

Secondly, while the model does allow for considering reactive power for loads, generators and ESS, this model does not consider reactive power flows. This simplification assumes that all power is purely active, which streamlines the calculations and focuses on the primary impact of ESS on active power distribution. As shown in Table 2.1, active power P has a larger influence on the voltage in low-voltage grids than reactive power Q. Moreover, active power values in LV grids are generally much smaller than reactive power values as seen in [29].

Thirdly, the model assumes that the ESSs operate at 100% efficiency. This means there are no losses during the charging or discharging processes of the ESS. This assumption simplifies the analysis by eliminating the need to account for energy losses, thus focusing on the theoretical maximum impact of ESS on the grid.

Also, the model uses quasi-static load and generation profiles, assuming that load and generation do not vary within a given timestep. The resolution of the time-series simulation is limited to the resolution of the power profiles. The timestep length Δt is a trade-off between computation time and resolution.

Lastly, the model assumes a fixed network topology that does not account for grid switching. Additionally, the transformer tap settings are kept constant throughout the simulations, as varying transformer taps would affect voltages and obscure the specific impacts of ESS on voltage levels.

3.2 Data Collection

The Artificial Load Profile Generator (ALPG) [28], developed at the University of Twente's Faculty of Electrical Engineering, Mathematics and Computer Science (EEMCS), was used to generate the consumption and generation data for the grid. This tool is designed to generate realistic synthetic load profiles based on various input parameters such as the type of household, time of the year and the penetration of emerging technologies such as EVs, PVs and heat pumps.

Two cases were considered in this study: a load-dominated case in November and a generation-dominated case in July. Analyzing these contrasting scenarios provides insights into the effects of ESS distribution under different grid conditions. The load-dominated case in November represents periods with high energy consumption relative to PV generation. In contrast, the generation-dominated case in July represents periods with high energy generation from PV power, especially during noon, exceeding the consumption power. By studying both scenarios, the simulations capture a broader spectrum of conditions.

For the first, load-dominated case, artificial demand data was generated for three days in November to simulate a load-dominated scenario with no PV generation and relatively high consumption. A dataset with the load data for a total of 100 households was created with the input parameter configuration as shown in Table 3.3.

The same parameters from Table 3.3 were applied to generate data for the generation-dominated scenario. This scenario simulates typical conditions during the summer months, where high PV penetration and relatively low heating demand result in an energy surplus, especially around noon. Data for three days in July was generated to represent this scenario.

Tab. 3.3.: ALPG configuration parameters.

Parameter	Value
Household type	`HouseholdSingleWorker` (25x) `HouseholdSingleRetired` (25x) `HouseholdDualWorker` (25x) `HouseholdFamilyDualWorker` (25x)
PV penetration	50%

A snapshot representing the most extreme case was chosen as a case for the static power-orientated method. For the load-dominated case in November, the timestep with the largest total consumption was chosen as the state of the grid for the load-dominated case. The load values of the 100 loads generated by the ALPG for that specific timestep were randomly assigned to the 192 loads in the grid (uniform distribution). Figure 3.2 shows the total load profile data, the selected snapshot and the individual load profiles.

A similar approach was taken to generate the data for the generation-dominated case. Only this time, the PV generation profile was subtracted from the load data to find the timestep with the most extreme discrepancy between consumption and generation within the local grid. Again, the individual consumption and generation values were randomly assigned to households within the grid. To represent the 50% PV penetration, 50% of the households randomly get assigned generator elements (uniform distribution). All of these selected PV households receive a non-zero PV generation value of the chosen timestep.

As an example, the voltage profile over the length of the feeders, line loading and transformer loading of the grid during the load-dominated case are shown in Figure 3.3. It can be seen that the loads cause voltage violations at the heavies loaded feeder where the bus voltage values are below 0.9 p.u.. Also, some lines and the transformer are overloaded as their loading levels exceed 100%.

For the time series simulations, the same three-day load profiles for two cases generated with the ALPG configuration described in Table 3.3 were used. Here, instead of selecting

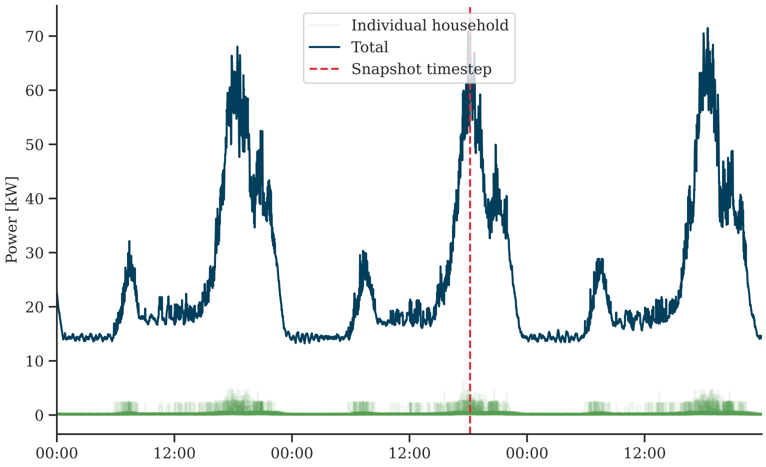

Fig. 3.2.: The three-day load profiles of 100 individual households in November generated by the ALPG. The selected timestep with the largest total load is shown in red.

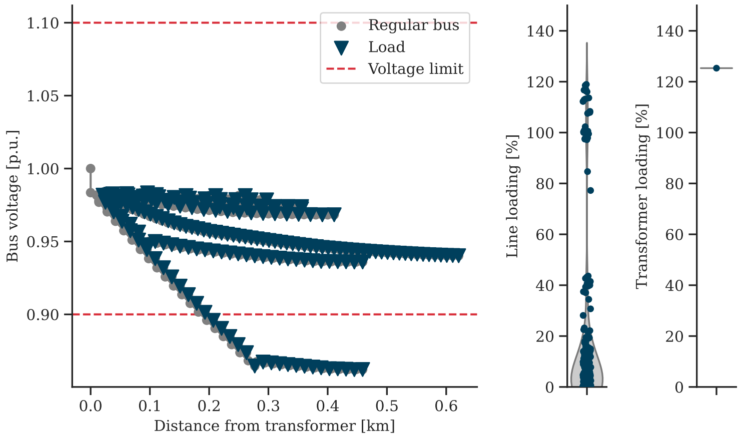

Fig. 3.3.: The bus voltage versus the distance to the transformer of the buses in the grid model on the left. Line loading and transformer loading are on the right.

a static snapshot of the load profiles, the generated load profiles could be used directly in the time series simulations. These profiles were randomly assigned to all loads (uniform distribution), while generation profiles were randomly assigned to 50% of the load buses (uniform distribution). To streamline the simulations, the number of timesteps was reduced by taking 5-minute averages of the load profiles.

3.3 ESS Control

Unlike other flexibility assets such as a controllable EV charger or a heat pump, an ESS has no other purpose than to satisfy some control objective or to handle (a portion of) a power imbalance. In fact, the ESS itself is just a ‘bucket’ that can absorb an amount of energy to release it at a later moment in time. It is the ESS control strategy that ultimately determines its primary function and its effects on the power flow in a system.

An ESS control strategy aims to achieve a defined objective by regulating charging and discharging power based on external factors such as bus voltages, energy prices and PV panel output, or internal factors such as its state of charge. Two ESSs with similar hardware might behave very differently in a power system depending on their operational objective, e.g. energy arbitrage, emergency backup or peak shaving [7]. Since the focus of this thesis is to assess the effects of the distribution of ESS in electricity grids from the perspective of the DSO, the control strategies used in this thesis are designed to reduce the stress on the grid and thus aim to prevent or reduce grid congestion.

In a power grid where loads and generators draw and supply power from a certain bus, an ESS on that same bus can be controlled to compensate for these powers by charging or discharging in the opposite direction. This relatively simple method would reduce grid load as it would balance discrepancies between consumption and generation. However, its disadvantage is that the ESS only responds to the activities at the bus to which it is connected. Therefore, this localized approach is unsuitable for studies assessing the broader effects of ESS distribution, as the ESS behaviour is only influenced by the characteristics of the loads and generators connected to the same bus rather than its overall position and role within the grid. To address this challenge, both control methods used in this thesis are centralized, meaning that they know the voltage and power at each bus of the (sub)grid and can control each ESS’s power accordingly.

In this thesis, three ESS control methods can be distinguished. The first, power-orientated method uses a greedy algorithm that provides insight into the effects of ESS distribution during edge cases: moments with peak generation or peak consumption. The second, energy-oriented method optimises ESS power over a time horizon while also considering their state of charge. The third ESS control method combines the power-oriented control with the energy-orientated control methods by optimizing ESS power over a time horizon to provide a dynamic window for the power-orientated control.

3.4 Optimizing in the Power Domain

The first, power-orientated ESS control method optimizes ESS power setpoint in a static snapshot of the grid state as discussed in section 3.2. An obvious approach would be to solve a power flow algorithm for the static situation and find a set of optimal ESS powers for each ESS in the grid such that the overall line loading is minimized. However, putting the results of the power flow algorithm inside an objective function is computationally expensive if not practically impossible to solve. Therefore, in this thesis, the concept of voltage sensitivity is used as a heuristic to optimize ESS power to find a (near) optimal set of ESS powers with an iterative optimization algorithm. This ESS control strategy, inspired by [63], aims to reduce the load on the grid by minimizing the difference between the bus voltages and a specified reference voltage. By finding a set of ESS powers that minimizes the voltage deviation i.e. the voltage drop or swell over a line, the current through these lines is also reduced.

3.4.1 Voltage Sensitivity

Although power flow analysis can be used for obtaining steady state bus voltages and power flows, it is not obvious how changes in power at the buses influence the bus voltages due to the interdependence between buses and their non-linear nature [73]. The voltage sensitivity matrix can be used to assess how changes in active and reactive power at one bus in a power system affect voltage magnitudes and angles at other buses. The voltage sensitivity has been widely used in literature [43, 86, 34, 85, 42, 2], mainly for research on controller methods for voltage regulation and optimization of voltage regulation device placement and sizing. The voltage sensitivity matrix $\mathbf{S}$ can be obtained by inverting the Jacobian matrix $\mathbf{J}$ from Equation 2.4 such that $\mathbf{J}^{-1} = \mathbf{S}$ (with $\mathbf{S} \in \mathbb{R}^{2n \times 2n}$) as shown in Equation 3.6.

$$\mathbf{S} = \mathbf{J}^{-1} = \begin{bmatrix} \frac{\partial \delta}{\partial P} & \frac{\partial \delta}{\partial Q} \\ \frac{\partial V}{\partial P} & \frac{\partial V}{\partial Q} \end{bmatrix} \tag{3.6}$$

In Equation 3.6, $\frac{\partial \delta}{\partial P}$, $\frac{\partial \delta}{\partial Q}$, $\frac{\partial V}{\partial P}$ and $\frac{\partial V}{\partial Q}$ represent sub-matrices within $\mathbf{S}$ that feature the sensitivity of the voltages angles δ and voltage magnitudes $|V|$ [p.u.] due to changes in active power P [MW] and reactive power Q [MVAR]. All sub-matrices represent a quadrant of $\mathbf{S}$ such that $\mathbf{S}^{\delta P}$, $\mathbf{S}^{\delta Q}$, $\mathbf{S}^{VP}$, $\mathbf{S}^{VQ} \in \mathbb{R}^{n \times n}$ for a system of n PQ buses. Figure 3.4 shows an exemplary grid layout and a heatmap of the values in $\mathbf{S}^{VP}$ of that grid layout. Note that this is a different grid layout than used in the simulations in this thesis as a grid with a limited number of buses is more suitable for illustration purposes. In the heatmap, the darkness of the colour represents the sensitivity of the voltage changes to power changes at another bus. If a power change ΔP_i occurs at bus i, the expected voltage change at another bus j $\Delta \left|V_j\right|$ caused by that power change can be calculated by multiplying ΔP_i at bus i with the voltage sensitivity value in row i, column j. It can be seen that the voltages of the buses at the end of the feeders are the most sensitive to active power changes at other buses on that same feeder.

3.4.2 ESS Power Optimization

Now that there is a relation between power and voltage, an algorithm can be made that finds a (near) optimal power for each ESS to minimize the voltage deviation over the entire grid under study. As defined in the objective function in Equation 3.7, the voltage deviation is the squared difference between the reference voltage V_{ref} and bus voltage magnitude V_i. The objective is to minimize the sum of the squared voltage deviations across all buses i in set $\mathcal{N}$. The voltage setpoint V_{ref} is set to the voltage of the slack bus of the grid model: 1 p.u.. Here, the decision variables are the power setpoints for the ESS in the local grid.

$$\min \sum_{i \in \mathcal{N}} \left(V_{ref} - |V_i|\right)^2 \tag{3.7}$$

When minimizing Equation 3.7, multiple optimal solutions can exist. Also, the control algorithms can cause neighbouring ESS to work against each other by charging in the

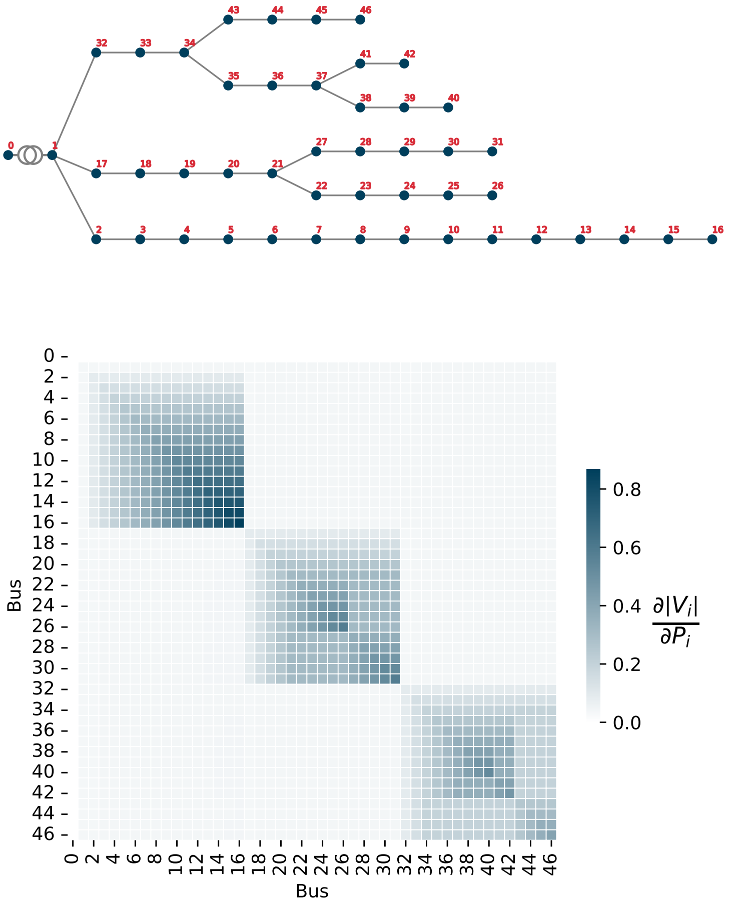

Fig. 3.4.: Heatmap of the values in the voltage sensitivity matrix **S** of the homogeneously loaded grid shown above. Note that this is a different grid model than used in the simulations in this thesis.

opposite direction. To limit the number of optimal solutions and favour the least power-consuming solution, the total absolute ESS power is multiplied by a small number β and added to the final objective function as shown in Equation 3.8. In this thesis, $\beta = 0.001$.

$$\min \sum_{i \in \mathcal{N}} \left(V_{ref} - |V_i|\right)^2 + \beta \cdot \sum_{s \in \mathcal{S}} |P_s| \tag{3.8}$$

The voltage deviation is minimized by controlling the ESS (dis)charging powers such that they contribute to a reduction in the voltage deviation. The translation from power to voltage is done by using the concept of voltage sensitivity. $\frac{\partial V}{\partial P}$ elements in the voltage sensitivity matrix **S** as shown in Equation 3.6. To ensure that the powers of each ESS stay within their power limits, the ESS (dis) charging powers P_s for each ESS s in ESS set $\mathcal{S}$ are constrained by Equation 3.9.

$$P_s^{min} \leq P_s \leq P_s^{max} \quad \forall s \in \mathcal{S} \tag{3.9}$$

For a system where set S denotes the number of buses where ESS units are connected, the optimization aims to find an optimal vector $\mathbf{P} \in \mathbb{R}^S$ (e.g. $\mathbf{P} = [P_1, P_2, \cdots, P_S]^T$) that contains the optimal ESS power values by updating the initial power vector $\mathbf{P}^0$ (all 0 for the initial load-flow) by a vector $\Delta\mathbf{P}$ as shown in Equation 3.10.

$$\mathbf{P} = \mathbf{P}^0 + \Delta\mathbf{P} \tag{3.10}$$

The voltage change ΔV_i at bus i as a result of the change in ESS powers at other buses $\Delta\mathbf{P}$ can be obtained by multiplying the power change ΔP_s with $\frac{\partial |V|}{\partial P}$ for each ESS bus in column i of $\mathbf{S}^{VP}$ as shown in Equation 3.11.

$$\Delta V_i = \sum_{s \in \mathscr{S}} \frac{\partial V_i}{\partial P_s} \cdot \Delta P_s \tag{3.11}$$

Now, the calculated ΔV_i values can be used to fill the vector $\Delta\mathbf{V}$ to be added to the initial voltages $\mathbf{V}^0$ to obtain the new bus voltages $\mathbf{V} \in \mathbb{R}^N$ (e.g. $\mathbf{V} = [|V_1|, |V_2|, \cdots, |V_N|]^T$) as shown in Equation 3.12.

$$\mathbf{V} = \mathbf{V}^0 + \Delta\mathbf{V} \tag{3.12}$$

Now, vector $\mathbf{V}$ contains all the values for $|V_i|$ used in the objective function in Equation 3.7 for a local grid with N buses.

However, in a system with multiple ESS units connected relatively close to each other (e.g., at neighbouring buses), solving Equation 3.12 for all the buses at once may yield unexpected results. Since buses are interconnected, injecting or drawing power P_s at one bus will change the voltage sensitivity matrix $\mathbf{S}$ for the entire system. This will alter all the $\frac{\partial V}{\partial P}$ elements for other buses in the system, leading to unexpected values for $|V_i|$. Also, multiplying the partial derivatives with a relatively large value for ΔP may not represent the nonlinear behaviour of the power system. Figure 3.6 shows the difference in voltage levels where it can be seen that there is a large difference between the voltage levels that were ‘expected’ by solving Equation 3.12. To overcome this, a new power flow is conducted with the new P_s values obtained by Equation 3.10 to update the voltages in $\mathbf{V}_k$ with the new voltages $\mathbf{V}_{k+1}$ computed by the new run of the power flow algorithm. These new values for $|V_i|$ can now be compared with the values for $|V_i|$ that were expected from Equation 3.11. The entire optimization method then repeats itself until the maximum difference between $\mathbf{V}_k$ and $\mathbf{V}_{k+1}$ is small (<0.005), as shown in Equation 3.13.

$$\max\left(\left|\frac{\mathbf{V}_k - \mathbf{V}_{k+1}}{\mathbf{V}_{k+1}}\right|\right) < 0.005 \tag{3.13}$$

Figure 3.6 shows the expected versus the actual voltage levels after the algorithm went through the convergence loop and the condition in Equation 3.13 is met. A flowchart of the power-orientated ESS control is shown in Figure 3.5.

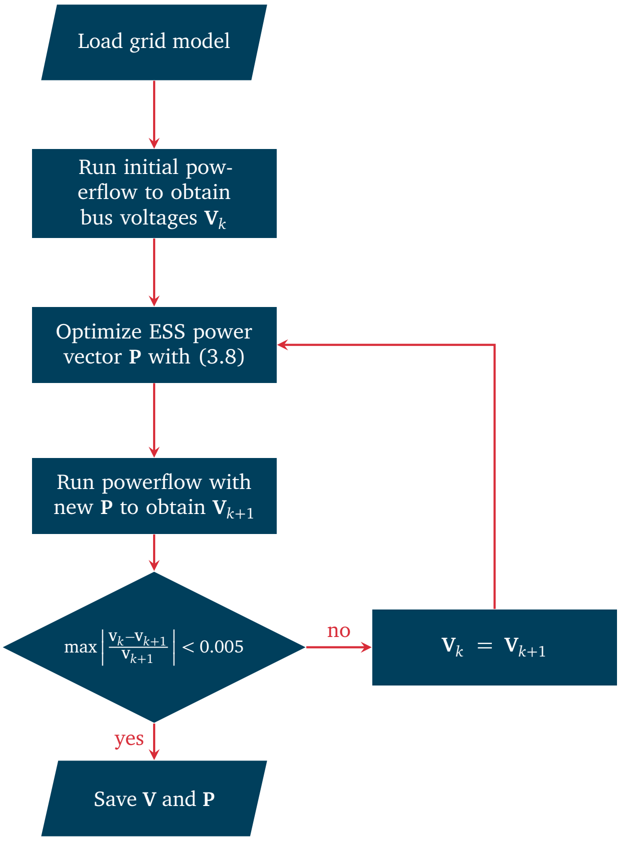

Fig. 3.5.: A flowchart of the DSO-orientated ESS control approach.

3.5 Optimization in the Energy Domain

In addition to the power-orientated ESS control strategy as discussed in section 3.4, another, energy-orientated control method was used in a time series simulation to capture the dynamic behaviour of the ESSs over time. A different approach was employed to make the simulations more suitable for studying the realistic behaviour of ESSs over a period, rather than a snapshot of a specific situation. More specifically, the power-orientated voltage sensitivity control algorithm is a greedy algorithm that always aims to reduce voltage deviation by supplying or withdrawing power from the system without considering past or future states. For example, during prolonged periods of slight undervoltage in load-dominated periods (e.g. during the night), when the voltage magnitude remains between 0.9 and 1.0 p.u., the voltage sensitivity algorithm will instruct the ESSs to supply power to bring the bus voltages closer to 1 p.u. Consequently, the ESS might be empty when the morning peak occurs. An alternative solution would be minimising the total voltage deviation over a time horizon to find a profile that buffers energy for when it is needed to overcome grid problems in the future. However, this has proven to be too computationally expensive for this thesis.

Therefore, a more computationally efficient approach was chosen to optimize ESS energy over a longer period. The time-series algorithm, inspired by the concept of profile steering from [23], aims to minimize the total load on the grid. It does this by defining a set of non-controllable powers and finding a set of controllable powers (e.g. ESS or flexible EV chargers) such that the squared sum of the powers is minimal over a specified time horizon

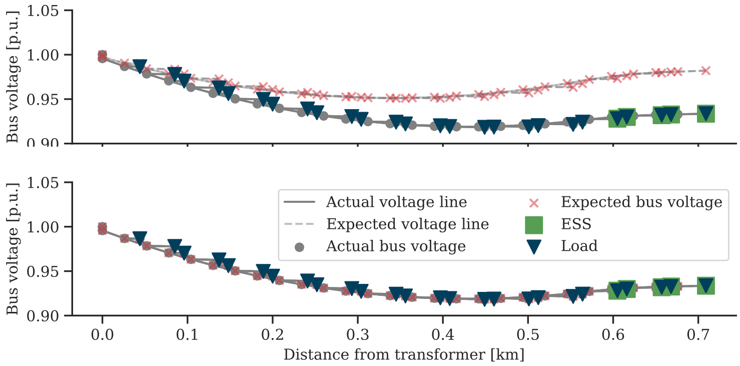

Fig. 3.6.: Expected voltage levels after activating ESS power according to the control algorithm versus the voltage levels according to the power flow before the convergence loop (top) and after the convergence loop (bottom).

of T intervals. In this thesis, all loads and generation in the grid are assumed to be non-controllable, meaning that loads cannot be shifted or reduced and PV power cannot be curtailed. The objective function is shown in Equation 3.14. The optimization is contained by Equation 3.15 to respect the ESS state of charge boundaries.

$$\min \sum_{t=1}^{T} \left(\sum_{l \in \mathscr{L}} P_{l,t} - \sum_{g \in \mathscr{G}} P_{g,t} + P_{ESS,t}^{tot} \right)^2 \tag{3.14}$$

$$E_{ESS,t}^{tot,min} \leq E_{ESS,t}^{tot} \leq E_{ESS,t}^{tot,max} \tag{3.15}$$

In Equation 3.14, the generation power from the generators in $\mathscr{G}$ at time t is subtracted from the load power of the loads in $\mathscr{L}$ at time t to obtain a net grid power, representing a shortage or surplus of power in the grid. An aggregated battery profile, $P_{ESS,t}^{tot}$, is then determined to address this imbalance. This profile accounts for the charging and discharging cycles of the ESS, ensuring that power is supplied during shortages and absorbed during surpluses. The objective is to find a profile of controllable aggregated ESS power, $P_{ESS,t}^{tot}$, that minimizes the squared sum of the net grid power over a time horizon T. Unlike the greedy voltage sensitivity algorithm, this control algorithm anticipates future needs, recharging and conserving power for the most critical periods by ensuring that the ESS profile respects the stored energy limits over time with Equation 3.15. The optimized aggregated profile, $P_{ESS,t}^{tot}$, is then equally allocated to the ESS units s in $\mathscr{S}$ in a system with S ESSs, as shown by Equation 3.16.

$$P_{s,t} = \frac{P_{ESS,t}^{tot}}{S} \quad \forall \in \mathscr{S} \tag{3.16}$$

Figure 3.7 provides an example illustrating a load and generation curve alongside the optimized ESS profile $P_{ESS,t}^{tot}$.

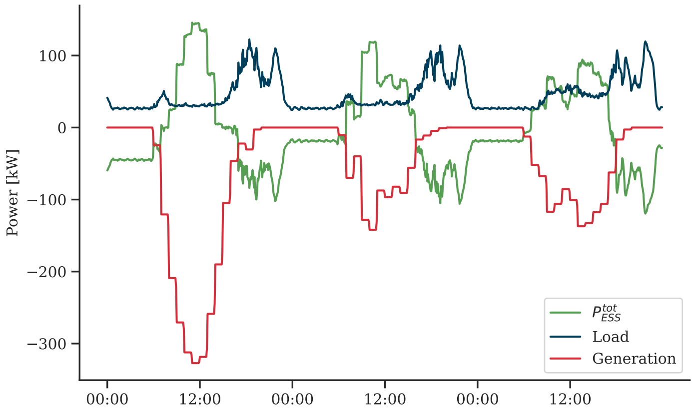

Fig. 3.7.: The three-day load and PV generation profiles of 100 individual households in July generated by the ALPG together with the optimized aggregated ESS profile.

3.6 Combined Optimization

A drawback of the power-orientated control approach is that it is a greedy algorithm that always aims to reduce voltage deviation by charging or discharging ESSs without considering future states. By focusing solely on immediate voltage correction, this approach might overlook more optimal strategies that could be derived from a longer-term perspective. For example, batteries discharge the entire night to reduce the relatively small voltage deviation compared to the voltage deviation during the morning or evening peak. However, because of the greedy nature of the control, the ESSs might be empty before the morning peak starts. As discussed, the energy-orientated method overcomes this issue by optimizing an ESS powers profile that is constrained by SoC limits over a time horizon T. By considering a time horizon T, the energy-orientated approach takes into account both current and future states. This allows for more informed decision-making that optimizes ESS power over a longer period rather than just reacting to immediate voltage deviations. However, a drawback of the energy-orientated methodology is that it is a centralized controller that does not consider the direct effects on the grid as the power-orientated approach does by considering the voltage sensitivity of the buses to power changes by the ESS.

To enjoy the benefits of both methods, a third method combines the power-orientated and the energy-orientated methods. First, similar to the energy-orientated control, it finds an optimal ESS profile with the objective function as in Equation 3.14. However, unlike the method presented earlier, it limits the depth of discharge such that the total SoC stays between 10% and 90% (instead of 0% - 100%) to create an SoC margin for the power-orientated control to work in. The resulting SoC profile can now be used to define dynamic lower and upper bounds for the power-orientated method. Figure 3.8 shows the global SoC planning together with the +/- 10% margin that forms the dynamic limits for the power-orientated control method. Each ESS receives the SoC planning.

Now, the individual ESSs minimize voltage deviation such that their SoC stays within +/- 10% of the global SoC planning provided by the energy-orientated methodology. For each timestep t, each ESS s compares its current state of charge $SoC_{s,t}$ with the SoC that it is

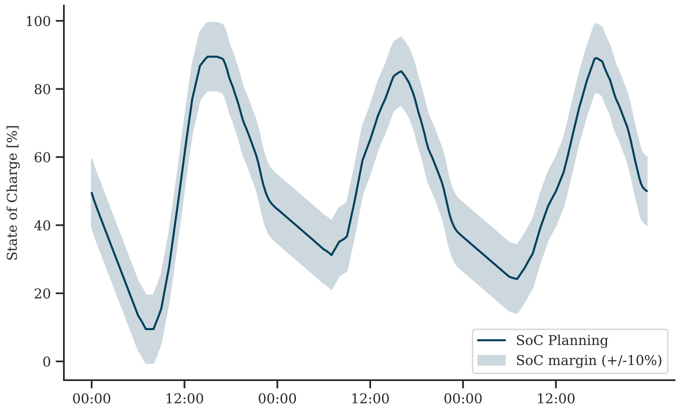

Fig. 3.8.: The global SoC planning together with the +/- 10% margin that forms the dynamic limits for the power-orientated control method.

allowed for the next timestep $t+1$ to calculate an upper margin $\Delta SoC^{upper}_{s,\Delta t}$ and lower margin $\Delta SoC^{lower}_{s,\Delta t}$ that each ESS's SoC could and should change over time interval Δt as shown in Equation 3.17.

$$\begin{aligned}\Delta SoC^{upper}_{s,\Delta t} &= (SoC^{tot}_{ESS,t+1} + 10\%) - SoC_{s,t}\\ \Delta SoC^{lower}_{s,\Delta t} &= (SoC^{tot}_{ESS,t+1} - 10\%) - SoC_{s,t}\end{aligned} \tag{3.17}$$

With this comparison, each ESS individually calculates how much it could and should (dis)charge during timestep t to stay within the margin provided by the planning by translating SoC to energy with Equation 3.18.

$$\Delta E_{s,\Delta t} = \Delta SoC_{s,\Delta t} \cdot E^{max}_{s} \cdot \frac{1}{100\%} \tag{3.18}$$

$\Delta E^{upper}_{s,\Delta t}$ and $\Delta E^{lower}_{s,\Delta t}$ can now be translated to lower power bound $P^{lower}_{s,t}$ and upper power bound $P^{upper}_{s,t}$ by dividing by timestep length Δt as shown in Equation 3.19.

$$P_{s,t} = \frac{\Delta E_{s,\Delta t}}{\Delta t} \tag{3.19}$$

Together with the ESS's minimum and maximum power P^{min}_{s} and P^{max}_{s} as shown in Equation 3.20, these power lower and upper bounds now serve as an input for the power-orientated approach to find a power that minimizes the voltage deviation with Equation 3.7.

$$P^{min}_{s} \leq P^{lower}_{s,t} \leq P_{s,t} \leq P^{upper}_{s,t} \leq P^{max}_{s} \tag{3.20}$$

Note that, since the ESS's powers are limited by the SoC planning anyway, the $\beta \cdot \sum |P_s|$ element of Equation 3.8 is unnecessary and Equation 3.7 is used instead to optimize each

ESS in sequence instead of all ESSs at once as in the method proposed earlier. This process repeats itself for each timestep t in time horizon T.

3.7 Experiment Design and Key Performance Indicators

The experimental design for this study is structured to evaluate the impact of ESS placement and sizing on the grid under study. Multiple ESS placement scenarios were developed to test different configurations within the grid, varying in terms of the number, location and capacity of ESS units to assess the effects of these variations in both the load-dominated case and the generation-dominated cases.

Each control algorithm was then tested separately. Simulation runs were conducted for each placement scenario and case (load-dominated and generation-dominated) A baseline scenario without ESS integration was simulated first to establish a reference point for comparison, followed by test scenarios for each ESS placement using the different control algorithms. This allows for a comparative analysis across the various placement scenarios. As discussed in section 2.1.7, undervoltage during peak consumption, overvoltage during peak generation, line overloading and transformer overloading are common problems in congestion-constrained grids. Therefore, during each simulation run, data on bus voltage magnitudes $|V_i| \forall i \in \mathcal{N}$ (in p.u.), line loading $L_e \forall e \in \mathcal{E}$ (in %) and transformer loading levels $L_t \forall t \in \mathcal{T}$ (in %) were collected. Voltage requirements go for every bus in the grid. Therefore, only minimum and maximum bus voltage magnitudes are presented for each time step. Only the maximum values were collected for each timestep for line loading and transformer loading.

Also, to compare the results with grid reinforcements, another simulation was run to simulate the voltage deviation and maximum line loading in a grid with upgraded cables.

4

Evaluation

This chapter provides an analysis of the results obtained from the simulation experiments. It aims to assess the effects of the different ESS placement and sizing scenarios on the metrics presented in section 3.7. First, the parameters for the grid model used in each simulation are presented including a description of the grid's structure, line impedance and transformer rating. The different placement scenarios are also introduced, specifying the number, location and capacity of ESS units tested in the simulations. Both the power-oriented control and the combined control methods as discussed in Chapter 3 are presented separately. This includes an analysis of the different placement scenarios for both the load-dominated and the generation-dominated cases. The intermediary results of the energy-oriented method alone can be found in section A. Also, comparative simulations of the voltage deviation and line loading in a reinforced grid with upgraded cables (i.e. reduced impedance) are presented. These simulations compare the outcomes of ESS integration with a scenario in which the grid is reinforced without ESS. This comparison aims to highlight the difference between deploying ESS versus traditional grid reinforcement methods.

4.1 Grid Parameters and ESS Placement Scenarios

A model of a low-voltage grid was chosen based on parameters such as the number of households connected to a feeder and the rated power of transformers. The characteristics of the used low voltage grid model are shown in Table 4.1.

Tab. 4.1.: Characteristics of the grid model.

Parameter	**Value**
Number of households	192
Number of feeders	9
Number of households per feeder	61, 32, 32, 20, 15, 15, 11, 5, 1
Line type	NAYY 4x50mm^2 (underground cable)
Line Impedance	R=0.642 $\frac{\Omega}{km}$, X=0.083 $\frac{\Omega}{km}$
Line I_{max}	0.142 kA
Transformer rated capacity	250 kVA

For different ESS placement scenarios, the ESSs were assessed on their effects on the aforementioned metrics: maximum and minimum bus voltage magnitude, maximum line loading and transformer loading. The selected scenarios represent a range of practical configurations to evaluate the impact of ESS placement on the metrics. After a baseline simulation without ESS, ESSs, controlled by the proposed control algorithms, were added to the grid in the following configurations:

- **ESS at the transformer bus:** ESS at the transformer bus: The transformer is one of the few above-ground grid assets in Dutch low voltage grids, making it an intuitive location for a neighbourhood ESS. This scenario examines the impact of placing a single ESS at the secondary side bus of the transformer.
- **ESSs at half of the feeders:** Investigating the effects of placing an ESS halfway through each feeder, with the number of ESS units equalling the number of feeders in the grid.
- **ESS at the end of the feeders:** Assessing the effects of placing an ESS at the end of each feeder, with the number of ESS units equalling the number of feeders in the grid.
- **ESSs distributed over households:** Distributing ESSs randomly across all household buses in the local grid reflects the most decentralized storage strategy, where individual homes have their own ESS units. In this scenario, 50% of the randomly selected households (uniform distribution) are equipped with an ESS (ESS penetration = 50%). This scenario investigates the impact of widespread home ESSs on the KPIs.
- **ESSs at PV households:** The ESSs are distributed over the household with a generator element. The number of ESS equals the number of generator elements in the grid under study. The comparison of results between this scenario and the scenario in which ESSs are randomly distributed serves as an insight into the effects of the proximity of ESS to PV.

Regardless of the number of ESSs in a scenario, the aggregated ESS parameters (i.e. rated power and energy) always remain the same in the different placement scenarios. This means that the one ESS placed near the transformer is one large (in terms of maximum power) ESS and the ESSs that are randomly distributed are multiple, smaller ESSs with their maximum powers and total energy capacity adding up to the same number as the power of the single ESS scenario. Also, all maximum (dis)charging powers are symmetrical meaning that $P^{max} = -P^{min}$ with P^{max} being the maximum charging power (since ESS signs are modelled as loads) and P^{min} being the maximum discharging power.

4.2 Power-Orientated Optimization

After a baseline measurement of the grid model with the load data from 3.2 and no ESS, the aggregated ESS power was increased from 100 kW to 500 kW with increments of 100 kW. For each placement scenario and aggregated power value, minimum and maximum bus voltage magnitude levels, maximum line loading and maximum transformer loading are measured.

4.2.1 Voltage Deviation

In the load-dominated case, the experiments simulate conditions where electricity consumption is high relative to generation. Figure 4.1 shows the effects of increasing the aggregated ESS power capacity for different placement scenarios on voltage deviation for the load-dominated case. The results show voltages below 1.0 p.u. for all buses with voltage violations ($|V_i| < 0.9$ p.u.) at some buses in the baseline measurement without ESSs. As shown in the example in Figure 3.3, these buses belong to the heavy-loaded line shown at the bottom of the graph. When increasing aggregated ESS power for the different placement scenarios, the ESSs that are randomly distributed over the households succeed most in reducing the voltage deviation in the grid. In the scenarios where the ESSs are placed at the end of the feeders and halfway through the feeder, the ESSs succeed in reducing the voltage deviation. It can be seen that the voltage at some buses is slightly increased to increase the voltages of all buses on that feeder for a better overall result. In the scenario where the ESS is placed at the transformer bus, the voltage deviation is only slightly reduced and voltage violations still occur. The ESS at the transformer bus can only increase the voltage of all the buses as a whole.

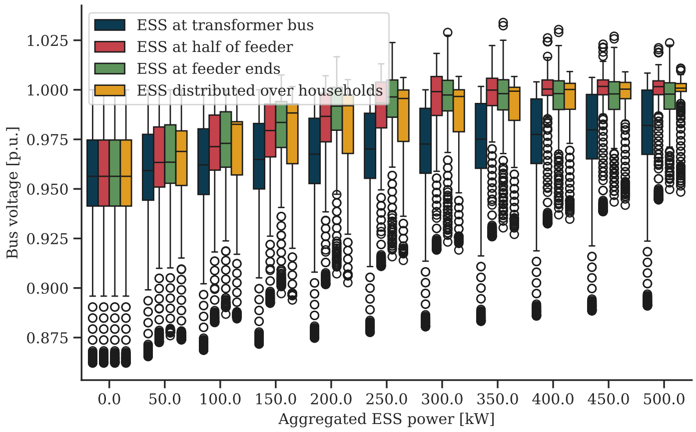

Fig. 4.1.: The distribution of the voltage magnitude levels of all buses in the grid for increasing aggregated ESS power levels and different placement scenarios in the load-dominated case.

The generation-dominated case explores situations where electricity generation from residential PV panels exceeds local consumption. Figure 4.2 shows the effects of increasing the aggregated ESS power capacity for different placement scenarios on voltage deviation for the generation-dominated case. Here, the results are similar to the results of the load-dominated case since the ESS placed at the transformer bus can only shift the voltages of all buses closer to 1.0 but can not reduce the voltage variation over the feeder itself. The ESS placed at the buses with a PV installation succeeded most in reducing the voltages within the grid, followed by distributing the same number of ESSs over households randomly. Placing the ESS units halfway along the feeder or at the end of the feeder yields comparable results in reducing average voltage deviation. However, in the halfway placement scenario, PV installations situated 'behind' the ESSs still cause increased voltages that the ESSs cannot reduce.

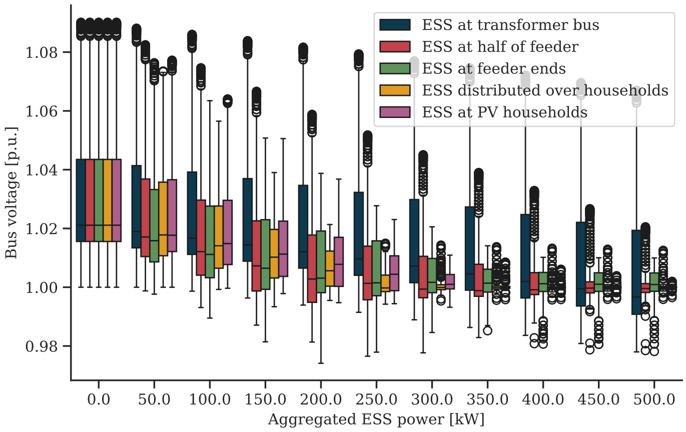

Fig. 4.2.: The distribution of the voltage magnitude levels of all buses in the grid for increasing aggregated ESS power levels and different placement scenarios in the generation-dominated case.

4.2.2 Line Loading

Regarding the line loading in the load-dominated case, as shown in Figure 4.3, it is evident that in the scenario with an ESS at the transformer bus, the line loading remains unaffected regardless of the ESS power. In contrast, in the scenarios where the ESS is placed at the end or halfway along the feeder, line loading increases with larger ESS power as the ESS attempts to minimize voltage deviation.

The same effect is observed in the generation-dominated case in Figure 4.4. The line loading is not influenced by the ESS placed near the transformer. The ESS units located at PV household buses reduce line loading the most when the aggregated ESS power is relatively large, closely followed by the scenario where the same number of ESS units are distributed randomly. Placing ESS units halfway along or at the end of the feeder yields intermediate results, showing comparable effects on line loading.

4.2.3 Transformer Loading

For transformer loading, the scenarios with ESS placed at the end or halfway along the feeder show the largest reduction in transformer loading compared to scenarios where ESS units are placed at random households or PV households. However, the ESS placed at the transformer exhibits abnormal behaviour in both the load-dominated case in Figure 4.3 and the generation-dominated case in Figure 4.6: the transformer loading increases as the aggregated ESS power increases. This occurs when the aggregated ESS power exceeds the

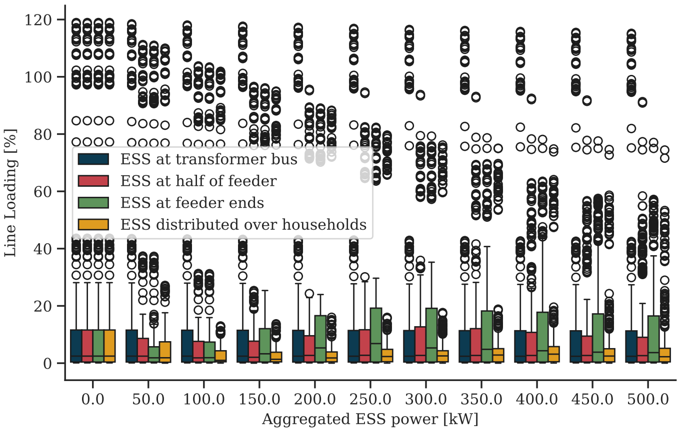

Fig. 4.3.: The distribution of the line loading levels of all lines in the grid for increasing aggregated ESS power levels and different placement scenarios in the load-dominated case.

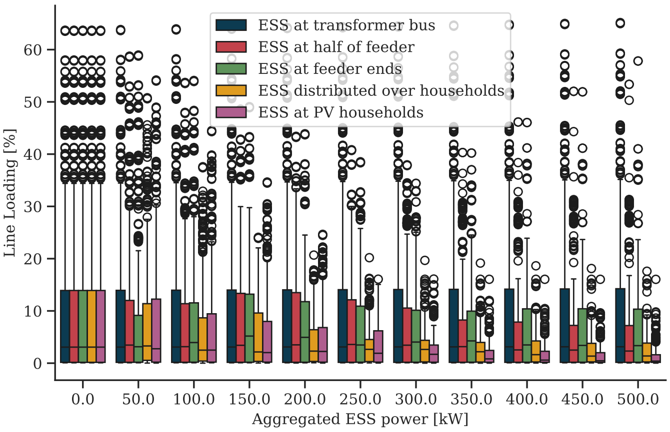

Fig. 4.4.: The distribution of the line loading levels of all lines in the grid for increasing aggregated ESS power levels and different placement scenarios in the generation-dominated case.

net demand that the grid needs to supply. When the ESS near the transformer has sufficient power to fully supply the loads or absorb all surplus power in the grid, the power flowing through the transformer is almost zero, resulting in an almost zero voltage drop across the transformer. Consequently, the low voltage bus of the transformer (where the ESS is connected) reaches 1 p.u. However, the rest of the feeders remain above or below 1 p.u. Since the goal of the ESS is to minimize overall voltage deviation, it will take on the role of the tap-changing transformer by discharging or charging extra power. This process aims to shift the entire grid closer to 1 p.u. by increasing the voltage drop or swell across the transformer itself through the additional power.

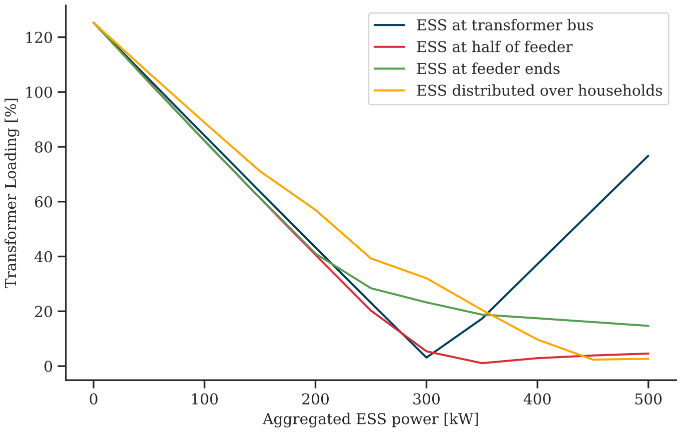

Fig. 4.5.: The transformer loading levels of the transformer in the grid for increasing aggregated ESS power levels and different placement scenarios in the load-dominated case.

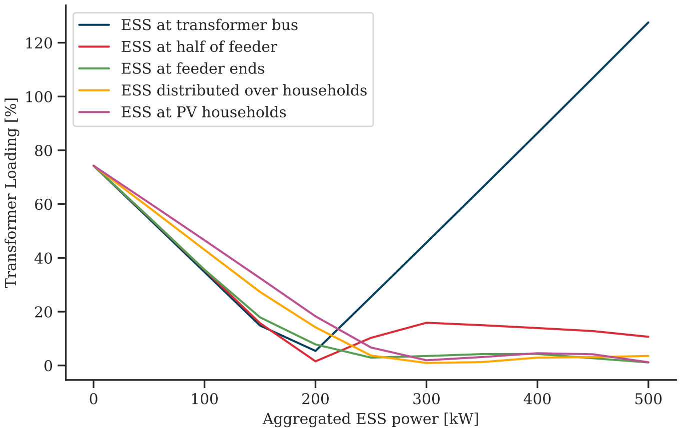

Fig. 4.6.: The transformer loading levels of the transformer in the grid for increasing aggregated ESS power levels and different placement scenarios in the generation-dominated case.

4.3 Combined Optimization

As discussed in section 3.6, the combined approach receives a planning from the energy-orientated optimization to use this planning to define bounds for the optimization in the domain. Similar to the power-orientated simulations, the ESS placement scenarios discussed in section 4.1 were integrated into the time series simulations. These scenarios involved measuring bus voltages, line loading and transformer loading over time for each ESS placement. The aggregated ESS power and energy capacity remained constant across all simulations, set at $P_{ESS}^{tot,max} = -P_{ESS}^{tot,min} = 300$ kW, $E_{ESS}^{tot,min} = 0$ kWh and $E_{ESS}^{tot,max} = 600$ kWh. Figure 4.7 shows the individual ESS's state of charge optimized with the power-orientated approach within the dynamic SoC margins provided by the energy-orientated optimisation for the scenario with ESSs placed at the end of each feeder during the generation-dominated case. It can be seen that, most of the time the ESSs are as greedy as the dynamic bounds allow. In the transitional periods where the ESSs go from charging to discharging and vice versa, the difference between individual ESSs is most pronounced since the exact moment of that transition is feeder-specific.

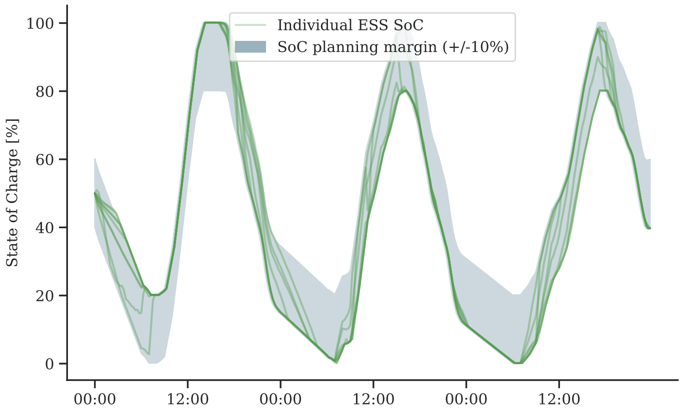

Fig. 4.7.: The individual ESS's state of charge optimized with the power-orientated approach within the dynamic SoC margins provided by the energy-orientated optimisation for the scenario with ESSs placed at the end of each feeder during the generation-dominated case.

4.3.1 Voltage Deviation

The results for the minimum and maximum voltage magnitude are analysed for both load-dominated and generation-dominated scenarios. In the load-dominated case, the experiments simulate conditions where electricity consumption is high relative to generation. Figure 4.8 shows the load duration of the maximum and minimum voltage magnitude over time for the load-dominated case. The scenario without an ESS shows a near voltage violation at almost 1.1 p.u. during a short period. In all scenarios, the ESSs succeed in reducing the voltage swells to varying extents. The ESS placed at the transformer bus is the least successful in mitigating voltage swells compared to the other ESS scenarios. The ESSs placed halfway through each feeder are less successful in mitigating voltage swells compared to the scenarios with ESSs at the feeder ends as these ESSs halfway can not compensate for the generation causing voltage swells further towards the end of the feeders. This is also visible in the heatmap in Figure 3.4 where it can be seen that bus voltages at the end of feeders are more sensitive to power changes at the end of feeders compared to power changes halfway through the feeders. The ESSs at the end of the feeders perform slightly better but still show intermediate results compared to the more decentralized placement scenarios with the ESSs randomly distributed and connected at PV household buses. Between these two, ESSs connected to PV buses succeed best in reducing voltage deviation.

The effects of ESSs close to PV installations compared to randomly distributed ESSs are even more pronounced in Figure 4.9, in which the load duration of the maximum and minimum voltage magnitude over time for the generation-dominated case are shown. Here, overvoltage occurs during almost 10% of the simulated period as voltages exceed 1.1 p.u. in the base case without ESS. In all ESS scenarios, the amount of time in which the overvoltage occurs is greatly reduced. The ESS connected to PV households shows the best performance regarding reducing voltage swells caused by high PV generation. In all placement scenarios, voltage drops are reduced. Here, the voltage sensitivity also is visible in the fact that the

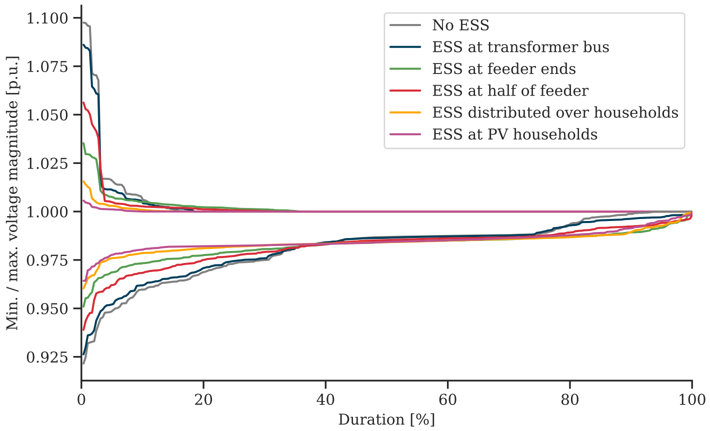

Fig. 4.8.: The load duration curves of the minimum and maximum bus voltage magnitudes for different ESS placement scenarios over three days in November.

ESS at the end of the feeder perform better compared to the ESS placed halfway through each feeder. The scenarios in which ESSs are randomly distributed and the scenario where ESSs are connected to PV household buses show almost identical results regarding reducing voltage drops since, from a load perspective, ESSs are randomly distributed in both of these scenarios. The ESS at the transformer bus shows comparable results to the scenario without ESSs.

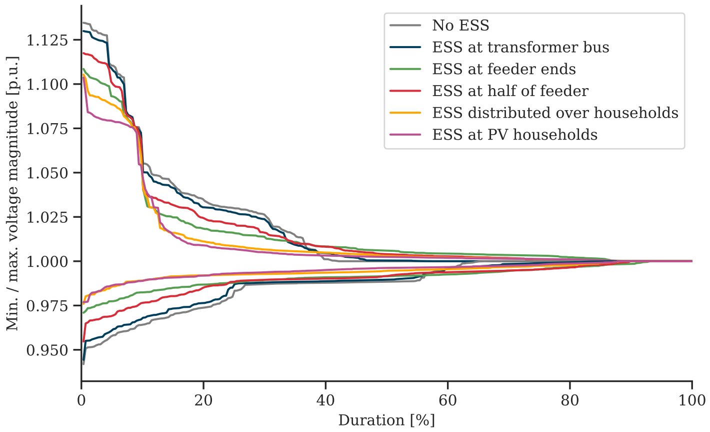

Fig. 4.9.: The load duration curves of the minimum and maximum bus voltage magnitudes for different ESS placement scenarios over three days in July.

4.3.2 Line Loading

The results for the maximum line loading levels are analysed for both load-dominated and generation-dominated scenarios. Figure 4.10 shows the load duration of the maximum line loading levels over time for the load-dominated case. Compared to the base case without ESSs, the maximum line loading is reduced in each of the ESS placement scenarios except for the ESS placed at the transformer bus, which almost shows the same results as the basecase. Out of the five scenarios, the ESSs placed at the end of the feeder and the ESSs placed halfway of each feeder show similar, intermediate performance compared to the two scenarios in which ESS are randomly distributed and the scenario in which ESSs are connected to PV household buses. These latter two, more distributed scenarios, also show similar behaviour compared to each other. This can be explained by the fact that, when an ESS is placed halfway or at the end of a feeder, power must still flow through these feeders to reach the ESSs. In the more distributed scenarios, power imbalances can be settled closer to the source with less line loading as a result.

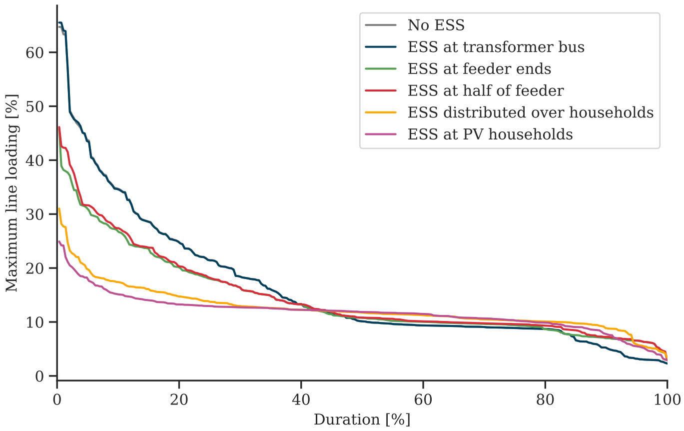

Fig. 4.10.: The load duration curves of the maximum line loading levels for different ESS placement scenarios over three days in November.

The same effect is witnessed for the generation-dominated case as shown in Figure 4.11. Also here, the maximum line loading is reduced in all five ESS placement scenarios compared to the baseline except for the ESS placed at the transformer bus. Again, the scenarios in which the ESSs are placed at the feeder end show almost identical intermediate results as the scenario in which the ESSs are placed halfway through the feeders. For the higher line loadings, the ESSs that are placed at the PV households distinguish themselves from the randomly distributed ESSs since heavy line loading during the generation-dominated cases is mainly caused by high PV production that can be absorbed without loading the grid by ESSs close to the PV installations.

4.3.3 Transformer Loading

Lastly, the results for the transformer loading are analysed for both load-dominated and generation-dominated scenarios. In the load-dominated case, the experiments simulate conditions where electricity consumption is high relative to generation. Figure 4.12 shows the load duration of the transformer loading levels over time for the load-dominated case. Compared to the base case without ESS, transformer loading is reduced in each ESS placement scenario. Results are almost identical for each placement scenario since the transformer only sees the net power of the local grid (i.e. generation plus load minus ESS power) which is (almost) identical in each ESS placement scenario. For the ESS placed at the transformer bus, however, the same effects as in the power-orientated simulations can be observed where the ESS takes on the role of the tap-changing transformer by creating a voltage rise over the transformer itself.

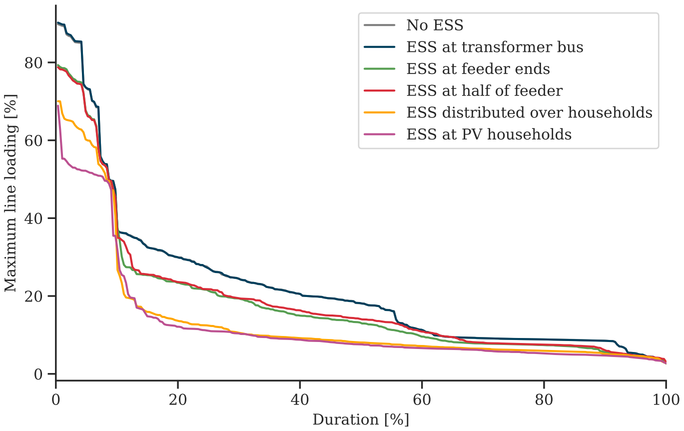

Fig. 4.11.: The load duration curves of the maximum line loading levels for different ESS placement scenarios over three days in July.

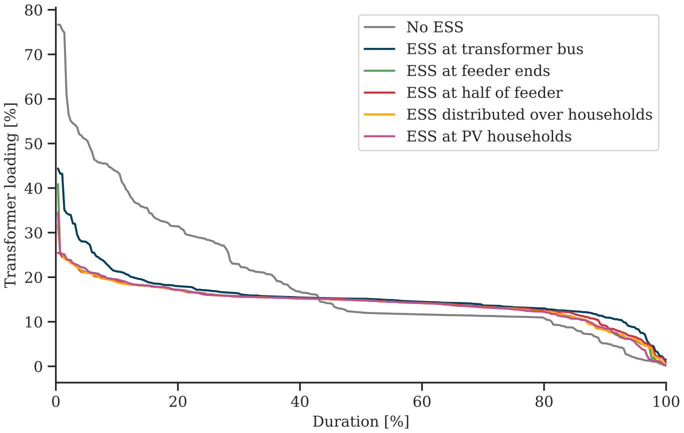

Fig. 4.12.: The load duration curves of the transformer loading levels for different ESS placement scenarios over three days in November.

The same effect can be seen for the generation-dominated case as shown in Figure 4.13. Also here, the ESSs show a large reduction in transformer loading compared to the base scenario in without ESSs. Similar to the load-dominated scenario, the ESS in the different placement scenarios have (almost) identical effects on the transformer loading. Also here, the ESS placed at the transformer bus, takes on the role of the tap-changing transformer.

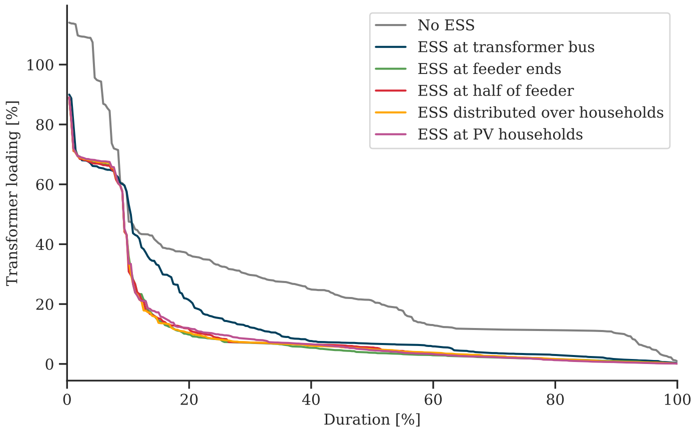

Fig. 4.13.: The load duration curves of the transformer loading levels for different ESS placement scenarios over three days in July.

4.4 Impact on Grid Reinforcement

As shown in this chapter, deploying ESSs (controlled with a grid load reduction objective) into low-voltage grids could have significant implications for grid reinforcement. The experiment results demonstrate that the placement and sizing of ESS have a substantial influence on their effects on the grid. Specifically, strategic placement of ESS can significantly reduce voltage deviations, line loading and transformer loading, while improper placement can lead to suboptimal outcomes or even adverse effects. For instance, ESS units placed near PV households are particularly effective in mitigating voltage swell during overproduction, whereas those placed at the transformer bus show negligible impact on voltage levels. The integration of ESSs *could* reduce the need for grid reinforcement activities such as upgrading cables, i.e. reducing the impedance of cables by replacing them with cables with a larger cross-sectional area or installing more cables in parallel with the existing cables. Or transformer upgrades i.e. replacing transformers with larger power ratings. This section covers the various impacts of ESS deployment on grid reinforcement, focusing on the effects observed in the presented results. Also, the effects of reducing the line resistance are presented and compared with the other simulation results.

The strategic placement of ESS can mitigate voltage deviations and manage line loading effectively, thus potentially reducing the need for upgrading cables. ESS units placed at PV households are particularly effective in reducing voltage swell during periods of PV overproduction and therefore stabilizing voltage levels across feeders. When ESS units are randomly distributed among households, they effectively manage voltage levels and line loading during both high consumption and high generation periods. On the other hand, ESS units placed at the transformer bus show negligible impact on voltage deviation and line loading, suggesting that this placement does not contribute significantly to reducing the need for cable upgrades.

The sizing of ESS also significantly impacts transformer loading, influencing the need for transformer upgrades and reducing the probability of transformer overloading. The different ESS placement scenarios show a similar, but substantial reduction in transformer loading.

By reducing the overall load on transformers, ESS units can extend transformer lifespan and prevent the need for upgrades. While effective in reducing line loading, scenarios involving random distribution and PV household ESS also contribute to smoothing the overall power profile and thus reduce transformer loading.

An exception is the ESS placed at the transformer bus showing abnormal behaviour by increasing transformer loading as aggregated ESS power increases with the power-orientated control method. This occurs when ESS power exceeds the net demand, supplying more and more power to increase the overall voltage in the grid. In reality, increasing the overall voltage of the grid can also be done by changing the tap position of the transformer. The increased transformer loading could potentially increase when ESSs are controlled with this version of the power-orientated control method and increase the need for transformer upgrades if not carefully managed.

As covered in section 2.1.7, one of the more conventional methods to address grid congestion is upgrading cables i.e. reducing the impedance of cables by replacing them with cables with a larger cross-sectional area or installing more cables in parallel with the existing cables. As a comparison to the presented ESS simulation results, Figure 4.14 shows the voltage deviation in the same grid layout as the other experiment for different line resistances for all lines. As shown in Table 4.1, the cables in the grid model used in this thesis are the NAYY 4x50mm^2 with a specific resistance of 0.642 $\frac{\Omega}{km}$. For reference, upgrading these cables to the NAYY 4x120mm^2 or NAYY 4x150mm^2 would decrease the specific resistance to 0.225 $\frac{\Omega}{km}$ or 0.208 $\frac{\Omega}{km}$ respectively (± factor 3 reduction). Figure 4.14 shows voltage deviation in the grid while decreasing the line resistance gradually to a factor 3 (R/3). Here, R/1 (thus R= 0.642 $\frac{\Omega}{km}$) represents the baseline measurement.

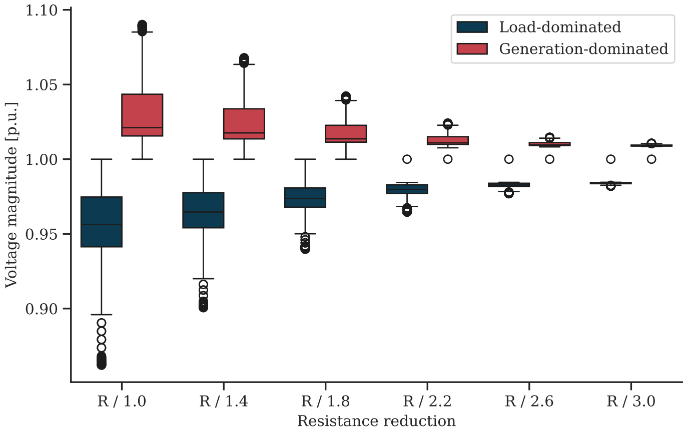

Fig. 4.14.: The distribution of the voltage magnitude levels of all buses in the grid for decreasing line resistance for the load-dominated and generation-dominated case.

Also, the simulation results show that almost all ESS configurations have a decreasing effect on line loading. Upgrading cables also has a reducing effect on the line loading of the cables: cables with a larger I_{max} have a lower line loading L_e for the same current I. Upgrading the NAYY 4x50mm^2 from the grid model used in the ESS simulations with an I_{max} of 0.142 kA to a NAYY 4x150mm^2 would increase I_{max} to 0.27 kA. Figure 4.15 shows the load duration of the line loading levels with the original cables without ESS, the line loading with ESS distributed over the PV households (the best case from Figure 4.10) and a scenario without

ESS but with the upgraded cables (0.27 kA instead of 0.142 kA). The results show an important difference between addressing grid congestion by upgrading conventional grid assets versus deploying ESS: Although upgrading cables reduces the overall size of the load duration curve, it does not change its shape. In other words, upgraded cables allow for more current, but the peaks remain unchanged. While the area under the red line for the ESS scenario in Figure 4.15 might be larger than the area under the blue curve for the upgraded cables scenario, the largest peak load in the ESS scenario is smaller than the peak load in the upgraded cables scenario. Since electricity grids must be able to transport power at all times, they must be designed to handle extreme cases (i.e. peaks). Without addressing these peaks, the grid must be designed to handle peaks while being oversized most of the time. As shown in Figure 4.15, ESSs can spread out the loading of lines, easing the requirements for handling peaks and resulting in more effective use of transport capacity. Moreover, from an energy perspective, integrating ESSs can provide flexibility that traditional grid reinforcement cannot. This flexibility is becoming more and more important for matching supply and demand in energy systems with increasing penetration of intermittent RES such as PV and wind power. Managing this intermittency is essential for the transition towards a more sustainable and stable energy system.

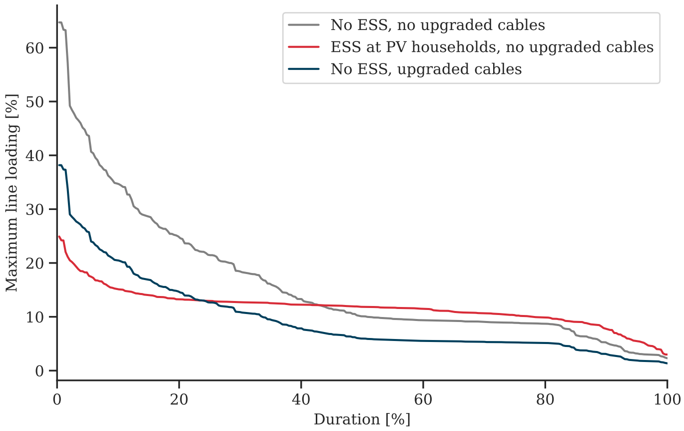

Fig. 4.15.: The load duration curves of the maximum line loading levels for a scenario without ESS and no upgraded cables, with ESS at PV households and no upgraded cables and with no ESS and upgraded cables for three days in November.

5

Socio-Economic Perspective

So far, this thesis has covered the technological effects of the siting and sizing of ESSs in electricity grids. However, beyond the technical role, the deployment of ESSs also has socio-economic implications that must be examined to ensure the successful deployment of ESSs in the Dutch electricity grid. This chapter covers the socio-economic effects of siting and sizing ESSs in Dutch low-voltage grids, focusing on how these systems impact energy justice by analysing smart grid pilot projects in the Netherlands. Additionally, this chapter addresses the challenges associated with the integration of ESSs regarding institutional barriers.

The transition towards a more sustainable energy system is not just a technological challenge. The implementation of novel technologies in a rapidly evolving energy system could have (unforeseen) socio-economic effects. For example, the case of net metering for residential PV panel owners in the Netherlands. Net metering allowed residential solar panel owners to offset their electricity consumption by feeding surplus power back into the grid. Under this policy, households received a one-to-one settlement for the electricity they supplied to the grid on a yearly basis, effectively reducing their energy bills [31]. The policy had the desired effect (at the time) as it greatly encouraged the adoption of solar panels over the last decade, increasing the share of PV power in the Dutch energy mix. As more households installed PV panels, the overall costs associated with purchasing and installing these systems (and therefore payback time) decreased due to economies of scale and increased competition in the market, making renewable energy accessible to more households.

On the other hand, the rapid increase in PV power in the Duch grid is partly responsible for the grid congestion problems addressed in this thesis. From the perspective of the DSO, it seems logical to phase out the net metering policy to encourage self-consumption. Furthermore, the costs for grid reinforcement required for the transportation of the excess PV energy are distributed over all grid users, including the grid users who do not or cannot own PV panels and have never benefited from the reduced energy bills. However, phasing out the net metering policy could increase the payback time of a PV installation, making PV technology less accessible for groups that could merely afford a PV installation thanks to the net metering policy.

5.1 Energy Justice

Energy justice can be defined as ‘equitable access to energy, the fair distribution of costs and benefits, and the right to participate in choosing whether and how energy systems will change’ [45]. In [44], four smart grid pilots were assessed on energy justice of which three are of interest in the context of this thesis. In this assessment, three dimensions of energy justice were dominant: Distributive justice (focusing on the fair distribution of costs and benefits), recognition justice (emphasizing inclusivity and addressing potential misrecognition of vulnerable stakeholder groups), and procedural justice (fair and equitable decision-making processes).

One of these pilots was a neighbourhood ESS (NESS) pilot in Rijsenhout, the Netherlands from [79] (also mentioned in the literature review of this thesis) in which 35 social housing tenants, who rented PV systems, participated in the neighbourhood battery pilot.

Another ESS pilot was a Virtual Power Plant (VPP) pilot in Amsterdam [72]. This pilot aimed to test storage systems, develop a business case for trading local flexibility on the wholesale market and provide residential prosumers access to energy markets. 48 households, who all had owned PV systems before, participated. In contrast to the single neighbourhood ESS in the Rijsenhout pilot, flexibility was created by aggregating the capacity of the home batteries of the participating households.

A third pilot was Gridflex (GF) [64] in Heeten, the Netherlands. The primary aim of the project is to maximize the self-consumption of locally generated renewable electricity by individual households and the neighbourhood as a community, thereby minimizing the load on the neighbourhood's transformer.

5.1.1 Distributive Justice

In the VPP pilot project, all home ESS capacities were aggregated and profit was generated by deploying this aggregated flexibility on the wholesale market. These profits were equally distributed among the participants. This mechanism was not evaluated as fair by [31] as in the VPP, the charging and discharging power were not necessarily equally distributed over the privately owned ESS (beyond the control of the owner), resulting in equal benefits, but unequal ESS losses and therefore unequal costs. To overcome this, participants were compensated based on their battery losses. As another alternative, participants suggested a model where aggregators rent a part of the ESS capacity for a fixed fee to use the remaining ESS capacity for self-consumption.

In the GF pilot, dynamic network tariffs were based on the load on the neighbourhood's transformer. The community received any cost reduction generated from the variable tariffs as a collective benefit, which was considered fair and aligns with the principle that a community's effort to achieve energy savings should result in benefits shared across all its members. This collective mechanism was perceived as fairer than the individual mechanism as tested in the VPP pilot. The collective mechanism was considered less disruptive by the participating households as they could rely on community solidarity to shift demand if they could not do so themselves because of circumstances. With the individual mechanism, any inability to shift peak demand would directly lead to higher costs. This is in line with [61], who argues that variable tariffs may negatively impact individuals with low demand flexibility.

In short, [44] argues that individual profit allocation is appropriate if there is no energy community, individual households can control their benefits directly and have transparency over their influence on the profit. The collective allocation, on the other hand, would be seen as fair if benefits depend on collective action, and households belong to an energy community that manages the collection and distribution of financial benefits. A collective benefit should reward a community effort to achieve energy savings for the entire community [44].

5.1.2 Justice as Recognition

The fact that all participants in the discussed pilot programs voluntarily signed up for the projects poses challenges for generalization and raises concerns about potentially overlooking the needs of other, especially more vulnerable, societal groups through structural misrecognition [44]. Justice evaluations regarding the accessibility of technologies in the four cases were dependent on whether participating households were required to own PV systems and/or batteries. This reflects the lack of inclusiveness of PV and ESS due to criteria related to income, space availability and house ownership. The NESS project was considered the most inclusive as it demonstrated the benefits of a community battery for social housing tenants which are a socio-economic group that would normally not qualify for the benefits of ESSs in electricity grids.

More generally speaking, in energy systems, the sharing of electricity network costs and subsidies for renewable energy tend to favour higher-income households with suitable homes for installing PV systems, enabling them to save on energy expenses. Vice versa, lower-income households without the means to install their own generation may experience higher energy bills due to greater adoption of renewables [14]. Also, with the increasing adoption of smart grid technologies and a growing trend of rewarding flexibility, there is a potential risk of further increasing energy inequality: Smart grids are for smart people. Besides ample financial means, smart grid technologies and dynamic pricing require a certain degree of IT literacy and understanding of the energy system to successfully operate.

5.1.3 Procedural Justice

Procedural justice refers to the fairness and transparency in decision-making processes related to policies, regulations and resource allocation. When comparing VPP and NESS, procedural justice evaluations depended on the degree to which decisions with the most visible impact on the households were participatory. In both projects, the control strategies for the batteries were chosen to be top-down, meaning that households had no participation in the control of the (dis)charging behaviour of the ESS(s). In the VPP project, this was considered insufficiently transparent. Since the ESS were used for trading, their charging and discharging behaviour was not directly coupled to the load and generation behaviour of the household where the ESS was placed. The fact that the VPP was a ‘black box’ for the ESS owners led to less engagement and less monitoring of their energy patterns. However, it should be noted that less engagement does not necessarily lead to less energy justice.

For the neighbourhood battery project, the top-down battery control was not considered insufficiently transparent. This is most probably because the ESS was not placed at the users’ plot and the individual consumer behaviour and ESS behaviour being coupled makes more sense. According to [44], this could be because households had the opportunity to influence one of the (for them) most critical decisions regarding the community battery: the exact location and visual design of the battery container. This underscores that for participation to be considered fair, project decisions that significantly affect users and are not easily reversible should involve their participation [71].

None of the pilot projects under study incorporated household participation through collaborative ownership of assets, despite this being a significant aspect of citizen involvement in other facets of the energy transition, such as the establishment of wind and solar parks. Studies have shown that collaborative ownership enhances public acceptance of these energy projects [16].

5.2 Institutional Barriers

Several institutional barriers hinder the adoption and effective utilization of the ESS solutions proposed in this thesis. For example, the net metering policy, as discussed in the introduction of this chapter, allows PV owners to use the grid as an infinitely large battery at no cost. This means that under this policy, storage has little financial viability for PV owners. At the time of writing this thesis, plans indicated that the net metering policy would be gradually phased out over the next few years. However, there has been significant confusion and uncertainty surrounding this issue due to changes in government and policy directions. This ongoing uncertainty may have already had and may continue to have, negative consequences for the adoption of ESS solutions. As the policy is phased out or if energy suppliers begin charging PV owners extra fees, ESSs might become more attractive for residential PV owners.

Also, as discussed in Chapter 2, the Dutch electricity market enforces strict ownership unbundling, separating network operations from commercial activities such as generation and retailing. This restriction prevents DSOs from directly owning and operating storage systems. Increasing the commercial ESS capacity in the Netherlands might cause more congestion when these systems are only used for commercial trading on the energy markets. As a result, they are not installed or installation must wait until the grid is reinforced [9]. Limiting the deployment of ESS in the Dutch grid as a whole.

Lastly, co-ownership of ESS in Dutch grids might enable co-optimizing investment, payback time and grid-friendly operation, enabling ESS deployment. Collective ownership has also proven to enable distributive and procedural justice for wind and PV energy projects [46].

5.3 Conclusion

This chapter analyzed how decision-making in smart grid solutions with ESS, as discussed in this thesis, can influence energy justice. From a distributive justice perspective, it is crucial to ensure that profits and costs are fairly distributed. Systems where cost savings are derived from collective efforts are considered more fair. This principle also applies to justice as recognition, ensuring that the benefits of smart grid solutions are accessible to all energy users, particularly those with low disposable income, tenants and households that lack the physical space to install an ESS.

Regarding procedural justice, it is important to involve energy users in decision-making processes. When an ESS is installed in a public space, users are generally less concerned about not being involved in the (dis)charging control. In such cases, fairness is better achieved by involving participants in decisions about the location and visual appearance of the ESS. This could apply to a scenario where a large ESS is placed near a transformer.

Involving participants in decision-making about the ESS's control strategy is more crucial when the ESS is installed on private property than when it is located in public spaces. Given the control methods proposed in Chapter 3, which are controlled with a centralized controller, the (dis)charging behaviour of the ESS may not directly correlate with the energy use of the individual housing the ESS. Therefore, transparency about the ESS's operations is essential.

Regarding the distribution of ESS costs, placing (privately owned) ESS units in households with PV installations can be considered fair because these energy users are often the primary contributors to grid congestion issues. This consideration also applies to EV owners, who typically have higher financial means and stand to benefit the most from PV and EV investments compared to, for instance, tenants without PV and EVs. Although these users may not appreciate losing direct control over the ESS, enhancing self-consumption with their ESS can reduce energy costs, particularly if the net metering policy is phased out.

Experimental results in Chapter 4 indicate that all ESS placement scenarios reduce the load on the transformer, suggesting that a dynamic grid tariff structure, similar to the one used in Gridflex, could be implemented across all scenarios. In this context, it would be fairer if households with heavy loads and substantial PV installations paid for the ESS, as they are often the main contributors to the increased transformer loads in the first place. Such a tariff structure would ensure equitable cost distribution among the households benefiting the most from ESS deployment. Furthermore, collective ESS management, as observed in pilot projects like Gridflex, supports procedural justice by involving community members in decision-making processes, thereby enhancing public acceptance and participation and promoting energy justice.

ESS co-ownership could further improve distributive and procedural justice. By allowing multiple households to co-own and manage ESS units, the benefits and costs can be more equitably shared. This approach aligns with the principles of collective benefit and community solidarity, as demonstrated in the Gridflex pilot, where dynamic tariff profits were shared among the community. Co-ownership also facilitates greater involvement in decision-making, ensuring that all stakeholders have a say in managing the ESS. For example, decisions about benefiting from dynamic grid tariffs linked to transformer load or from profits in the energy markets, as in the VPP project, can be made collectively, with the DSO setting break-even points through dynamic grid tariffs.

Successful co-ownership models in other renewable energy areas, such as wind and solar parks, have increased public acceptance and participation. Applying similar models to ESS deployment can enhance transparency, build trust among community members and ensure that the benefits of ESS are accessible to a broader range of households, including those with lower incomes or less technical expertise.

Besides assessing the impact of ESS distribution on energy justice, the impact of not deploying ESS on energy justice could also be assessed. As shown in section 4.4, The challenges of grid congestion, including over/under-voltage issues and line overloading, can be mitigated by upgrading cables to reduce their resistance. However, the socio-economic impacts of such grid reinforcement efforts should also be considered. As mentioned in the 1, reinforcement of the grid involves investing over 8 billion euros per year from 2025 [51, 53] which is an investment in one of the largest co-owned assets in the energy system: the electricity grid.

The magnitude of grid load peaks significantly influences the transport capacity requirements of this shared grid, as explained in section 4.4. These peaks are increasingly driven by the synchronized overproduction of PV installations in residential low-voltage grids and the synchronized charging of EVs. As discussed in earlier sections of this chapter, PV and EV owners have benefited from both the financial and environmental advantages associated with these technologies. Not deploying ESS in Dutch low-voltage grids as a temporary solution, relying solely on conventional grid reinforcement measures, such as upgrading cables, would result in every grid user bearing the cost of a grid capable of handling peaks caused largely by a specific socio-economic group, albeit unknowingly.

As demonstrated in Figure 4.15, while deploying ESSs at the household level may not significantly reduce overall line loading compared to cable upgrades, it does reduce peak loading, thereby reducing the need for grid reinforcements in residential low-voltage grids. Financing these ESSs, particularly by PV overproducers, could be considered more fair from a distributive justice perspective. This approach would ensure that the benefits of owning an overproducing PV system, along with the costs associated with managing this overproduction through a privately owned ESS, are less disproportionately shifted onto all grid users via collectively funded grid reinforcements. Phasing out the net-metering policy could encourage PV owners to increase their self-consumption with a home ESS, thereby enhancing energy justice.

6

Conclusions and Future Work

This thesis aims to investigate the effects of the distribution of energy storage systems in Dutch low-voltage grids with a focus on both the technical and socio-economic aspects. The research was guided by several sub-questions as presented in section 1.2, each of which was addressed through a combination of literature research, modelling and socio-economic analysis. This chapter summarizes the findings and contributions of this thesis. It also outlines recommendations for future research.

6.1 Conclusions

In this section, each sub-question will be systematically answered to ultimately answer the main research question: **What is the impact of the distribution of electricity storage systems in Dutch low-voltage grids?**

What are the characteristics and topology of Dutch low-voltage grids?

Dutch low-voltage grids are part of a larger international grid structure with multiple hierarchical levels, where low-voltage networks represent the lowest level. These grids typically feature radial structures with three-phase four-wire underground cables, managed by Distribution System Operators (DSOs) committed to serving the public interest. The rapid integration of renewable energy sources, such as photovoltaic systems alongside the increasing electrification of heating and transportation, has introduced significant challenges. These include voltage fluctuations, line overloading and transformer overloading, which force DSOs to place requests for new or larger connections on hold until these issues are addressed. A phenomenon referred to as grid congestion. Traditionally, grid congestion is addressed through infrastructure upgrades, such as upgrading cables and transformers. However, alternative solutions such as demand-side management, curtailment and the deployment of energy storage systems *could* also reduce the stress on the grid. Within low-voltage grids, ESSs can be categorized into home ESSs and more centralized neighbourhood ESSs.

How can ESS placement and sizing be optimized

To optimize the placement and sizing of Energy Storage Systems (ESS) within distribution grids, various methodologies have been proposed, including analytical methods, mathematical approaches and heuristics. Analytical methods involve testing predefined sets of variables against an objective function, making them suitable for quickly providing accurate results in small, simple systems. Mathematical approaches, such as linear programming and mixed-integer linear programming, are used to find the exact optimal solutions for ESS placement and sizing. While these methods offer precise solutions, they are computationally expensive and may become impractical for larger, more complex grids. Heuristic methods, which trade off optimality for speed, are particularly effective for large-scale optimization problems where mathematical methods may be too slow.

The literature highlights the effectiveness of ESS in congestion-constrained grids. Both as a temporary solution until the grid is sufficiently reinforced and a permanent solution to enhance the grid's flexibility. When it comes to optimization, sensitivity analysis seems to be a more suitable approach for broader assessments, allowing for a general understanding of how grid variables such as voltage deviation and line loading respond to ESS placement and sizing. Making it a particularly useful method for the broader evaluations aimed at in this thesis.

What are the effects of the distribution of ESSs on grid reinforcement?

The simulation scenarios include ESS placements at the transformer bus, halfway along feeders, at feeder ends, distributed across households and at PV households. Each scenario, in which the ESSs are controlled with a control objective aimed to reduce stress on the grid, is compared to a baseline without ESS to simulate their effect on voltage magnitudes, line loading and transformer loading in the local grid. ESSs can reduce the need for grid reinforcement actions such as upgrading cables and transformers but their effectiveness in improving voltage stability, reducing line loading and reducing transformer loading may vary depending on their placement and sizing. ESSs that are sited near large generation assets such as PV installations are the most effective in reducing voltage deviation, line loading and transformer loading. The comparison between upgrading grid infrastructure and deploying ESSs shows that while upgrading cables might improve overall current carrying capacity and reduce the overall loading of cables and transformers, ESSs could be more effective in managing peak loads and spreading line and transformer loading more evenly, thus offering a potentially more flexible approach to grid reinforcement that could better cope with the intermittent nature of future load and generation profiles.

What are the socio-economic effects of ESS distribution in Dutch low-voltage grids?

ESS distribution and its effects on grid reinforcement have significant socio-economic effects. From a distributive justice perspective, fair distribution of costs and benefits is essential. Distributive justice requires that the advantages of ESS, such as cost savings, are accessible to all users, including those with limited financial resources, physical space, IT literacy or ability to react to dynamic pricing schemes. Procedural justice emphasizes the need to involve energy users in decision-making. For ESSs placed in the public domain, user involvement should focus on the location and visual appearance of ESSs. For home ESS, transparency about operations is considered more important by smart grid pilot participants, as users might not directly see how their energy use influences ESS (dis)charging behaviour.

Not deploying ESS could lead to an unfair distribution of costs for grid upgrades. Relying solely on traditional grid reinforcement methods, such as upgrading cables, could lead to disproportionate costs for all grid users. ESS deployment can help mitigate these costs and enhance energy justice by ensuring the financial burden of managing grid congestion is more fairly distributed. Here, fair cost distribution should consider that households with overproducing PV systems or large EV chargers, which often contribute to grid congestion, should finance home ESSs. Phasing out the net metering policy in the Netherlands could encourage overproducing PV installation owners to increase their self-consumption and reduce stress on the grid.

6.2 Recommendations for Future Work

The research questions addressed in this thesis have been answered. However, several areas still require further research. This section offers recommendations for future work.

In the simulation, the ESSs were controlled with a DSO-orientated control strategy meaning that its objective is to reduce the stress on the grid. Future work is needed to investigate the effects of ESS distribution when ESSs are not necessarily controlled to reduce grid stress but with other objectives such as maximising revenue on imbalance markets.

Secondly, in this study, the ESS power-orientated and combined control algorithms see each bus voltage and know the impedance of lines in the grid to compute the voltage sensitivity and optimize ESS power based on that. In reality, this data might not be available (at all times) and more research is needed.

Also, this thesis studied the effects of ESS distribution from a technical and socio-economic perspective. ESS distribution could also have (significant) effects on the financial aspects of ESSs. Single, larger ESS might benefit from economy of scale compared to home ESS. Future work could focus on the financial effects of ESS distribution.

Moreover, low-voltage grids do not stand on their own. They are connected to the medium voltage grid. Future work is needed to investigate the effects of ESS distribution at higher grid levels. This could also include simulating a larger variety of load profile data such as wind power production profiles and industrial or commercial consumption profiles.

Lastly, the ESSs in this work are modelled with 100% efficiency. In reality, ESSs have an efficiency below 100% meaning that the total amount of discharged energy will be less than the total amount of charged energy. In future work, ESSs could be modelled with more realistic efficiency levels and the effects of ESS distribution on grid losses could be optimized.

A

Energy-Orientated Optimization Results

A.1 Discussion

The results for the minimum and maximum voltage magnitude were analysed for both load-dominated and generation-dominated scenarios in Figure A.1 and Figure A.2 respectively. ESS units placed at PV households are most effective in mitigating voltage swell during PV overproduction, while also slightly increasing voltage during high consumption periods, such as the evening peak. ESS units at the transformer bus have a negligible impact on voltage levels, showing outcomes nearly identical to those without ESS in both scenarios. Conversely, ESS units at the end of each feeder help reduce higher voltages during PV peaks but may slightly increase voltage drops due to their high charging activity.

Regarding average line loading in Figure A.3 the scenario with ESS at the transformer bus shows almost identical average line loading compared to the scenario without ESS. The scenario with ESS units at PV buses achieves the lowest average line loading during PV overproduction. However, randomly distributed ESS units across households result in lower average line loading levels during high-load periods.

For transformer loading in Figure A.5 and Figure A.6, all ESS placement scenarios yield similar results. In each scenario, the ESS units smooth the overall power profile of the grid, thereby smoothing the loading profile of the transformer as well.

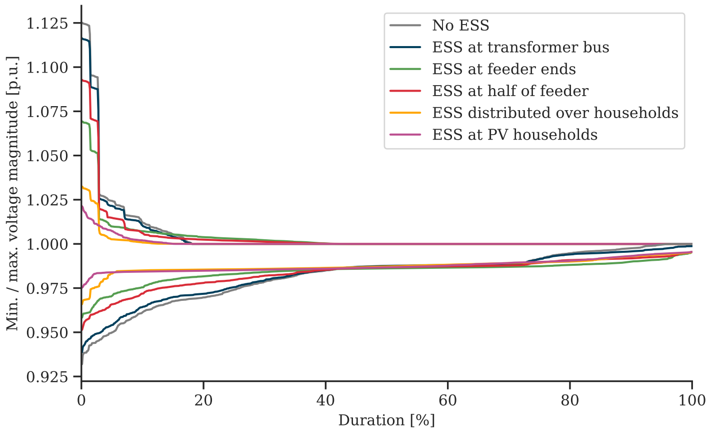

Fig. A.1.: The minimum and maximum voltage of all buses in the grid for different ESS placement scenarios over three days in November.

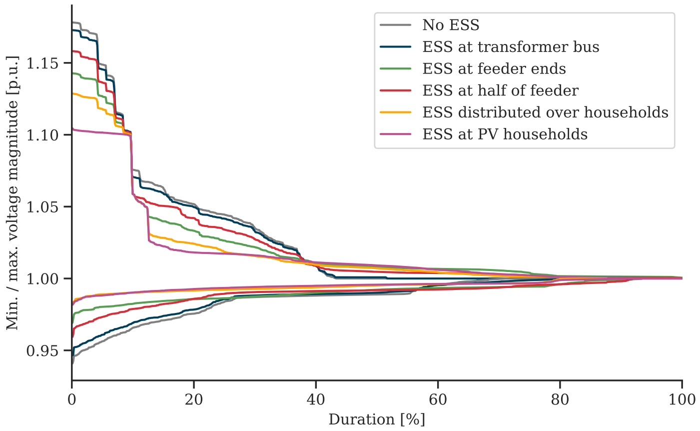

Fig. A.2.: The minimum and maximum voltage of all buses in the grid for different ESS placement scenarios over three days in July.

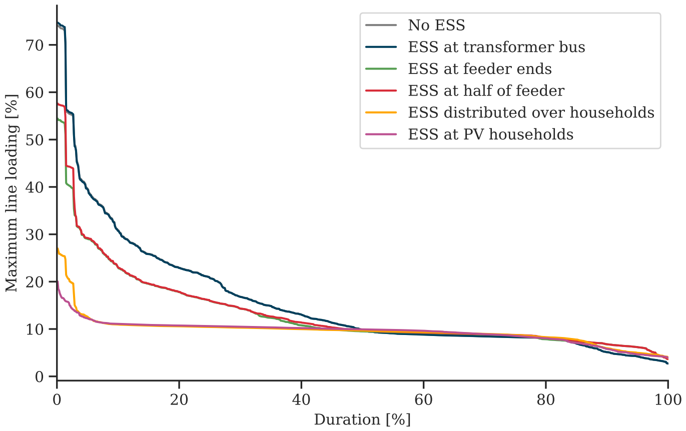

Fig. A.3.: The maximum line loading levels of all lines in the grid for different ESS placement scenarios over three days in November.

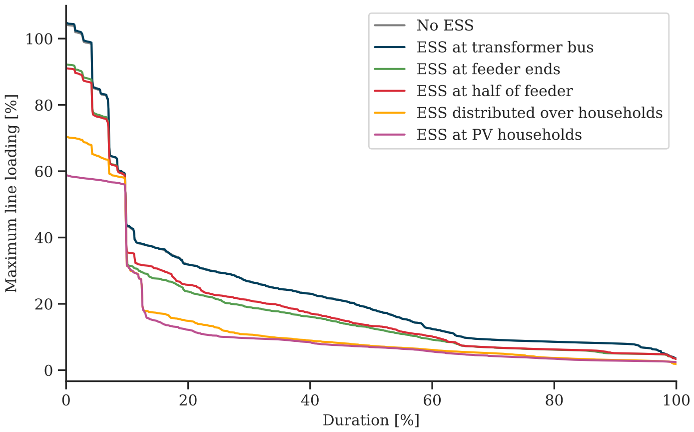

Fig. A.4.: The maximum line loading levels of all lines in the grid for different ESS placement scenarios over three days in July.

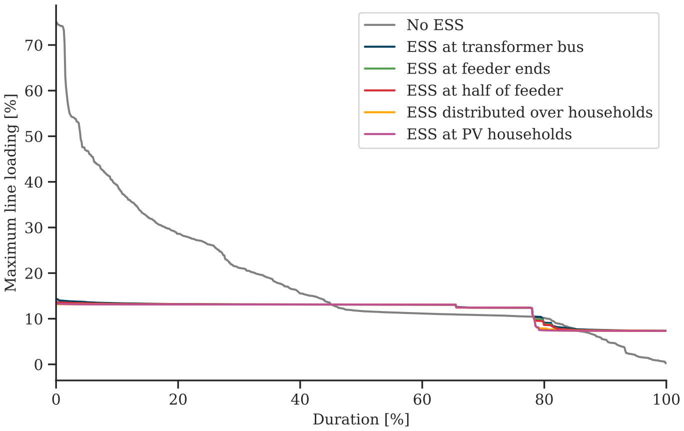

Fig. A.5.: The transformer loading in the grid for different ESS placement scenarios over three days in November.

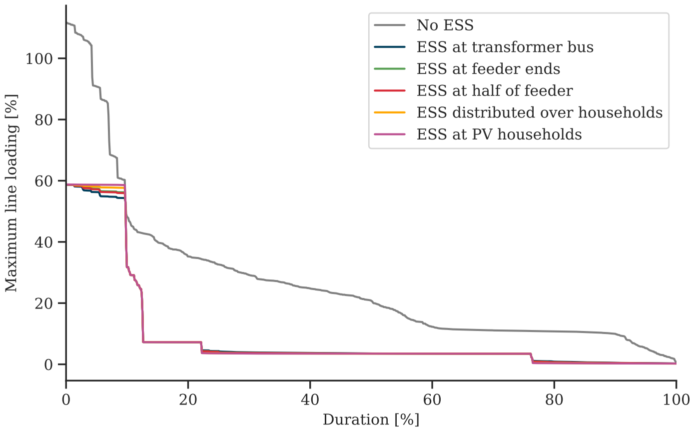

Fig. A.6.: The transformer loading in the grid for different ESS placement scenarios over three days in July.

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