Ensuring Effective Prioritization of Dutch Low Voltage Grid Investments in a rapidly evolving energy system.

Evaluating the robustness of prioritization methods used in project Buurtaanpak

By

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Abstract

The rapid energy transition in the Netherlands, coupled with decades of regulations prioritizing cost-efficiency over future capacity investments in the low-voltage (LV) grids, has resulted in an overwhelming number of LV grids desperately requiring capacity upgrades. Dutch regional grid operators have been making significant efforts to proactively upgrade neighborhood grids, while managing significant resource limitations. To ensure that limited resources are well spent, Dutch regional grid operators are employing novel prioritization methods, to determine a sequence of neighborhoods that should receive capacity upgrades. This thesis investigates how one of these Dutch regional grid operators, Stedin, can ensure the effectiveness of the prioritization of investment in the LV grids in neighborhoods amidst emerging uncertainties from regulatory, policy and market developments. The primary objective of this study is to provide Stedin and other regional grid operators with actionable recommendations that can improve the robustness of prioritization methods.

To achieve this objective an exploratory approach is taken, combining a literature review of prioritization strategies in large infrastructure projects, extensive desk research into practices by Dutch grid operators, expert interviews to get a detailed understanding of Stedin's prioritization method, and an analysis of uncertainties emerging from the energy transition.

The main findings reveal that while Stedin's current method incorporates proven prioritization approaches, including risk assessment, cost-benefit analysis, and a proactive approach, its heavy reliance on scenarios designed in collaboration with Netbeheer Nederland introduces significant risks due to oversimplification of the energy transition. Several practical recommendations were developed that can be considered by Stedin to improve the robustness of its prioritization method amidst a rapidly developing energy landscape. The main recommendations include reducing dependency on the scenarios, maintaining a proactive approach, and improved collaboration with key stakeholders. These recommendations could not only strengthen Stedin's prioritization method but also offer insights for other grid operators navigating similar challenges.

CONTENTS

List of Abbreviations

ACM (Authority for Consumers and Market)

Analytical Hierarchy Process (AHP).

Carbon Capture and Storage (CCS)

Climate Ambition (CA)

Cost Benefit Analysis (CBA)

Critical Peak Pricing (CPP),

Decentralized Initiatives scenario (DEC)

Demand-Side Response (DSR).

Effort Sharing Regulation (ESR)

Electric Vehicle (EV)

European Green Deal (EGD)

European Integration scenario (EUR)

EU Emission Trading System (EU ETS)

European Union (EU)

Emission Trading System 2 (ETS2)

Energy Efficiency Directive (EED)

Greenhouse Gasses (GHG)

International Ambition (IA)

International Trade scenario (INT)

Land Use, Land-Use Change and Forestry (LULUFC)

Low-Voltage (LV)

Multi-Criteria Analysis (MCA)

National Drivers (ND)

National Grid Congestion Action Program (LAN)

National Leadership scenario (NAT)

National Plan Energy System (NPES)

Net Present Value (NPV)

NMa (Netherlands Competition Authority)

Real-time pricing (RTP)

Renewable Energy Directive (RED)

Stedin Energy Transition Assessment Model (SETIAM)

Time-of-Use (TOU)

Variable Peak Pricing (VPP)

CHAPTER 1 INTRODUCTION

1.1 BACKGROUND

To deal with the challenges resulting from global warming, the European Union (EU) has introduced the European Green Deal (EGD) (European Commission, 2020). One of the main goals of this deal is to have no net emissions of greenhouse gasses (GHG) by the year 2050. To guide this transition, the EGD includes an intermediary goal of reducing net GHG emissions by 55% in 2030 compared to 1990. A transition from primarily relying on fossil fuels to predominantly using renewable energy is necessary to achieve this GHG emission reduction. This transition toward renewable energy includes a major increase in electricity grid use, as renewable sources like wind and solar require extensive grid capacity to distribute the generated electricity. Besides shifting to renewably generated energy, electrification of transport and heating is expected to increase in order to reach the set climate goals (Strielkowski et al., 2021). This electrification will fundamentally change the way electricity is used in residential areas. Increasing electric vehicle (EV) charging stations, heat pumps, and induction cooking will result in a higher overall electricity requirement and potentially cause high coincident electricity demand (Celli et al., 2022). During high coincident demand, components of the low-voltage (LV) distribution grid can potentially reach and exceed the maximum rated capacity, which can cause voltage drops, congestion, or power outages (Jetten, 2024).

If not adequately managed by Dutch grid operators, the evolving energy landscape and increased electricity distribution and transmission grid usage can cause frequent outages and failures across the country. These issues could impact millions of Dutch residents and businesses. Currently, companies requesting an industrial connection to the Dutch grid are already experiencing the consequences of the increasingly congested grids, as there are long waiting times to be connected to the grid (Netbeheer Nederland, 2023).

To avoid a doomsday scenario in which frequent power outages and failures cripple the Dutch economy and impact the daily life of Dutch residents, Dutch grid operators are heavily investing in upgrading their grid networks. These investments include implementing new grid facilities consisting of transformers, powerlines, and substations (Spiliotis et al., 2016). In the Netherlands, the distribution network is operated by six independent regional grid operators. One of these regional distribution networks is operated by Stedin, which is responsible for delivering electricity to 2.3 million consumers (Stedin Group, 2023). Stedin plans to invest 8 billion euros in upgrading grid capacity by 2030 to ensure that Stedin's grid can meet with the rising demand for transmission capacity. However, the complexity of the distribution grids system in combination with constraining factors like available workforce, and material, restrict the speed at which the grid can be upgraded. To manage this limited capacity to upgrade the grid, careful decisions must be made to prioritize parts of the grid that most critically need upgrades. Previously, distribution grid operators employed a reactive approach to decide where grid infrastructure needed upgrades, as a result of constraining regulations by ACM (Authority for Consumers and Market).

This included operators starting to plan upgrades only when issues arose in specific parts of the grids. Continuing this reactive strategy, however, would likely result in numerous components becoming overloaded due to the increasing electrification and renewable energy production, leading to widespread grid instability and failures. Therefore, grid operators are now employing a proactive approach in making their grids futureproof.

A significant part of proactively upgrading the electricity grid at the neighborhood level is the "Buurtaanpak" initiative by the regional grid operators and Netbeheer Nederland (Stedin, 2023). This project is a collaboration between regional grid operators and the municipalities with the aim of making all the LV grids in neighborhoods future-proof by 2050. Making these neighborhoods future-proof consists of installing additional cables and transformers. Instead of addressing specific parts of the grids where issues arise, Buurtaanpak takes a systematic approach, upgrading entire neighborhoods one by one. By upgrading entire neighborhoods at once, the aim is to make grids future-proof for at least forty years, reducing the need for additional upgrades in the short term. Additionally, upgrading entire neighborhoods achieves economies of scale and reduces repeated disruptions for residents. Determining the sequence in which neighborhoods are upgraded is crucial to the success of the project Buurtaanpak. If neighborhoods critically in need of upgrades are overlooked, they could experience outages and failures, while neighborhoods receiving upgrades may not require them urgently. To assist in the decision-making process regarding the sequence of neighborhoods, Stedin and other grid operators are developing and using prioritization models that evaluate risks in neighborhoods and rank them based on the impact and likelihood of failures.

This thesis study originated from discussions with representatives of Stedin in which the question was raised: How can we evaluate our prioritization method used in the project Buurtaanpak and make sure that the method is effective in an uncertain system. This question was raised as the prioritization method and the project Buurtaanpak are still in the experimental phase. The first results of the prioritization method have not had enough time to be evaluated, and the accuracy of the sequencing of neighborhoods is therefore still largely unknown.

1.2 PROBLEM STATEMENT

The ongoing energy transition presents complex challenges for distribution grid operators. LV grids in neighborhoods that were originally designed to meet transmission capacity demands during their lifetime suddenly require upgrades as a result of renewable energy integration and electrification. To ensure future supply of electricity in neighborhoods Dutch grid operators are undertaking the complex Buurtaanpak project which includes systematically upgrading Dutch LV grids. A major challenge within this project is effectively prioritizing which neighborhoods most critically need upgrades to prevent outages, undervoltage, and overvoltage issues. This prioritization is critical to the success of the project as constraining factors limit the speed and quantity of neighborhoods that can receive upgrades.

Incorrect prioritization or a misinterpretation of external risks and uncertainties may cause grid operators to fail to upgrade the most critical parts of the grids, potentially resulting in significant operational and financial setbacks.

This thesis study originated from discussions with representatives of Stedin in which the absolute importance of correct sequencing of neighborhoods became clear whilst the prioritization method is still in the experimental stage. From these initial conversations with experts currently working on project Buurtaanpak, it became clear that the effectiveness of the prioritization of projects is mainly dependent on two factors. First, prioritization effectiveness depends on the accuracy and design of the prioritization method. This can be seen as the internal component of this problem. Secondly, uncertainties and risks emerging from outside developments, such as regulatory, policy, and market changes, can impact the prioritization of projects.

The prioritization methods are only just starting to being used by Dutch grid operators which makes these approaches interesting to study. The model only being in the experimental phase suggests that there is still room for improvement. Additionally, the influence of uncertainties and risks emerging from outside developments on the sequencing of neighborhoods may still be underestimated in the current prioritization methods. This thesis will therefore, extensively study prioritization methods to identify strengths that can positively impact the robustness of experimental prioritization methods currently used by Dutch grid operators in the Buurtaanpak project. Additionally, uncertainties and risks that can potentially emerge from regulatory, policy, and market developments impacting the LV grids in neighborhoods are studied in detail.

1.3 CONTEXT

To study the prioritization methods of regional grid operators, it is important to first, have an understanding of the context in which regional grid operators function. Over the last fifty years the Dutch electricity sector has undergone significant restructuring as part of the liberalization process. The restructuring of the electricity sector was deemed necessary to improve the efficiency of the system, to introduce market forces, and address monopolistic practices. From studying the liberalization of electricity markets around the world Jamasb and Pollit (2005) conclude that there are four key steps commonly involved in electricity reform processes. These steps are as follows:

- **Restructuring:** Vertical unbundling of generation, transmission, distribution, and supply activities to ensure operational independence of each function.
- **Competition and markets:** The introduction of a wholesale market and retail competition, while enabling new entrants into generation and supply.

- **Regulation:** The establishment of an independent regulator, provision of third-party network access, and implementation of incentive-based regulation for transmission and distribution networks.
- **Ownership:** The inclusion of new private actors and privatizing the existing publicly owned businesses.

This electricity reform that has taken place in the Netherlands follows several of these steps, which are discussed in the following sections.

1.3.1 HISTORICAL BACKGROUND

The history of grid operators in the Netherlands dates back to the early 20th century, when municipalities and provinces were responsible for the construction and exploitation of electricity grids. This structure resulted in hundreds of vertically integrated local utility companies, which managed the entire process from electricity generation to its distribution to end-users. As the 20th century progressed, the growing industrial demand, urbanization, and the need for reliable electricity supply led to an increased desire for a national electricity infrastructure. This marked the beginning of a transition from locally controlled grids towards a more liberalized energy sector which is the foundation of today's grid operators.

In 1986, it was agreed that the Dutch electricity sector would be restructured, and in 1989 a new electricity law went into effect that introduced a mandatory division between the generation and distribution of electricity (Hesseling and Sari, 2005). Additionally, a minimum capacity of 2.500 megawatts was introduced for electricity generators to encourage economies of scale and improve efficiency, which led to mergers among smaller generation companies. This law can be seen as the first step toward further liberalization as defined by Jamasb and Pollit (2005).

The Dutch electricity law of 1998 liberalized the electricity sector further by introducing market forces, allowing producers and suppliers to compete (Niesten, 2010). This competition was aimed at driving prices down, improving efficiency, and accelerating innovation. Additionally, under the new law, end-consumers were allowed to choose their own energy supplier. These market forces introduced price differences for the first time, as electricity prices became dependent on the supplier and contract terms chosen by consumers. The Dutch Electricity Act of 1998 also introduced a juridical and functional division of distribution and generation of electricity. This juridical division required that generation and grid operation were legally separated into different companies, while the functional division required operators to function independently from generation companies. This separation aimed to prevent conflict of interest and ensure that grid operators can operate neutrally, without being influenced by generation companies Despite this liberalization, grid management remained a heavily regulated activity as grid operators continued to have a natural monopoly. This natural monopoly exists because constructing multiple electricity grids in the same area is economically inefficient (De Vries et al., 2019). Therefore, it is included in the electricity law of 1998 that only one distribution grid operator may be active per region. At this point in time, the regulation of the grid operators was done by NMa (Netherlands Competition Authority), who monitors the grid tariffs and ensures that investments of grid operators align with societal needs.

In 2006 the “Splitsingswet” was put into effect, mandating the complete ownership unbundling of grid operators from generation activities to guarantee their independence. As a result, the large electricity companies definitively separated their production and grid operation activities, with the grid operations continuing as independent regional grid operators. To ensure that regional grid operators operate without commercial incentives and in the interest of society, they were put under strict regulatory oversight (Tieben et al., 2013). On the first of January 2008, Tennet was made responsible for all of the high-voltage grids. This restructuring established the foundation for the current electricity distribution structure, with Tennet as the transmission system operator, several independent regional grid operators, and the regulator ACM overseeing the system.

1.3.2 REGULATORY CONTEXT

In the earlier phases of the electricity distribution sector, regulations were primarily aimed at maintaining low costs. This focus on cost-efficiency stemmed from the desire to ensure affordable electricity for households and companies while promoting universal access. These low costs were achieved by only allowing minimal profit margins and strict control on investments. Until the Dutch Electricity Act of 1998 came into effect, regulation of grid operators was handled by local municipalities and the national government. With the implementation of the Dutch Electricity Act of 1998, regulatory oversight shifted to NMa. In 2013, ACM replaced NMa as the national regulator for Dutch grid operators and still regulates their operations today.

Since the introduction of the Dutch Electricity Act of 1998, grid operators have been regulated by an incentive regulation model. This model was designed to simulate competition to keep the costs low and to incentivize efficiency of the system. The regulator uses this model to determine grid tariffs, which are based on the operational costs, necessary investments, and an average return on investment on invested capital. The model assumes that grid operators can improve the efficiency of their activities by reducing costs or optimizing processes. Grid operators are rewarded if they can exceed the efficiency targets. The X-factor plays a central role in this model, which is an efficiency correction that is applied to the tariffs of grid operators (Meulmeester and de Laat, 2006). The X-factor indicates the amount of costs that a specific grid operators must reduce. If a grid operator achieves cost reductions greater than their X-factor, it can retain the surplus as extra profit. The idea behind this is that by incentivizing cost reductions, efficiency and innovation are stimulated.

However, this model creates challenges for long-term investments. On the short-term, this model incentivizes postponing large investments, as delaying costs allows operators to maximize their profits. Furthermore, this regulation model effectively prohibited proactive capacity upgrades, as such investments were not compensated within the regulated tariff structure. This means that even if grid operators wanted to proactively upgrade grids to accommodate the future energy transition, they were not able to, as they could not recover the investment costs.

For years, there have been numerous warnings in the media to the regulators that the energy transition requires significant proactive investments (van Hest and Kleinijenhuis, 2022). For instance, as early as 2008, a report was published by WRR, an independent advisory body to the Dutch government, in which was concluded that the upcoming energy transition would require substantial grid investments. The report also warned that favoring short-term efficiency goals over long-term public value introduces considerable risk for the society. The WRR recommended that the regulator incorporates incentives for long-term values in the regulation process. In 2012 a similar conclusion was drawn in a report by PwC which was commissioned by the regulator. This report emphasized the need for incentives to promote proactive grid investments by region grid operators (PwC, 2012). This report is particularly notable as it highlights the fact that the regulator was at the time well aware of the concerns. However, despite these clear warnings, these recommendations have long gone unanswered.

In 2019, ACM finally changed the tariff regulation model, and allowed grid operators to charge consumers for investments to meet future capacity needs. This significant change from the earlier tariff model, which only compensated for immediate investments and operational costs, facilitated Dutch regional grid operators to proactively invest in their grids. Since this change all Dutch regional grid operators have adopted a proactive strategy to keep up with the energy transition. However, decades of prioritizing short-term cost reduction over long-term stability of the grid have created an overwhelming amount of critically necessary investments. As a result, distribution grid operators regularly raise their concerns in the media about potential consequences of delays, such as capacity shortages, longer waiting times for new connections, and potentially failing national climate goals.

1.3.3 STAKEHOLDER ANALYSIS

To get a better understanding of the context in which grid operators reside it can be helpful to analyze the main stakeholders that influence the system. In this section the roles, priorities, and tensions among key stakeholders for Dutch grid operators are discussed. The stakeholders that are included in this analysis are the regulator (ACM, the national government, municipalities, and end-consumers. Table 1. shows the stakeholders, main roles and main priorities that are influencing the electricity distribution system.

Stakeholder	**Main role**	**Main priorities**
Regional grid operators	Maintaining, upgrading, and expanding the electricity distribution grid to provide continuous high-quality electricity to end consumers.	Ensuring reliable operations of the electricity grid. Scaling grid capacity to meet growing demand. Complying with regulatory frameworks while remaining financially healthy.
Regulator (ACM)	Monitoring the electricity market and ensuring that grid operators operate efficient and fair.	Protecting customers by keeping grid tariffs affordable. Ensure that non-discriminatory access is provided for all energy producers. Promoting an efficient grid to counter monopoly-related inefficiencies.
Dutch national government	Setting long-term energy and climate goals and design supporting policies and regulations.	Achieving the goals outlined in the Climate agreement of Paris 2015. Support grid operators to enable achieving these goals. Encouraging innovation to enable the energy transition.
Municipalities	Implement climate goals at the local level while balancing them with the interests of the residents.	Facilitating the energy transition in neighborhoods that align with national climate objective. Representing the interests of residents. Enabling stable and reliable electricity for residents.
End consumers	Daily use of the electricity grids.	Have access to affordable electricity. Experience minimal electricity outages or interruptions. Have access to sufficient capacity to electrify home appliances. Experience little nuisance in their neighborhoods.

Table 1. Showing the stakeholders including their roles and main priorities.

1.3.4 TENSIONS FOR GRID OPERATORS

The priorities of grid operators often conflict with the priorities of other stakeholders, creating significant tensions.

A key source of tension for grid operators arises from the regulatory framework that is imposed by ACM. The strict emphasis on short-term cost-efficiency has historically constrained proactive investments, leaving grid operators with little flexibility in preparing the grid for future capacity requirements. While recent reforms by ACM have provided grid operators more leniency for proactive investments, the process of obtaining approval from ACM remains time-consuming. These delays can significantly hamper grid operators in their challenge to upgrade grids, potentially causing issues.

Another tension that grid operators experience originates from the government. The national government has set ambitious national climate goals that require rapid upscaling of the grid. These goals place immense pressure on grid operators to scale-up the entire operation. However, the government does not always provide the necessary support to grid operators, leaving them to manage emerging problems largely themselves. When there are delays or issues, the grid operators are often held accountable in the media, even though the cause may lie in lacking policy or support by the government.

Grid operators depend on municipalities to provide clear future plans for the local energy needs for neighborhoods. These plans are essential for grid operators as without them it is impossible to make an accurate estimation of the grid capacity that is required in the neighborhoods. However, municipalities often face resource constraints, such as understaffing or lack of technical expertise which limits their ability to deliver detailed and timely plans. Additionally, municipalities may prioritize other pressing issues over the energy planning. This can cause tension for the grid operator as indecisions by municipalities can cause significant delays.

The relationship between grid operators and end-consumers is inherently delicate, as their priorities often conflict. Consumers expect low electricity tariffs and minimal disruptions. However, for grid operators to ensure high quality electricity in the future, tariffs must be raised to finance proactive grid investments, which causes consumer dissatisfaction. Thereby comes that the infrastructure projects in residential areas cause inconvenience for end-consumers, which increases tension in the relationship. If the grid operators fail to timely invest in upgrades, reliability of supply can be compromised, also creating tension with end-consumers.

The tensions and conflicting priorities among stakeholders exert significant pressure on the regional grid operators. Figure 1. illustrates the complex pressure field that grid operators face from key stakeholders. The figure highlights how grid operators are subject to conflicting pressures from multiple directions, making it difficult to satisfy all stakeholder priorities. This illustrates the delicate balance required from grid operators, who must navigate these competing interests.

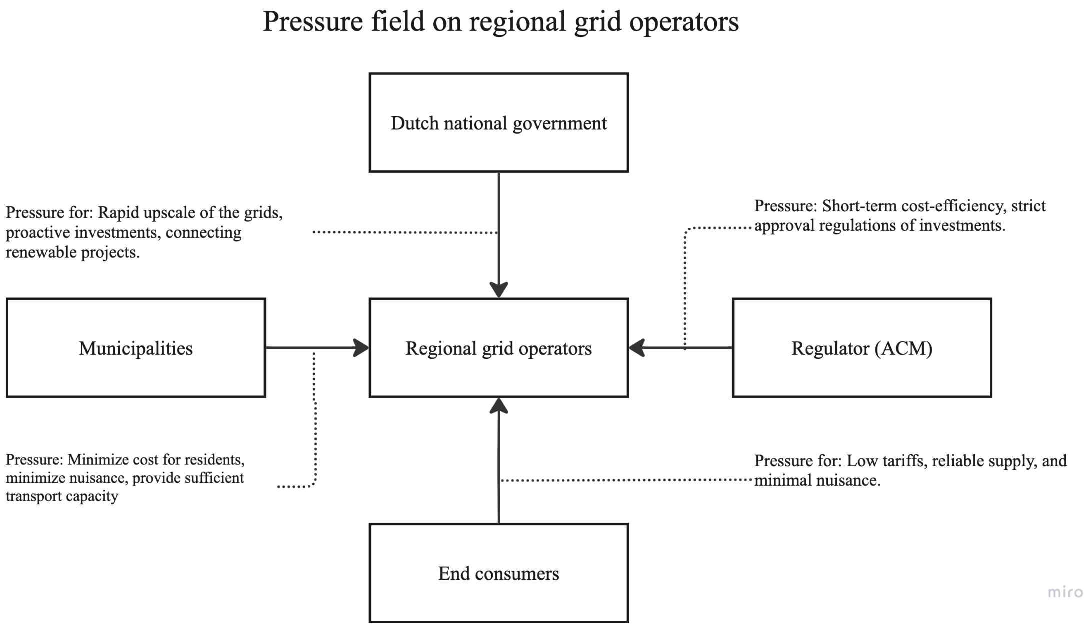


Figure 1. Showing the pressure field that regional grid operators experience.

1.4 RESEARCH OBJECTIVES

The main objectives of this study are the following:

1. **Understanding prioritization methods for large infrastructure investments.** This first objective focuses on understanding strategies and methods that are discussed in academic literature regarding the prioritization of investments in large infrastructure investments. It is thought that valuable insights can be generated for Stedin by identifying the best practices regarding prioritization method as described in academic literature.
2. **Understanding prioritization methods currently employed by Dutch grid operators.** This second objective focuses specifically on understanding the prioritization methods of investments in grid infrastructure by Dutch grid operators. By understanding these methods fully, comparisons can be made between Stedin's approach and other grid operators with which valuable insights can be generated.
3. **Mapping uncertainties and related risks emerging from external factors.** This third objective focusses on identifying sources of uncertainty that can potentially impact the effectiveness of Stedin's prioritization method. By mapping these uncertainties and comparing them to the uncertainties considered in Stedin's prioritization method, insights can be gained into the robustness of the prioritization method.
4. **Providing Stedin with actionable recommendations and considerations to ensure the effectiveness of the prioritization of neighborhoods.** This fourth objective focusses on providing recommendations that can positively impact the effectiveness and robustness of the prioritization method in a rapidly transitioning energy system.

1.5 RESEARCH QUESTIONS AND APPROACH

1.5.1. MAIN RESEARCH QUESTION

The following research question has been derived to guide the study and achieve the objectives.

How can the Dutch distribution grid operator Stedin ensure the effectiveness of LV grid investment prioritization, considering emerging uncertainties from different regulatory, policy, and market developments?

Several sub-research questions were formulated to break down the main research question into more manageable components. These sub-questions will also help structure the research process and guide the collection of data. The following sub-research questions have been derived:

1.5.2. SUB-QUESTION 1

What are the current methods for the prioritization of investments in large infrastructure projects?

The first sub-question provides a foundation by exploring prioritization methods used in large infrastructure projects. With large infrastructures, this study refers to complex infrastructures that span vast geographical areas, consist of interconnected subsystems that require coordinated management, and provide essential services for societies. Examples of these systems are, roadworks, the energy system, and the sewerage system. This research question aims to understand the underlying components of prioritization strategies. By understanding these underlying components, strengths and weaknesses of different prioritization methods can be identified. Understanding these methods will help in identifying models, methods, or strategies that can potentially be incorporated in Stedin's approach in determining a sequence of investments.

1.5.3. SUB-QUESTION 2

How do Dutch grid operators prioritize grid expansion projects?

The second sub question aims to explore the prioritization methods that Dutch grid operators currently use. Understanding prioritization methods that Dutch grid operators use generates insights into how other grid operators deal with the complex challenges of the energy transition. These insights can potentially be valuable for Stedin. This sub-question consists of two parts. First, desk research into the prioritization methods of Dutch grid operators is performed. This desk research consists of studying grey sources, such as company reports, and company documentation. The second part of answering this research question includes an extensive analysis of Stedin's prioritization method. This part of the study includes expert interviews to get a deeper understanding of Stedin's prioritization method.

1.5.4. SUB-QUESTION 3

What uncertainties and risks can emerge from regulatory, policy, and market developments that impact the prioritization of neighborhoods?

The third sub-question aims to identify risks and uncertainties that arise from external factors. Regulatory, policy, and market developments can introduce new uncertainties and risks that need to be considered in the prioritization process. This sub-research question consists of extensive desk research into possible sources of emerging uncertainties. Mostly reports and publications by Dutch government and the European Union are considered in this desk research.

1.4.5 EXPLANATION OF RESEARCH QUESTIONS

From initial research and conversations with experts it became evident that answering the main research question involves two fundamental aspects. These two fundamental aspects are:

1. An **internal component,** which focusses on the design of Stedin's prioritization method.
2. An **external component**, which focusses on the robustness of the prioritization method against emerging uncertainties and risks arising from outside developments such as regulatory, policy, and market changes.

Each sub-research question contributes to understanding these components. Sub-question 1 explores existing prioritization methods used in large-scale infrastructure projects. By studying these methods, key elements of effective prioritization frameworks and theoretical approaches can be identified. This directly addresses the internal component of the main question, providing a foundation for evaluating the design of Stedin's prioritization method.

Sub-question 2 explores the prioritization methods of Dutch grid operators, including Stedin. By mapping the current strategy of prioritizing grid investments, potential gaps or weaknesses can be identified. This directly addresses the internal component of the main research question. Additionally, studying the current methods including the approach of managing uncertainties lays the foundation for identifying vulnerabilities to external emerging uncertainties, bridging the internal and external components of the main question.

Sub-question 3 directly addresses the external component of the main research question. By identifying potential external uncertainties and risks and comparing them to Stedin's current method for managing uncertainties, the robustness of Stedin's prioritization method can be assessed.

By integrating the insights and results from these sub-questions, this thesis examines both the internal design of Stedin's prioritization method and its external resilience to emerging uncertainties. Together, these insights provide a comprehensive basis for answering the main research question and designing actionable recommendations for improvements.

1.4.6 POTENTIAL LIMITATIONS OF THE RESEARCH APPROACH

The most crucial limitation of this study originates from the fact that this study is done in collaboration with one of the stakeholders in the system, Stedin. By performing this study at one of the stakeholders a deeper understanding of Stedin's prioritization method through access to confidential methods and internal documents. However, this collaboration introduces a potential bias, as the data and information gathered from internal company reports and expert interviews may reflect Stedin's perspectives and priorities, rather than providing a fully objective view of the broader system.

Another significant limitation that might complicate the research is the availability and accessibility of data. As mentioned before, the Dutch distribution grid is operated by different DSOs. Although these DSOs are not competing for market share because of regulated monopolies, they might still be reluctant to share valuable company data regarding prioritization.

Another potential limitation is that ensuring objectivity in the proposed qualitative approach can be challenging. When interviewing experts and stakeholders, they likely have biased views on either investment prioritization or developments of external factors.

An additional limitation is that it is hard to measure the effectiveness of a prioritization method. The effectiveness of prioritization method depends on long term outcomes that are far beyond the timeframe of this study.

1.6 RESEARCH RELEVANCE

1.6.1 ACADEMIC RELEVANCE

The academic relevance of this study primarily lies in systematically analyzing Stedin’s method for prioritizing investments in LV distribution grids within neighborhoods, by using academic concepts such as risk assessment, cost-benefit analysis, and multi-criteria analysis. By studying these academic concepts and applying them to the current prioritization method employed by Stedin, this research acts as bridge between academic theory and practical challenges experienced in the real world. Such an evaluation and application of academic concepts to an actual, ongoing challenge is relatively rare in academic literature, which often focusses more on theoretical frameworks and designed test-cases. This combination of academic knowledge and practical application adds to the academic knowledge on methodologies used in complex infrastructure prioritization, specifically focused on the electricity distribution system.

Additionally, this thesis examines uncertainties and risks related to the electricity distribution grid that may emerge from future external developments. Such forward-looking analyses of uncertainties and related risks are relatively uncommon in academic literature, which often focuses on current perceived uncertainties and risks within the system rather than identifying potential future uncertainties. By proactively mapping these emerging uncertainties and risks, this study provides a foundation for making prioritization methods for electricity distribution grids more robust and adaptive.

While many theses aim to find answers to academic knowledge gaps, this is not the primary aim of this thesis. While the analysis of potentially emerging uncertainties and risks addresses a knowledge gap regarding these factors, the primary academic value of this thesis lies in evaluating, comparing, and improving prioritization methods for investments in electricity distribution grids. By integrating academic frameworks and practical methodologies, this thesis provides actionable recommendations that enrich both academic knowledge and practical applications. These insights can be applied in further academic research on prioritization methods and their practical implementation in rapidly evolving energy systems.

1.6.2 SOCIETAL RELEVANCE

The societal relevance of this thesis lies in contributing to the pressing challenges in the LV electricity distribution grids in neighborhoods that Stedin faces. This research is valuable for society as it supports the energy transition by obtaining a deeper understanding of prioritization methods and providing recommendations for improvement of the prioritization methods by regional grid operators. By ensuring the effectiveness of the prioritization by Stedin over the course of the energy transition, grid failures can be minimized, resources are efficiently allocated, and delay of the energy transition due to grid congestion issues is minimized. Additionally, by ensuring effective prioritization by Stedin, inefficient investments can be avoided which could lead to increased tariffs for end users. The incremental recommendations provided in this thesis aim to have a positive impact on the prioritization of LV grid investments, which ultimately enables the success of the energy transition, benefitting both the society and the environment.

1.6.3 RELEVANCE TO COSEM

Designing interventions in socio-technical systems is a central theme CoSEM program at TU Delft. The program focuses not only on the technical aspect of a problem but also on institutional, social, and financial aspects. This thesis aligns well with the CoSEM program as the LV distribution grid is inherently socio-technical as it integrates technical infrastructure, such as transformers and cables, with institutional aspects like EU regulations, and financial considerations. The aim of this thesis is to design recommendations and incremental interventions that benefit the prioritization of grid investments in which technical and non-technical factors must be considered. This approach in which not only technical aspects are considered but a holistic approach is taken aligns closely with the CoSEM course's emphasis on recognizing that the success of technological innovations and interventions does depends not only on the technical side but also on how the engineer navigates complex dynamics and interdependencies within the socio-technical system.

1.7 RESEARCH FLOW DIAGRAM

In Figure 2. the structure of the research is visually shown, which shows the three main stages that were included in this research approach. The exploratory stage sets the foundation of this research by introducing the background, problem statement and defining the main research questions. This stage of the research mostly included exploratory desk research and conversations with experts. The research stage is divided into the three sub-research questions. SQ1 examines prioritization methods in large infrastructure projects through an academic literature review, addressing the internal component of the research problem. SQ2 investigates how Dutch grid operators prioritize grid upgrades by combining desk research and expert interviews, addressing both the internal and external component of the research problem. In the discussion and conclusion stage findings are integrated, results are discussed, suggestions for future research are made, and the main research question is answered.

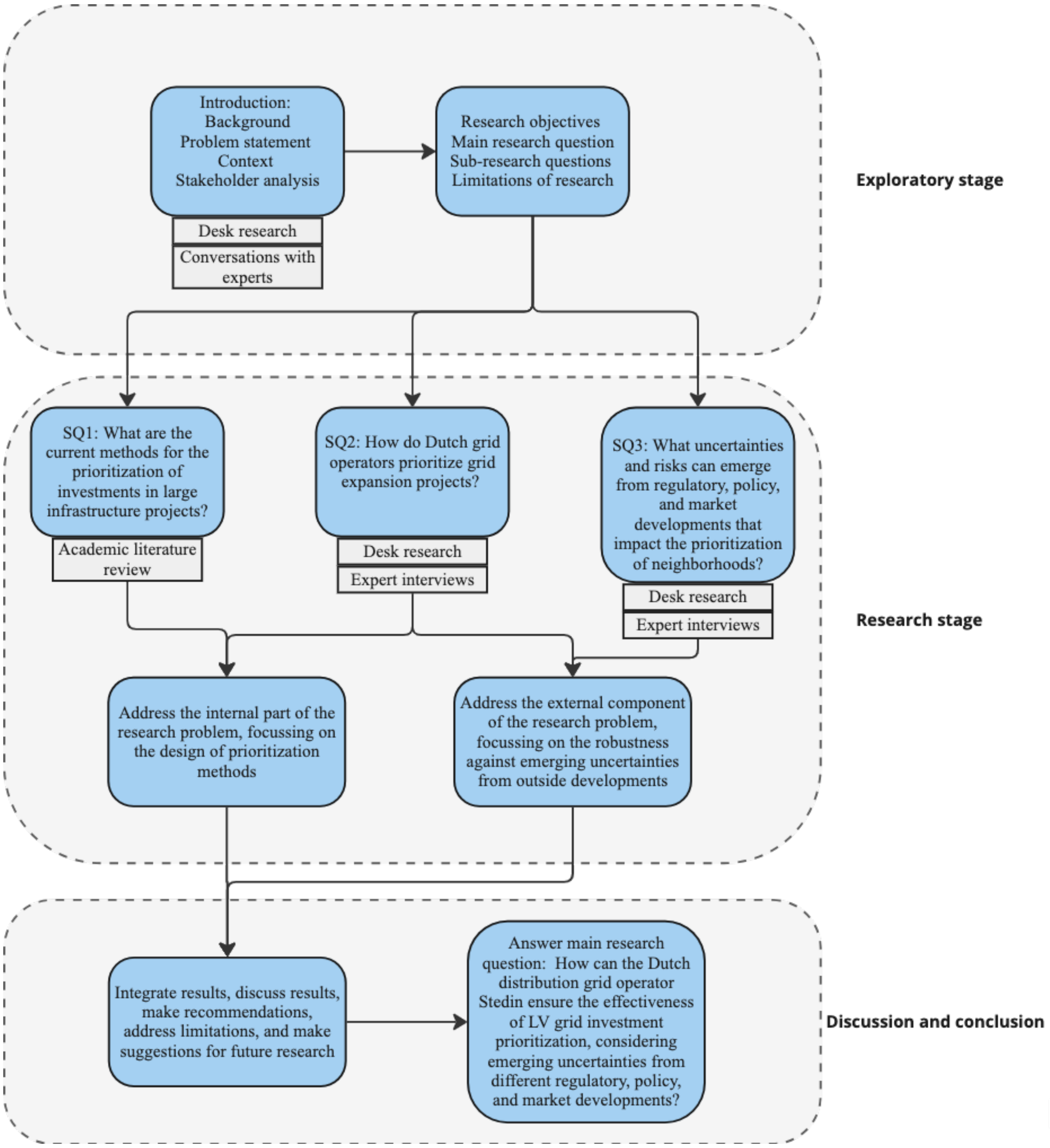


Figure 2. Research flow diagram

CHAPTER 2 METHODOLOGY

2.1 COMPARING PRIORITIZATION METHODS

2.1.1 DEFINING COMPARISON CRITERIA

An essential part of this study is comparing different investment prioritization methods used in large-scale infrastructure projects. In this chapter, a method is defined with which these comparisons can be made. The main aim of defining this method is to compare the prioritization method used by Stedin to prioritization methods proposed in academic literature and prioritization methods used by similar companies. To be able to compare different prioritization methods, several criteria are defined with which the methods can be evaluated and compared. When researching previous academic work on comparing prioritization methods, it becomes clear that a significant amount of academic work has been published regarding the comparison of prioritization methods. The search string used in the Scopus database to find this literature was **“Comparing OR analyzing AND prioritization AND methods.”** This search string resulted in 1,101 documents found. After limiting the language to “English” and keywords to “Prioritization,” 261 papers remained. After screening for articles in which actual comparisons are made between prioritization methods, 8 documents remain (Table 2).

Source	Compared methods	Comparison Criteria	Key findings
Perini et al., 2009	AHP and CBRank	1. Time requirement for the entire prioritization task. 2. Ease of use. 3. Accuracy of ranking.	The results of this study indicate that AHP performs better for prioritization problems in which ordering accuracy has the highest priority. Compared to CBRank, AHP performs worse in terms of ease of use and time requirement.
Vestola, 2010	Numerical assignment (NA), AHP, Hierarchy AHP, Minimal Spanning Tree (MST), Cumulative Voting (CV), HCV, Priority groups, BPL, and Buble sort	1. Result scale 2. Speed 3. Suitability for a number of requirements	The study's main conclusion is that it is impossible to appoint the best method overall as its effectiveness depends on specific situations.
Ahl, 2005	AHP, Binary search tree (BST), 100 points method,	1. Time to execute a method 2. Accuracy of results 3. Scalability of the method 4. Ease of use	The results of this study indicate that BST is the best method prioritization method as it is east to execute, gives accurate results and provides the most accurate results. AHP is found to be the worst method as it is time consuming and hard to scale up.
Hudaib et al., 2018	NA, MoSCoW, Priority groups, Bubble sort, BST, AHP, Hundred dollar and MST	1. Ease of use 2. Reliability of results 3. Time required for entire prioritization task. 4. Scalability	This study concludes that picking the best prioritization method is not possible because the preferred method is dependent on the specific projects. The study presents a framework in which the user chooses the weight of criteria to find a method best suited for a particular project.

		5. Accuracy of results	
Danesh and Ahmad 2010	AHP and NA	1. Accuracy 2. Ease of use	This study concludes that the AHP method is more accurate and faster compared to the numerical assignment.
Scheibmayr et al ., 2009	AHP, CV, and Likert scale technique.	1. Time duration 2. Scalability 3. Accuracy	Cumulative voting is found to be the most scalable. AHP has the best accuracy. The Likert scale technique is the most time-efficient.
Fernandes et al., 2015	AHP and Electre I	1. Ease of use 2. Scalability 3. Efficiency	AHP produces better results than Electre I.
Karlsson et al., 1997	AHP, Hierarchy AHP, MST, Bubble sort, BST, and Priority groups.	1. Required number of decisions. 2. Total time consumption. 3. Time consumption per decision. 4. Ease of use. 5. Reliability of results. 6. Fault tolerance.	AHP is the most promising approach. However, it may be problematic to scale up for larger projects.
Tufail et al., 2019	NA, CV, AHP, Ranking, Top-10 requirements, MoSCoW, Planning game, Wieger's Method, Cost value ranking, Value-oriented prioritization	1. Complexity 2. Scalability 3. Customizable 4. Ease of use 5. Accuracy	Each technique has its pros and cons in specific projects.

Table 2. Comparison table of literature comparing prioritization methods.

From examining these documents, it appears that the evaluation criteria used across these works to compare prioritization methods are relaitvely consistent. Figure 3. visually shows how many times specific criteria were used in the reviewed papers. In nearly all the selected literature, the prioritization methods are assessed based on time consumption, ease of use, accuracy of results, and scalability. There seems to be a consensus within the academic community that an evaluation of a prioritization method should include these criteria. Therefore, these criteria will be used when evaluating Stedin's prioritization method and comparing it to other prioritization methods.

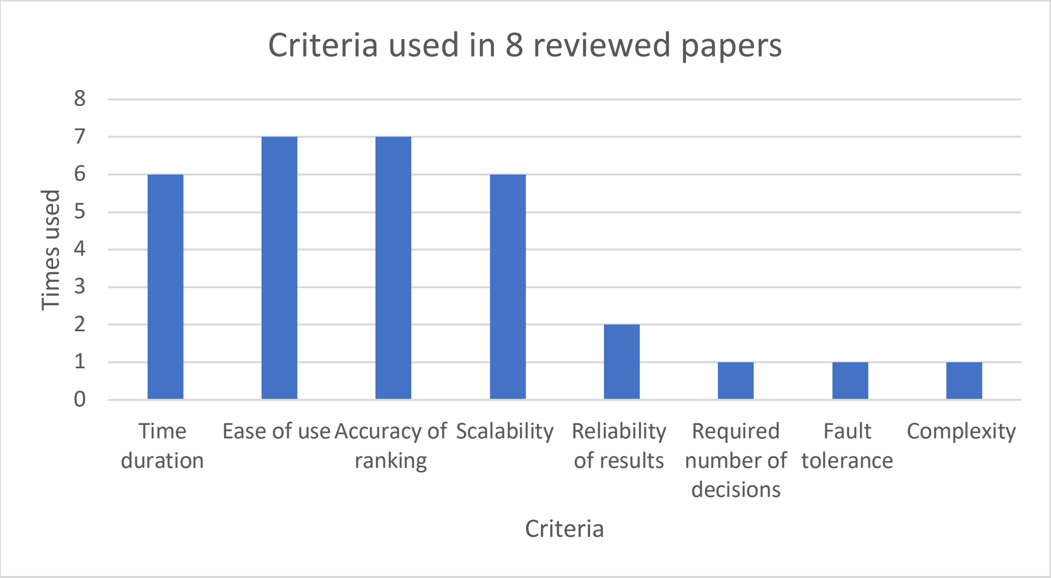


Figure 3. Frequency of specific evaluation criteria used in reviewed papers.

CHAPTER 3 THEORETICAL FRAMEWORK

In this chapter, a literature is reviewed with the aim of finding an answer to sub-question 1: *What are the current procedures for prioritizing large infrastructure investments?* In the first part of this chapter, academic sources discussing prioritization methods used in large infrastructures such as energy infrastructure, waterway infrastructure, natural gas infrastructure, and rail and roadway infrastructure are reviewed.

3.1 METHODOLOGY LITERATURE REVIEW

A literature review is performed to get a good overview of the current state of research regarding the prioritization of large infrastructure investments. The first part of this literature review will consist of understanding the prioritization methods currently used in large infrastructure investments. The method used to gather information for this literature review is shown in table 3. The database used to perform this search for relevant articles is the Scopus database by Elsevier. This database was picked because it includes a vast number of articles and provides useful advanced search tools. As can be seen in Table 3. five search strings were used to identify relevant literature. The initial search strings resulted in 928 documents. To reduce this number of articles, inclusion grounds were formulated. First, the results were limited to documents written in English. Secondly, the document type of the results was limited to "article" and "review". This was done to ensure only high-quality, reliable studies were included in the literature review. Finally, the search results were limited to papers including the keyword "prioritization", resulting in 401 documents. To screen this large number of documents the ASReview lab AI by University Utrecht was used, which helps the user to review large numbers of documents systematically. Some additional papers wer acquired through snowballing techniques

	Search string	Number of documents found pre limitations	limitations and exclusions	Number of documents found	Relevant documents after screening and deleting doubles
1	Electritcity AND prioritization	77	Limited to Article Limited to Review Limited to English	52	6
2	sewerage OR water AND infrastructure AND prioritization	421	Limited to Article Limited to Review Limited to English Limited to Prioritization	112	1
3	pipeline OR (natural AND gas) AND distribution OR infrastructure OR investment AND prioritization	267	Limited to Article Limited to English	115	2

4	railway AND infrastructure OR investment AND prioritization	89	Limited to Article Limited to English Limited to prioritization	82	9
5	Road AND infrastructure AND investment AND prioritization	74	Limited to Article Limited to English	40	6
	TOTAAL	928		401	25

Table 3. Methodology of literature review

The resulting papers are shown in an extensive comparison table which can be found in Appendix A.1

3.2 RISK AND UNCERTAINTY

This section defines the concepts of risk and uncertainty. This is important for this study as these concepts are often used in sub-questions 2 and 3.

3.2.1 THE CONCEPT OF RISK

In academic literature, many different definitions and meanings of the concept of risk exist. This wide range of definitions makes it crucial to clearly define the concept of risk that will is used to study decision-making processes regarding LV grids. Researching risks may lead to unclear results without a clear definition, making developing effective strategies and solutions challenging. One of the most famous definitions of risk originated over 100 years ago. Knight (1921) was the first to define a distinction between the concepts of uncertainty and risk. Knight defined risk as “a known chance or a measurable probability.”

On the contrary, he defines uncertainty as “an indeterminable chance or unmeasurable probability.” More recently, Røste (2021) defined risk as the variability of expected outcomes and emphasized that although only the negative side of risk is usually considered, risk can also mean that a more favorable outcome than expected is achieved. Aven (2012) mentions that there are many different definitions of the concept of risk and that there currently is no agreed definition. These definitions of the concept of risk over the last 300 years can be categorized into nine distinct groups. According to Aven (2012), these groups are as follows:

Risk = Expected lost value

Risk = Probability of an event

Risk = Objective uncertainty

Risk = Uncertainty

Risk = Potential of a loss

Risk = Probability and scenarios/consequences/severity of consequences

Risk = Event or consequence

Risk = Consequences/damage/severity of these + uncertainty

Risk is the effect of uncertainty on objectives

After extensively researching these nine categories, Aven (2012) concludes that the definition Risk = Consequences/damage/severity of these + uncertainty should be adopted more widely in future decision-making processes. While this definition offers a nuanced perspective on risk, initial research and discussions with experts in the electricity distribution grid reveal that the definition of risk that is commonly used in this field is: Risk = consequences of event multiplied by the probability of an event occurring (Kim et al., 2016). To remain aligned with established practices and definitions within this complex system this work will adapt this definition as well.

3.2.2 THE CONCEPT OF UNCERTAINTY

It is widely acknowledged by policymakers and scientists providing decision support that uncertainties play a pivotal role in decision-making processes. However, similar to the concept of risk, there is a lack of agreement on the definition of uncertainty (Walker et al., 2003). There are many different definitions of uncertainty. For example, in the work of Knight (1921), uncertainty is defined as an indeterminable chance or unmeasurable probability. Meanwhile, definitions exist that conclude that risk is the same as uncertainty. However, Perminova et al. (2007) argue that risk and uncertainties are not synonymous and can be better described as cause and consequence. According to Sniazhko (2019), uncertainty is defined as the lack of knowledge about the probabilities of future events. This definition of uncertainty is similar to the definition of Keynes (1937) who defines uncertainty as a state in which it is impossible to attribute a reasonably definite probability to the expected outcome. Many of the definitions of uncertainty in the academic literature relate to the unknown probability or unpredictability of events and their impact. The definition used in this thesis will be in line with these definitions. Uncertainty = The unpredictability of an event’s occurrence and the extent of its impact.

3.3 PRIORITIZATION OF LARGE INFRASTRUCTURE INVESTMENTS

This section aims to find an answer to sub-question 1: *What are the current procedures for prioritizing large infrastructure investments?*

Researching prioritization methods from academic literature on the prioritization of infrastructure investments in both the energy sector and other industries can provide valuable insights into how investments sequences are determined. By studying these processes, methods can be identified that could be partially or fully applied to LV distribution grid investment prioritization.

3.3.1 COST-BENEFIT ANALYSIS AND MULTI-CRITERIA ANALYSIS

Cost Benefit analysis (CBA) is a tool that can be used to prioritize investments in large infrastructure projects such as energy, roadway, water, and natural gas network expansion projects. This approach calculates the Net Present Value (NPV) of all available projects, which are then prioritized from highest to lowest NPV. An and Caspar (2010) use a CBA to prioritize investments in roadway projects and conclude that for evaluating these projects CBA can be effectively used to prioritize roadway projects. While this can be a useful method to determine the sequence of project investments, Wijnia and Herder (2005) argue that investments in energy infrastructure cannot be prioritized solely based on CBA. This is due to several factors. First, allocating future cash flows to specific parts of the grid is challenging as most investments do not necessarily generate new income. This would result in these investments having a negative NPV and should be rejected according to CBA rules. Secondly, due to the monopolistic characteristics of the distribution grid, distribution grid operators are obligated to provide a connection to those who request one. This means that even though the NPV of a project might be negative, the distribution grid operator still needs to carry out this project. Finally, investment decisions by grid operators are often based on future non-financial benefits like safety, reliability, or sustainability. Attempting to express these benefits in monetary terms will introduce a lot of uncertainties and inaccuracies (Chi and Bunker, 2021). Therefore, Wijnia and Herder (2006) suggest that asset managers should include a Multi-Criteria Analysis (MCA) in their decision-making process.

Celli et al. (2018) agree that traditional energy infrastructure planning based on economic tools is outdated and no longer effective. Modern grid planning should be based on multi-objective approaches, as distribution grid planning often includes conflicting objectives. The objectives of distribution grid operators can range from efficiency objectives like maximizing capacity and reducing energy losses to monetary objectives like reducing CAPEX and reducing OPEX. Celli et al. (2018) propose prioritizing grid investments using a Multi-Criteria Analysis (MCA). The proposed methodology aims to rank a large set of alternatives using a fuzzy analytical hierarchy process (AHP). The MCA consists of three steps. First, an automatized scoring stage in which stakeholders express their preference for alternatives in a pairwise comparison process. The second step consists of evaluating the score of each alternative based on the criteria. Finally, the overall score of each alternative is calculated, resulting in a ranking of alternatives. The alternative with the highest score is the option that best fits the expectations of the stakeholders. The proposed MCA approach has significant benefits over CBA. However, the comparison of alternatives and the complexity of the approach make it very time-intensive.

Troncia et al. (2018) agree that CBA alone cannot effectively be used to make investment decisions. However, they argue that CBA and MCA can be complementary. A joined MCA-CBA is proposed that network operators can use to consider both monetary and non-monetary impacts in their decision-making. By combining the two tools, the weaknesses of each can be mitigated. The approach of the MC-CBA is similar to a regular MCA, using AHP to decompose the decision problem into a hierarchy of criteria that can be used to evaluate the alternatives. Unlike a traditional AHP, which typically uses only non-monetary performance criteria, Troncia et al. (2018) add an economic criterion and the key performance indicator NPV, which is evaluated with CBA. This results in being able to score alternatives based on an economical partial score and a partial score for grid performance. Although the paper demonstrated the ability to successfully use the proposed MC-CBA approach, its applicability in real power systems is questioned. When the number of alternatives and the number of criteria increases, identifying the best alternative becomes very complex and time-consuming. According to Grond et al. (2013), the large-scale and long-term time horizons of distribution system planning are important reasons network operators rarely use decision-support tools in practice.

3.3.2 Analytical Hierarchy Process

The Analytical Hierarchy Process (AHP) is a technique for analyzing complex multi-criteria decisions developed by Saaty (1987). The AHP provides a framework for decision-making when decisions involve multiple criteria. The AHP can be used in decision-making processes in numerous fields, including engineering and prioritization of infrastructure projects. One of the important advantages of using AHP is that both qualitative and quantitative criteria can be used. The AHP consists of several steps. First, the decision problem is decomposed into a hierarchy of sub-problems that can be analyzed independently. Usually, the AHP hierarchy consists of three levels. The highest level is the goal of the decision. The second level is the criteria level, which includes the factors used to evaluate the decision alternatives. The final level is the alternatives level, in which the different options for consideration are included. An additional level can be added in which key performance indicators of the criteria can be included. Once the hierarchy levels are determined, experts compare criteria in a pairwise comparison. In this pairwise comparison, values ranging from one to nine are given to express their relative importance. According to Saaty (1987), the values have the following meanings:

Both criteria have equal importance

3. Moderate importance of one over another
5. Strong importance of one over another
7. Very strong importance of one over another
9. Extreme importance of one over another

2, 4, 6, 8 are used as intermediate values between two adjacent judgements

The results of the pairwise comparisons of criteria are presented in a comparison matrix.

This AHP methodology ensures a systematic approach to ranking alternatives by considering multiple criteria and their relative importance. This can be a helpful tool in prioritizing grid upgrades, as it allows the inclusion of qualitative criteria without the need to convert them into quantitative terms. This capability significantly reduces the uncertainty often introduced in CBA, where qualitative values are translated into financial metrics

3.3.3 REACTIVE, FULLY PROACTIVE, AND STEPWISE PROACTIVE

Erbrink et al. (2023) discuss three investment strategies for the investments in distribution grids: reactive, fully proactive, and stepwise proactive. The reactive strategy is an approach in which neighborhood capacity problems are solved once they emerge. The problem is solved as cheaply and as quickly as possible. Solving problems with this strategy is focused only on the short term. The Fully proactive strategy is based on solving expected issues in the LV grid at once for a large service area. In this strategy, the LV grid should be without significant problems for the next 40 years. The stepwise proactive strategy consists of solving issues that occur in the grid and futureproofing them for at least 40 years. Comparing these strategies results in some interesting findings. Erbrink et al. (2023) conclude that the fully proactive strategy is significantly more beneficial than the other strategies. To start, because proactive projects are less urgent than reactive projects, reactive projects can be scheduled better. Better scheduling reduces costs by combining projects and preventing reworks at the same location. Thereby, compared to the reactive strategy, the proactive large-scale investment strategy is more efficient in terms of time, workforce, and materials. Tlili and Nafi (2012), who discuss prioritization for waterpipes projects, agree with Erbrink et al. (2023) that a proactive investment approach is significantly more efficient in the long-term compared to a reactive strategy. This efficiency is mainly due to the number of expected projects being halved compared to other strategies (Erbrink et al., 2023). Although the fully proactive strategy is the most efficient, large-scale implementation is impossible. Due to the increasing pressure on LV grids, too many grids are expected to experience problems that need immediate attention. This means a mixed strategy in which large-scale proactive projects are performed if possible while also addressing pressing problems in neighborhoods. Prioritization of problematic neighborhoods should be based on large-scale problems and not singular incidents.

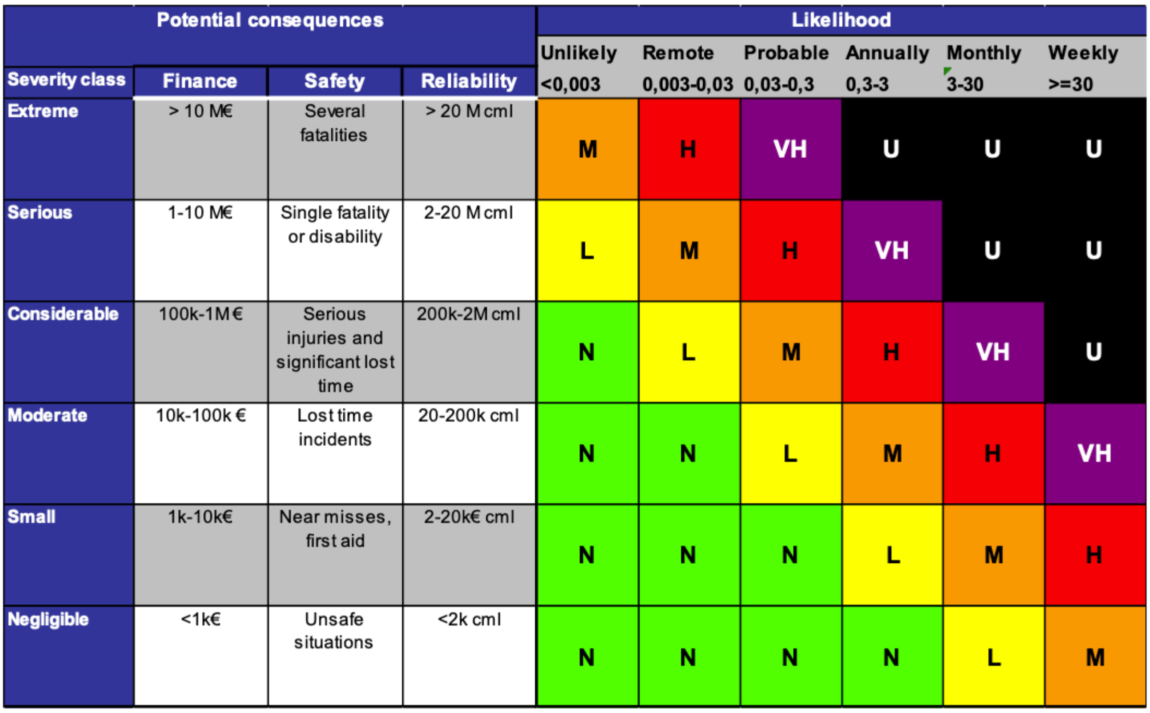
3.3.4 RISK-BASED PRIORITIZATION

Risk-based prioritization of investments in large infrastructure networks allows decision-makers to strategically allocate funds to the assets that present the highest risk to the system’s performance and reliability. Kim et al. (2016) discusses the renewal prioritization of water supply pipelines based on risk assessment. A major challenge that decision-makers face in this sector is that not all pipelines that qualify for renewal can be renewed because of budgetary constraints. To assist in defining a sequence of investments, Kim et al. (2016) proposes a risk-based method that calculates a risk score by multiplying the probability of failure with the consequence of failure. Quantifying the probability of failure is difficult because the criteria that are used are mainly qualitative, such as type of pipe, installation year, and laying environment. Kim et al. (2016) apply quantification theory to convert these qualitative factors into quantitative data. This data is then analyzed and used to predict the probability of failure based on past failures and pipeline characteristics. The consequences of failure are measured by the suspension quantity, which indicates the loss of water supply during a failure, and the water pressure during a failure. The prioritization sequence of renewal projects is set by focusing on the pipelines with a high probability of failure, which would result in a significant water supply disruption.

Halfway et al. (2008) propose a similar risk-based method to prioritize renewal investments in water and sewerage networks. Like Kim et al. (2016), they define the risk of failure by multiplying the consequence of failure by the probability of failure. However, Halfway et al. (2008) use a more subjective approach to define the consequence of failure. In this subjective approach, criteria influencing failures are rated on a scale from 1 to 5, with 5 indicating the most critical and 1 indicating the least critical. The consequence of failure is determined by calculating the weighted average of the criteria ratings. The probability of failure is calculated by dividing the current age of a component by its remaining service life. The remaining service life is predicted by a deterioration model. The risk index is calculated for all components, and the highest-scoring components are prioritized for renewal.

3.3.5 RISK-BASED PRIORITIZATION WITH A RISK MATRIX

According to Wijnia (2016), managing assets in the energy distribution infrastructure heavily relies on managing risk. Often, investment decisions in this sector are based on risk prioritization. Risk management involves identifying potential system failures and designing mitigation strategies. A tool that is often used in managing risks is a risk matrix which can help in prioritizing and visualizing risks. A risk matrix works by plotting the likelihood of an event occurring against the impact of that event. The likelihood of an event occurring is usually represented as a frequency of occurrence (e.g., 1-10 times per year). The impact of failure, if it occurs, usually ranges from minor to catastrophic. These two factors are multiplied to obtain a risk score, which can be categorized and color-coded to visualize the most critical risks. Figure 4. shows an example of a risk matrix. Risks that are categorized as high risk according to the risk matrix need to be prioritized for mitigation.



Potential consequences				Likelihood					
				Unlikely	Remote	Probable	Annually	Monthly	Weekly
Severity class	Finance	Safety	Reliability	<0,003	0,003-0,03	0,03-0,3	0,3-3	3-30	>=30
Extreme	> 10 M€	Several fatalities	> 20 M cml	M	H	VH	U	U	U
Serious	1-10 M€	Single fatality or disability	2-20 M cml	L	M	H	VH	U	U
Considerable	100k-1M €	Serious injuries and significant lost time	200k-2M cml	N	L	M	H	VH	U
Moderate	10k-100k €	Lost time incidents	20-200k cml	N	N	L	M	H	VH
Small	1k-10k€	Near misses, first aid	2-20k€ cml	N	N	N	L	M	H
Negligible	<1k€	Unsafe situations	<2k cml	N	N	N	N	L	M

Figure 4. example risk matrix (Wijnia 2012)

Although risk matrices are widely used as a tool to assist in decision-making processes, Wijnia (2012) points out that there is a lack of a standardized framework for constructing a risk matrix. This can result in asset managers having to design risk matrices largely on their own, which increases the risk of errors and could lead to matrices that fail to accurately represent risks, providing limited value for decision-makers. Wijnia (2012) highlights several additional limitations and weaknesses that should be kept in mind when using a risk matrix for prioritization. First, reducing risks to only two dimensions can oversimplify them, potentially failing to capture the full complexity of the risks decision-makers have to manage. In addition, risks that fall in the same cell in the matrix are prioritized equally, even though there may be significant differences in the actual risk levels. For example, in Figure 4., consider two financial risks, both classified as severe with a remote likelihood. Risk A has potential consequence of 1M€ with a likelihood of 0.003, while risk B has a potential consequence of 10M€ with a likelihood of 0,03. Although Risk B has a 100 times higher risk score, the risk matrix would prioritize them equally and fails to distinguish the more critical risk. Secondly, the categorization of likelihood and impact can introduce significant subjectivity. Qualitative labels such as "catastrophic" or "moderate" can be interpreted differently. Different stakeholders, and even executives from the same organization, may interpret the same risk differently depending on their risk appetite. Another challenge that Wijnia (2012) highlights is that risk matrices often fail to account for uncertainty. Many matrices are constructed under the assumption that the likelihood and impacts are known with certainty. However, in practice, both are often uncertain and challenging to define accurately.

Although Wijnia (2016) critiques the risk matrix, he remains convinced that a risk matrix can be a powerful tool for prioritizing risks, provided that it is properly designed and certain design rules are followed. The design rules that need to be followed, according to Wijnia (2016) are:

1. **Both likelihood and impact should be on a logarithmic scale.** Using logarithmic scales helps maintain a constant relative uncertainty across different orders of magnitude. This means that the proportion of uncertainty remains consistent, regardless of whether you are dealing with small or large numbers.
2. **Decision-makers should be indifferent if risks fall in the same category.** This means that risks in the same severity category should carry equal weight in the decision-making process, regardless of other factors. For impacts measured on quantitative scales, it is important that the per-unit tradeoffs remain constant. This ensures that decision-makers prioritize based on the total impact and not on the size of individual risks.
3. **Risk levels should be based on expected values and expressed on a logarithmic scale.** This means that risks should be quantified using expected levels. This ensures that decision-makers do not over-prioritize frequent but less severe risks compared to low-probability/high-impact risks.
4. **The number of categories for likelihood and impact should ideally match the number of risk levels.** This ensures that the matrix provides meaningful insights. If the categories of risk and likelihood are not aligned, the matrix might oversimplify risks or fail to properly differentiate risks.

Provided that these rules are followed Wijnia (2016) argues that a risk matrix can be useful in risk assessment. However, if impactful decisions need to be made, only using a risk matrix is not sufficient. For these decisions it is recommended that other tools are combined with the matrix. Wijnia (2016) suggests combining CBA with the risk matrix for better considered decisions.

3.4 CONCLUSION OF CHAPTER

This literature review was conducted with the aim of answering the sub-research question: *What are the current methods for the prioritization of investments in large infrastructure projects?* The literature review presented several methods of prioritization of investments in large infrastructure projects. Key methods that were identified include CBA, MCA, AHP, and risk-based prioritization. Each method provides unique strengths making them suited for different project needs and stakeholder priorities. A recurring theme that was found in the literature was that combining multiple methods can significantly improve the accuracy of results by leveraging the strengths of different methods can to mitigate their individual weaknesses. Additionally, the literature review emphasizes adopting a proactive large-scale strategy is the best practice for sectors undergoing rapid developments such as the energy sector.

4. PRIORITIZATION METHOD OF DUTCH GRID OPERATORS

This chapter is dedicated to analyzing the investment strategies and prioritization methods used by Dutch grid operators, including Stedin. The chapter aims to provide insights into the current employed prioritization methods by grid operators and helps to answer sub-research question 2: *How do Dutch grid operators prioritize grid expansion projects?* The information presented in this chapter is based on company reports obtained from Dutch grid operators and Netbeheer Nederland. This chapter begins with an overview of the landscape in which the Dutch grid operators are active. This includes collaborations between the grid operators and an introduction to the common first step of the prioritization methods: scenario development. The development of the scenarios, which is a crucial component of the planning and decision-making processes of all Dutch grid operators is extensively discussed. Following this the investment strategy, including the prioritization method of the Dutch transmission grid operator Tennet is discussed. After this, a similar analysis is performed for major Dutch regional grid operators.

By exploring how Dutch grid operators currently navigate the challenges of planning and prioritizing grid investments in the evolving energy sector, this chapter establishes a foundation for comparing these methods with Stedin's approach. This comparison will in later chapters be used to identify potential areas of interest, improvements, or recommendations for Stedin.

4.1 DEVELOPMENT OF SCENARIOS

The Dutch transmission system operator and regional Dutch distribution grid operators face similar challenges in prioritizing their investments. To guide this process, Netbeheer Nederland and the Dutch grid operators have collaborated to develop four scenarios aimed at achieving a climate-neutral energy system in 2050, as well as three intermediary scenarios targeting a 55% reduction of emissions by 2030 compared to 1990. These scenarios are based on a combination of internal company reports, policy documents, and academic studies. The scenarios form the foundation of investment decisions by Dutch grid operators. The scenarios aim to assist in forecasting the future energy demand and supply, defining the required future energy infrastructure, assessing future transport needs, and planning required investments. The scenarios include different assumptions for uncertainties that affect the future energy system. The main uncertainties that are considered in the scenarios include:

- The degree of electrification in the energy system, including assumptions on the integration of heat pumps, EVs, and PV.
- The development of renewable gasses and renewable electricity production.
- The degree of flexibility of demand and supply.
- Future energy price development.

The scenarios form the initial step of the investment strategy of all Dutch grid operators, significantly impacting their prioritization methods of grid operators and are therefore discussed extensively in the following sections. First, long-term scenarios are discussed followed by the short-term scenarios.

4.1.1. Decentralized Initiatives scenario

The first long-term scenario is the Decentralized Initiatives scenario (DEC) (Netbeheer Nederland, 2023). In this scenario, the Dutch government is assumed to stimulate regional climate-neutral initiatives with a high level of autonomy for local communities, citizens, and companies to choose their preferred technology for achieving climate neutrality by 2050. The differing initiatives are supported by the government by the implementation of financial incentives and educational campaigns. Examples of local initiatives include local renewable energy production, such as solar and wind energy, and local renewable heat solutions, like HPs, geothermal energy, green hydrogen, and heat-cold storage. Due to the intermittent availability of renewable energy due to the high integration of renewable generation and limited acceptance of carbon capture and storage (CCS), energy-intensive industries are expected to relocate out of the Netherlands in this scenario. Along with expected higher energy efficiency, this results in a lower total Dutch energy requirement in 2050.

4.1.2. National Leadership scenario

The second long-term scenario is the National Leadership scenario (NAT) (Netbeheer Nederland, 2023). This scenario assumes a future in which the Dutch government takes a central role in shaping the energy transition and determining the energy mix. Unlike the DEC scenario, in which citizens and companies have the autonomy to choose their own path to climate neutrality, the NAT scenario assumes the Dutch government implementing regulations and obligations to ensure the envisioned climate-neutral energy system is realized by 2050. Besides implementing regulations, the government actively invests in large-scale energy projects of national importance. Examples of these projects are the large-scale development and implementation of offshore wind farms and the building of several nuclear reactors to provide a baseload of energy. Another important element of this scenario is the development and implementation of new industries. These new industries include synthetic fuels, electrification of industrial processes, and the use of green hydrogen. Green hydrogen will have a critical role in both balancing fluctuations in the electric grid, and as a fuel for generating high temperatures for industrial processes. For residential heat supply, this scenario assumes a centrally coordinated roll-out of heating grids running on waste heat, geothermal energy, and power-to-heat technologies.

4.1.3 European Integration scenario

The third long-term scenario is the European Integration scenario (EUR) (Netbeheer Nederland, 2023). This scenario assumes a future in which the Netherlands is part of an efficient integrated European energy system in which member states collaborate and utilize each other's advantages and resources to achieve climate neutrality by 2050 collectively. A key feature of this scenario is the emphasis on crossborder cooperation, allowing European countries to optimize resource use. An example of this is the North Seas Energy Cooperation, a collaboration between countries bordering the North Sea to optimize energy production from offshore wind in the North Sea. By coordinating these large projects, overall efficiency can be improved, and natural resources can be exploited to their full potential. The European energy mix in this scenario is largely composed of renewable energy, particularly solar and wind. Additionally, the European member countries aim to realize a large-scale green gas production operation and implement CCS and Bio-Energy with Carbon Capture and Storage (BECCS). The Netherland will play a central role in CCS as it will store CO2 for surrounding countries. The industrial sector will see a significant increase in the use of biomass and green hydrogen to decarbonize European heavy industries. In addition, it is assumed that the Netherlands will increase its nuclear energy capacity to 8GW by 2050. Like in NAT, residential heating supply is supplied through district heating grids. This scenario is unique in the fact that the electrification of the mobility sector has a high priority. An inter-country EV charging facility network is implemented, and the high-speed train network is expanded.

4.1.4 INTERNATIONAL TRADE SCENARIO

The fourth scenario is the International Trade scenario (INT) (Netbeheer Nederland, 2023). In this scenario, the Dutch government aims to exploit opportunities in the international energy and resource trading markets. The Netherlands will position itself as a hub in the global energy and resource trade with the aim of looking for cost-efficient energy solutions. The Netherlands will actively trade climate-neutral energy carriers, such as hydrogen, and become a transit country for a large part of European hydrogen flows. The INT scenario assumes that Dutch energy-intensive industries focus on becoming climate-neutral by electrifying their business processes and using hydrogen as a primary fuel. However, it is expected that in this scenario, the energy-intensive industry will mostly reposition business operations outside of the Netherlands. Essential in this scenario is that the reduction of GHGs is mainly realized by carbon taxing and financial incentives based on market forces instead of government regulations and policies. The INT scenario assumes hybrid heating systems that combine traditional systems with locally produced hydrogen for heat production.

Three shorter-term scenarios have been developed to make investment plans more concrete and to provide intermediary goals that are in line with the European Climate law that demands a GHG emission reduction of 55% compared to 1990. Grid operators base their investment decisions on these three scenarios: National Drivers (ND), Climate Ambition (CA), and International Ambition (IA). Figure 5. shows how the three shorter-term scenarios are linked to the previously discussed long-term scenarios.

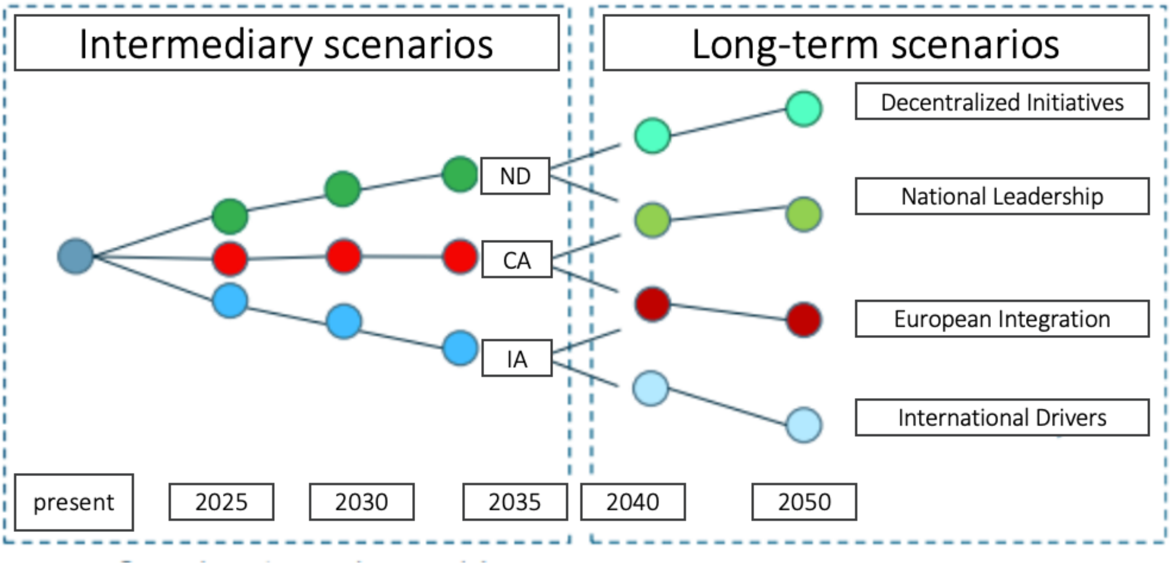


Figure 5. Connection between scenarios (adapted from Netbeheer Nederland, 2024)

4.1.5 CLIMATE AMBITION SCENARIO

The Climate Ambition scenario, which is seen as the central scenario, is based on existing and proposed energy and climate policies outlined by Kabinet-Rutte IV (Netbeheer Nederland, 2023). This scenario is considered to be an ambitious scenario in which the Dutch government implements additional climate policy with the aim of achieving emission reduction targets successfully. As well as implementing strict regulations and policies, the government actively supports initiatives and projects that help reduce emissions. An essential part of this scenario is that every sector must contribute to achieving climate goals. This means that the production of renewable solar and wind energy is stimulated, and the industry sector needs to be electrified and transition toward using hydrogen as a primary fuel. In addition, the transition toward electrical mobility is accelerated, renewable heating is implemented, and the agricultural sector reduces methane emissions. Important in this scenario is that the government aims to deploy a mix of technologies to shape the energy transition and not rely on a single technology.

4.1.6 NATIONAL DRIVERS

The National Drivers scenario is based on the Netherlands aiming to achieve high self-sufficiency regarding the energy supply and economy (Netbeheer Nederland, 2023). The Dutch government is fully committed to domestic renewable energy production and the electrification of all sectors, including industry, transport, and heat production, to reduce emissions and reliance on fossil fuels. An important feature of the ND scenario is the focus on energy efficiency solutions and reducing the overall energy needs. This is achieved through measures such as insulating buildings, improving the efficiency of industrial processes, and implementing smart technology that helps optimize energy consumption and manage grid operations in real time. In this scenario, flexibility in the energy system is crucial due to the high dependency on electricity and the inherent intermittency of solar and wind energy. This flexibility is achieved by a wide implementation of energy storage systems, demand response, and decentralized energy production.

4.1.7 INTERNATIONAL AMBITION

The International Ambition (IA) scenario is based on the storyline that the Netherlands commits to high energy imports and prioritizes international collaboration and trade. In this scenario, the Netherlands functions as a transit country for biofuels, CO2, and hydrogen (Netbeheer Nederland, 2023). Compared to the earlier mentioned scenarios, this scenario emphasizes renewable gases, such as hydrogen and green gas, while relying less on electrification. These gasses will play a significant role in reducing emissions in the IA scenario, especially in sectors where electrification is more challenging. An important element of this scenario is that the Netherlands invests in multiple energy infrastructures. One is a backbone infrastructure for renewable gasses, and the other, allowing electrification. These infrastructures are likely to differ on a regional level due to specific needs of certain regions.

These scenarios are used to guide investments in grid infrastructure. However, it is important to note that the actual development of the energy system will likely not follow any single scenario exactly but fall somewhere in between the scenarios.

4.2 PRIORITIZATION METHOD DUTCH TRANSMISSION SYSTEM OPERATOR

The transmission system operator in the Netherlands, TenneT, faces similar challenges compared to those of Stedin when prioritizing infrastructure investments. However, the consequences of prioritization are more significant for Tennet than for the regional grid operators. This is primarily due to the nature of Tennet’s projects, which are fewer in number but much larger and complex, with longer implementation times. As a result, incorrect prioritization poses a higher risk of capacity or quality bottleneck risks materializing, potentially impacting large areas and many consumers. These bottlenecks can be difficult to resolve quickly due to the scale and complexity of the involved infrastructure components. For this reason, Tennet’s prioritization process is more thoroughly considered and discussed in their investment plans. Therefore, studying investment procedures by Tennet can result in valuable insights that can potentially be incorporated into Stedin’s Prioritization methodology. Tennet uses a risk-based methodology to determine where investments in the transmission grids are most critically needed (Tennet, 2024). The capacity and the quality issues in the grids are the main risks that Tennet analyses to determine what parts of the grid need upgrades most urgently. Determining the total investment portfolio consists of several steps. As mentioned before the prioritization process starts with the scenarios and analyzing the market to estimate future capacity requirements. Based on these assumptions from the scenarios, the future usage of the grid can be simulated using a grid model. By running these simulations, future bottlenecks in the grid can be identified, which can be eligible for investments.

4.2.1 IDENTIFYING CAPACITY BOTTLENECKS

A significant part of Tennet's investment portfolio consists of capacity bottlenecks. Identifying these capacity bottlenecks consist of quantifying the scenarios and running simulations. The scenarios are quantified based on a combination of industry sources, internal reports of grid operators, policy documents and historical data. This quantification process is important as it allows grid operators to model market simulations, which is an essential part of asset planning. The following data is used in market simulations to model the electricity markets for a given year (Tennet, 2024):

- Production capacity for fossil fuel-generated electricity in MW.
- Renewable electricity generation for each hour in MW.
- Electricity demand for each hour in MW.
- Total capacity flexible demand in MW.
- Energy storage capacity and power in GWh and MW.
- Interconnection capacity with bordering countries for each border in MW.
- Fuel and CO2 prices.

The simulation runs result in hourly values for national electricity demand, generation of electricity, and import and export through interconnectors for each scenario. These values are used as a foundation to identify future capacity bottlenecks in the grid. These results are then used to simulate the load flows. Tennet uses a network model to simulate the load flows through their HV network. This network model is a detailed model of the entire network, which includes the topology of transmission lines, substations, transformers, and load points. The forecasted load data and generation data over time are incorporated

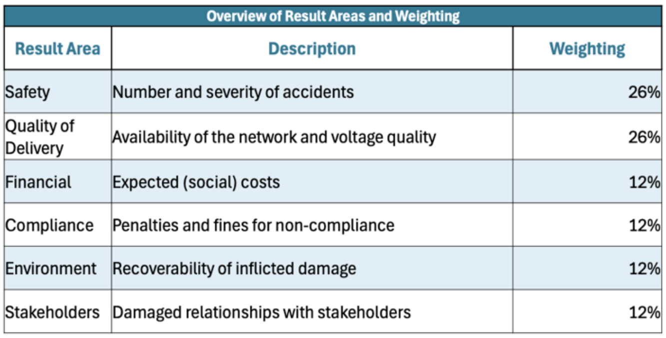
The network model uses the results of the market simulation runs as input data and uses them to model hourly power flows through the infrastructure components for the duration of the scenarios. When a power flow through a component exceeds the maximum capacity of the component, the component is flagged as a capacity bottleneck. The moment in time for which the component exceeds its maximum capacity is noted as the required final completion date. These capacity bottlenecks including their required final completion date are included in the investment portfolio and are included in the prioritization process.

4.2.2 IDENTIFYING QUALITY BOTTLENECKS

An additional number of projects that are included in the prioritization process consists of currently deployed assets that need revisions or replacement. To maintain a functioning grid, these currently deployed assets need to be monitored. Tennet uses a Health Index to determine the status of components. This Health Index helps identify components that need replacement or maintenance. The health index of a component is scored based on the expected remaining lifespan, the year of construction, and the current condition based on inspections. The resulting health scores of a component are classified as either excellent, sufficient, mediocre or insufficient. Excellent means that the technical condition of a component will be sufficient for the coming six years and will only require regular maintenance. Sufficient means that the technical condition of a component will be sufficient for the coming six years if additional maintenance is performed. Mediocre means that the technical condition of a component is insufficient for the coming six years and that additional action is needed to restore the component's health to green. Insufficient means that the technical condition of a component will be insufficient during the coming three years and requires revisions or replacements. Components that according to the health index are mediocre or insufficient are denoted as quality bottlenecks. Tennet includes these components in the prioritization process for replacement projects.

4.2.3 DETERMINING RISK PROFILE OF BOTTLENECKS

The next step is to determine the risk profile of the bottlenecks that have been identified in the grid calculations and the Health Index. Each bottleneck has a specific point in time when the risk of failure is expected to begin. If the completion date of a related project is later than the date on which risks are expected to appear, then the bottleneck is considered active. The active bottlenecks are included in the risk prioritization. To determine the risk profile, risk scores of the active bottlenecks are used. Table 4. shows the categories of risk scores, including their weights that are used to determine the risk profile.



Overview of Result Areas and Weighting

Result Area	Description	Weighting
Safety	Number and severity of accidents	26%
Quality of Delivery	Availability of the network and voltage quality	26%
Financial	Expected (social) costs	12%
Compliance	Penalties and fines for non-compliance	12%
Environment	Recoverability of inflicted damage	12%
Stakeholders	Damaged relationships with stakeholders	12%

Table 4. Overview of risk scores Tennet (adapted from Tennet, 2024)

As shown in the table, safety and quality are the most important company values and have an increased weight compared to the other company values. To create a full risk profile for each project, the frequency and impact of events are combined for each company value. Figure 6 shows a risk matrix that Tennet uses to evaluate the risk scores. Tennet includes all capacity projects that have a risk score of 0,1 or higher in the investment plans.

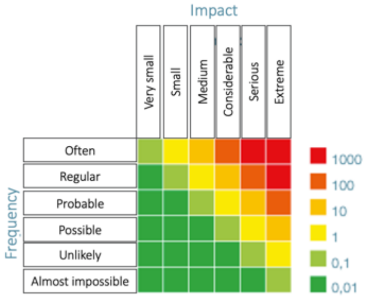


Figure 6. shows that only risks with a dark green color are not included in the investment portfolio (Adapted from Tennet, 2024)

4.2.4 PRIORITIZATION AND OPTIMALISATION OF THE INVESTMENT PORTFOLIO

Due to the large amount of projects that are included in the investment portfolio and the speed of the energy transition, not all projects can be implemented simultaneously. To deal with this the projects are prioritized. Tennet starts the prioritization process by dividing the projects into five investment categories. These categories are ranked in order of importance from highest to lowest. The categories that Tennet defines are:

1. **Absolute priority**: This category contains offshore projects, reconstructions, and customer connections without major grid investments. These projects get the highest priority due to their critical role in supporting the energy transition and immediate operational requirements
2. **Replacement investments and functionality projects:** This category includes projects that focus on maintaining and improving existing grid infrastructure. This includes projects address aging components identified as quality bottlenecks. This category gets a relatively high priority to prevent outages and maintain the safety and quality of the existing grid.
3. **Risk-driven capacity expansions:** This category contains projects that are identified as capacity bottlenecks that pose significant risks for the grid's performance or reliability. These projects are considered to be essential but are ranked below absolute priorities and replacement.
4. **Externally driven new substations.** This category consists of requests for new substations by large customers that require significant investments. These projects have a relative low priority as the impact of delaying projects in this category introduces little risk for the safety and quality of the grid.
5. **Customer connections at existing substations that require rail expansions.** This category consists of projects that involve modifications to existing substations. These projects can improve customer satisfaction but have little impact on the overall grid capacity and functionality.

Concluding, the first prioritization step of Tennet is dividing the projects into one of the five categories. Each category gets assigned a percentage of the total budget with categories. After this first round of prioritization, Tennet prioritizes projects within categories by determining a value/effort ratio. The ratio indicates how much risk reduction is achieved per euro invested. Projects with a high value/effort ratio are prioritized for implementation. This ensures the efficient allocation of available resources and deliver the most substantial risk reduction over the entire investment portfolio. Tennet reiterates the prioritization process three times each year to keep the sequence of investments up to date.

4.3 PRIORITIZATION METHOD DUTCH REGIONAL GRID OPERATORS

This section explores the open source data that is available on the prioritization methods for investments in the LV distribution grids used by the Dutch distribution grid operators. The focus in this section lies on identifying best practices and variations that Stedin could consider in future prioritizations of investment. The distribution grid operators that are included in this analysis are Stedin, Liander, Enexis, Coteq, Rendo, and Westland Infra. In the coming sections these companies are referred to as "the grid operators" From studying the investment plans and company reports of these operators reveals that they largely employ similar prioritization methods (Stedin, 2024) (Liander, 2024) (Enexis, 2024) (Coteq, 2024) (Rendo, 2024) (Westland Infra, 2024) . Slight variations exist to account for specific regional requirements. This section will first explore the shared prioritization methodology of these grid operators. Followed by a summary of key similarities and differences.

4.3.1 CORE COMPANY VALUES

For all the grid operators the overall company strategies form the foundation to guide all activities including investment decisions. The grid operators define their strategies with core company values. These values are relatively similar for the considered grid operators. The following values are identical for the grid operators:

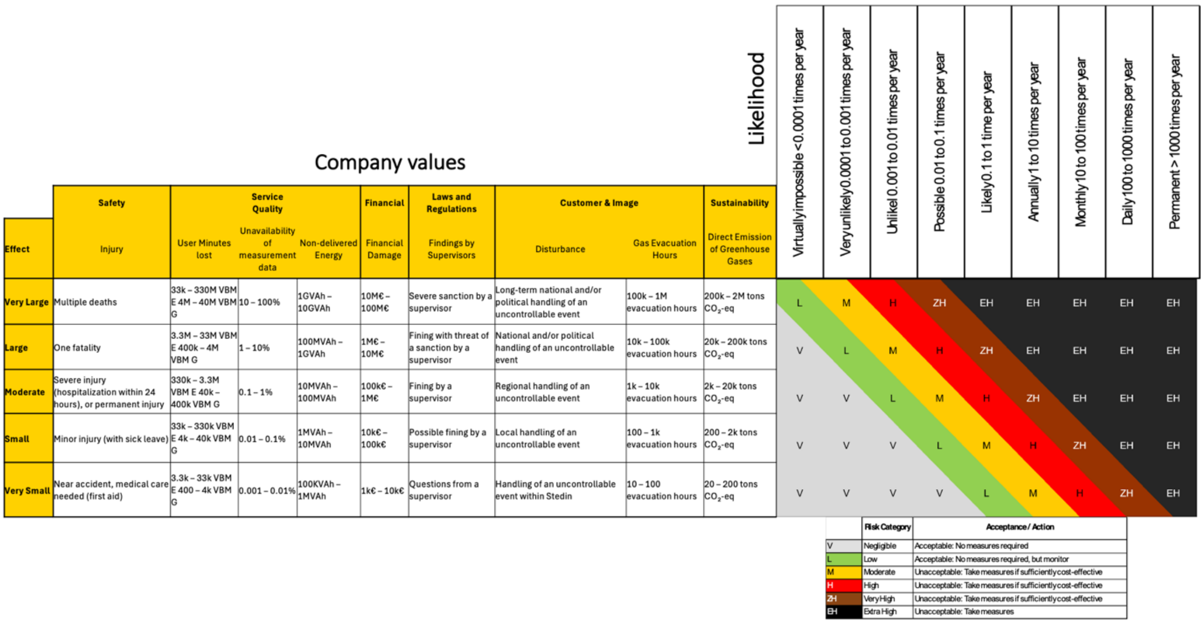
- **Safety:** This value measures the extent to which grid operator's actions impact the physical safety of customers, employees, and the public space. This value is measured by the number and severity of injuries caused by grid operator's actions.
- **Quality of supply:** This value relates to the degree to which grid operators can provide continuous energy supply to customers. This value is expressed in customer minutes lost, which is a metric consisting of the outage duration multiplied by the outage frequency, and by the amount of non-delivered energy.
- **Reputation:** This value relates to the degree of which regular operations damage the perception stakeholders have of the grid operators. This value is measured by negative media attention and or complaints.
- **Financial:** This value relates to the degree to which the financial targets of the grid operators are achieved. This value is measured by the financial risk and financial opportunities.

- **Sustainability:** This value relates to the degree to which the operations of grid operators contribute to direct GHG emissions. This value is expressed in net CO2 equivalents that are emitted as a consequence of operations.

The following core company values show some variation for the grid operators

- **Regulatory compliance:** All operators except Enexis include regulatory compliance as a core company value. This value relates to the degree of adherence to laws , policies, and regulations. This value is measured by assessing the severity of any regulatory sanctions or warnings.
- **Grid accessibility:** Enexis and Coteq include grid accessibility as a core company value. This value relates to the degree to which grid operators can meet the customer demand for capacity. This value is measured by assessing the scarcity of transport in distribution networks.

All the grid operators translate these core company values into a risk matrix. Figure 7. Shows the core company value model and risk matrix designed by Stedin as an example.



Company values

	Safety	Service Quality			Financial	Laws and Regulations	Customer & Image		Sustainability
Effect	Injury	User Minutes lost	Unavailability of measurement data	Non-delivered Energy	Financial Damage	Findings by Supervisors	Disturbance	Gas Evacuation Hours	Direct Emission of Greenhouse Gases
Very Large	Multiple deaths	33k – 330M VBM E 4M – 40M VBM G	10 – 100%	1GVAh – 10GVAh	10M€ – 100M€	Severe sanction by a supervisor	Long-term national and/or political handling of an uncontrollable event	100k – 1M evacuation hours	200k – 2M tons CO_2-eq
Large	One fatality	3.3M – 33M VBM E 400k – 4M VBM G	1 – 10%	100MVAh – 1GVAh	1M€ – 10M€	Fining with threat of a sanction by a supervisor	National and/or political handling of an uncontrollable event	10k – 100k evacuation hours	20k – 200k tons CO_2-eq
Moderate	Severe injury (hospitalization within 24 hours), or permanent injury	330k – 3.3M VBM E 40k – 400k VBM G	0.1 – 1%	10MVAh – 100MVAh	100k€ – 1M€	Fining by a supervisor	Regional handling of an uncontrollable event	1k – 10k evacuation hours	2k – 20k tons CO_2-eq
Small	Minor injury (with sick leave)	33k – 330k VBM E 4k – 40k VBM G	0.01 – 0.1%	1MVAh – 10MVAh	10k€ – 100k€	Possible fining by a supervisor	Local handling of an uncontrollable event	100 – 1k evacuation hours	200 – 2k tons CO_2-eq
Very Small	Near accident, medical care needed (first aid)	3.3k – 33k VBM E 400 – 4k VBM G	0.001 – 0.01%	100KVAh – 1MVAh	1k€ – 10k€	Questions from a supervisor	Handling of an uncontrollable event within Stedin	10 – 100 evacuation hours	20 – 200 tons CO_2-eq

Likelihood

Effect	Virtually impossible <0.0001 times per year	Very unlikely 0.0001 to 0.001 times per year	Unlikel 0.001 to 0.01 times per year	Possible 0.01 to 0.1 times per year	Likely 0.1 to 1 time per year	Annually 1 to 10 times per year	Monthly 10 to 100 times per year	Daily 100 to 1000 times per year	Permanent > 1000 times per year
Very Large	L	M	H	ZH	EH	EH	EH	EH	EH
Large	V	L	M	H	ZH	EH	EH	EH	EH
Moderate	V	V	L	M	H	ZH	EH	EH	EH
Small	V	V	V	L	M	H	ZH	EH	EH
Very Small	V	V	V	V	L	M	H	ZH	EH

	Risk Category	Acceptance / Action
V	Negligible	Acceptable: No measures required
L	Low	Acceptable: No measures required, but monitor
M	Moderate	Unacceptable: Take measures if sufficiently cost-effective
H	High	Unacceptable: Take measures if sufficiently cost-effective
ZH	Very High	Unacceptable: Take measures if sufficiently cost-effective
EH	Extra High	Unacceptable: Take measures

Figure 7. Core company value model and risk matrix (Adapted from Stedin, 2024)

4.3.2 CAPACITY AND QUALITY BOTTLENECK IDENTIFICATION

The investment strategies of regional grid operators begin with the input of the Netbeheer Nederland scenarios, which provide predictions for future electricity demand and supply for all grid components over the next ten years. Regional grid operators combine the strategic analyses of trends in the energy transition with customer requests for connection to the grid to forecast future transport capacity demands within specific areas of their Networks. This forecasted transport capacity demand is compared to the transport capacity of existing infrastructure. Grid operators flag parts of the grid as capacity bottlenecks when forecasted demands exceed the capabilities of existing components. Grid operators perform these load flow simulations with similar software programs. Reiterating this process for each scenario results in an overview of specific grid components that are expected to cause capacity bottlenecks for each scenario, including the expected timing of these constraints.

Quality bottlenecks can occur at grid components that near their end of service life or assets with specific issues. To ensure the reliable operation of the grid, regional grid operators assess the aging infrastructure for potential quality bottlenecks. Identifying quality bottlenecks is unrelated to the future demand scenarios and is mainly based on monitoring the condition of the current assets.

4.3.3 DETERMINING THE RISK PROFILE

Because there are not enough resources to start working on all the bottlenecks at once, decisions have to be made. To make informed decisions, Dutch regional grid operators determine the risk profile for each bottleneck. Grid operators calculate a risk score for each bottleneck. To calculate these risk scores, risk matrices are used. For each of the company values that is impacted by potential bottlenecks, the likelihood and severity of this risk are determined. By adding these scores together, a total risk score is calculated for each bottleneck. Putting the neighborhoods in order of highest total risk score to lowest score gives the grid operators an overview of which neighborhoods most pressingly need attention according to the risk assessment.

4.3.4 PRIORITIZATION OF PROJECTS

Once the total risks scores are calculated for all the bottlenecks and the projects are ranked based on their risk level, the grid operators define the annual implementation capacity. This capacity is often lower than the number of neighborhoods that have critical risk levels. A final prioritization round is performed to determine which of the high-risk projects are actually prioritized for upgrades. This final round of prioritization usually includes a cost-benefit analysis in which remaining projects are prioritized based on the highest amount of risk reduction achieved per euro spent. This results in the final sequence of implementation.

4.4 CONCLUSION OF CHAPTER

The desk research in this chapter were conducted with the aim of answering the sub-research question: How do Dutch grid operators prioritize grid expansion projects? This part of the research presented an overview of the prioritization methods used by Dutch grid operators. It became evident that the steps that Dutch grid operators take to prioritize their investments are very similar. The prioritization process of Dutch grid operators starts with defining core company values and designing a risk matrix. The next step in the prioritization method is simulating future electricity flow over the grids and identifying the time and location of capacity bottlenecks arising. To simulate these electricity flows over the grids, the assumptions from the scenarios by Netbeheer Nederland are used. Once these bottlenecks are identified, a risk appetite is determined, with which a set of neighborhoods is designated that is expected to exceed the risk appetite for each year. This resulting set of neighborhoods is then in a final prioritization step ranked according to the highest risk reduction per euro spent, ensuring that the most efficient measures are implemented first. Another key insight that emerged is that, following the prioritization, municipalities must meet specific requirements before projects can begin. These conditions include making a definitive decision on the neighborhood's future heat supply and providing Stedin with sufficient space for transformers. If municipalities do not fulfill these requirements, Stedin will not proceed with these projects, regardless of the risk levels and prioritization status. These findings will be extensively discussed and critically analyzed in chapter 7.

CHAPTER 5 INTERVIEW RESULTS

This section aims to gain a deeper understanding of Stedin's specific prioritization approach. Chapter 4 outlined the basic steps that Dutch grid operators take, based on open-source data. However, the information in Chapter 4 provides only a partial view of the prioritization methods used by Dutch grid operators, as critical data and processes are often protected by confidentiality. To get a more complete view on the prioritization methods of Dutch grid operators and to be able to give a more satisfactory answer to sub-question 2: How do Dutch grid operators prioritize investments in the LV distribution grid? experts interviews were conducted.

These expert interviews are conducted with two main objectives. First, the interviews provide a deeper understanding Stedin's prioritization methodology and the challenges involved in the decision-making for LV grid investments. Through these interviews information that would otherwise not be accessible due to confidentiality can be accessed, a more detailed view of the prioritization method by Stedin can be achieved. Second, the interviews aim to identify and map the uncertainties and risks that distribution grid operators must navigate when investing in LV distribution grids. By discussing these uncertainties and risks with experts, an idea of how Stedin manages emerging can uncertainties in the future can be achieved

5.1 INTERVIEW METHODOLOGY

5.1.1 CHOICE OF PARTICIPANTS

As the main aim of the expert interviews is to explore Stedin's prioritization method of investments in the LV grid, participants are selected based on their knowledge and involvement in this process. This group forms the core of the participants. As the team working on the prioritization method of Stedin is relatively small, additional experts on closely related subjects are included in this part of the study. Experts on closely related subjects include a regional manager with valuable knowledge on challenges related to the implementation of LV projects in neighborhoods, a representative of Netbeheer Nederland, and investment strategists. Table 5. shows the role and expertise of the interviewees and the themes discussed with them. By including these related subjects, a more complete view on the method and the implications of the method can be achieved. These participants were found through recommendations from Stedin supervisors, and additional participants emerged from the interviews.

Interviewee	**Role/expertise**	**Themes discussed**
Interviewee 1	Technical regulations specialist	Risks/uncertainties and prioritization method Stedin
Interviewee 2	Strategic investment	Risks/uncertainties.
Interviewee 3	Asset management/Risk analyst	Prioritization method Stedin.
Interviewee 4	Energy transition strategist	Prioritization method Stedin, and risks/uncertainties.
Interviewee 5	Program manager project Buurtaanpak	Risks/uncertainties
Interviewee 6	Regional manager for energy transition	Risk/uncertainties and collaborations with municipalities
Interviewee 7	Expert asset management	Prioritization method of Stedin.
Interviewee 8	Energy strategist	Prioritization method of Stedin.
Interviewee 9	Asset management/Risk analyst	Prioritization method of Stedin

Table 5. This table shows the role and expertise of the participating interviewees.

5.1.2 INTERVIEW STRUCTURE

To achieve the two main objectives of the expert interviews, participating experts were questioned on the prioritization method of Stedin, the risks and uncertainties, or both, depending on their area of expertise. The interviews are structured as semi-structured interviews including open questions and in-depth discussions. This interview structure ensures that the intended concepts are discussed while allowing participants to explore specific concepts in detail.

As mentioned, the interviews had two main aims: exploring the investment strategy and prioritization method of Stedin in greater detail, and mapping uncertainties and risks regarding these investments. To address these aims interview questions were designed specifically based on the expertise of the interviewee. This means that no interview was identical and not all interviewees answered the same questions. This approach was necessary because only a small group of employees had detailed knowledge on the state-of-the-art of the prioritization process. During the interviews it was frequently observed that when specific aspects of the prioritization methods were discussed interviewees often responded by stating, “I am not fully aware of this process”, and refer to a select group of experts that for detailed information. By tailoring the interview questions to the knowledge and expertise each participant, the interviews ensured that valuable data was obtained while preventing getting stuck on specifics outside the interviewee’s knowledge.

Although the interviews varied in content and structure due to this tailored approach, the questions ensured that at least one of the main themes was discussed in each interview. As no interviews were identical, a strict interview protocol was not used. However, the semi structured interview framework is provided in Appendix B.1, detailing the questions related to each of the main themes. Appendix B.2-B.10 includes the summaries of all interviews in which specific interview questions can be found.

5.2 PRIORITIZATION METHOD OF STEDIN

In this section, the findings from interviews with experts are discussed, focusing on Stedin's prioritization method. Building on the information available in open sources discussed in section 4.3, this section aims to provide a deeper understanding of specific processes and considerations underlying Stedin's prioritization method of investments in neighborhoods. By gaining a more complete understanding of Stedin's prioritization method, this study aims to provide insights on potential improvements through a comparison with insights from the literature and practices from other grid operators. The desk research into the prioritization methods of Dutch regional grid operators identified several key steps that Stedin follows when prioritizing grid upgrades. These steps are examined greater detail in the following sections, providing specifics on how Stedin prioritizes grids and ultimately makes investment decisions.

5.2.1 CORE COMPANY VALUE MODEL AND STRATEGY

To get a deeper understanding of the core company value and the usage of the risk matrix, experts were asked the following questions.

Question 1: Can you describe the main strategy that Stedin uses in upgrading the grids in neighborhoods?

Question 2: Where does the prioritization of projects in the LV grids in neighborhoods start?

Question 3: How is the core company value model developed?

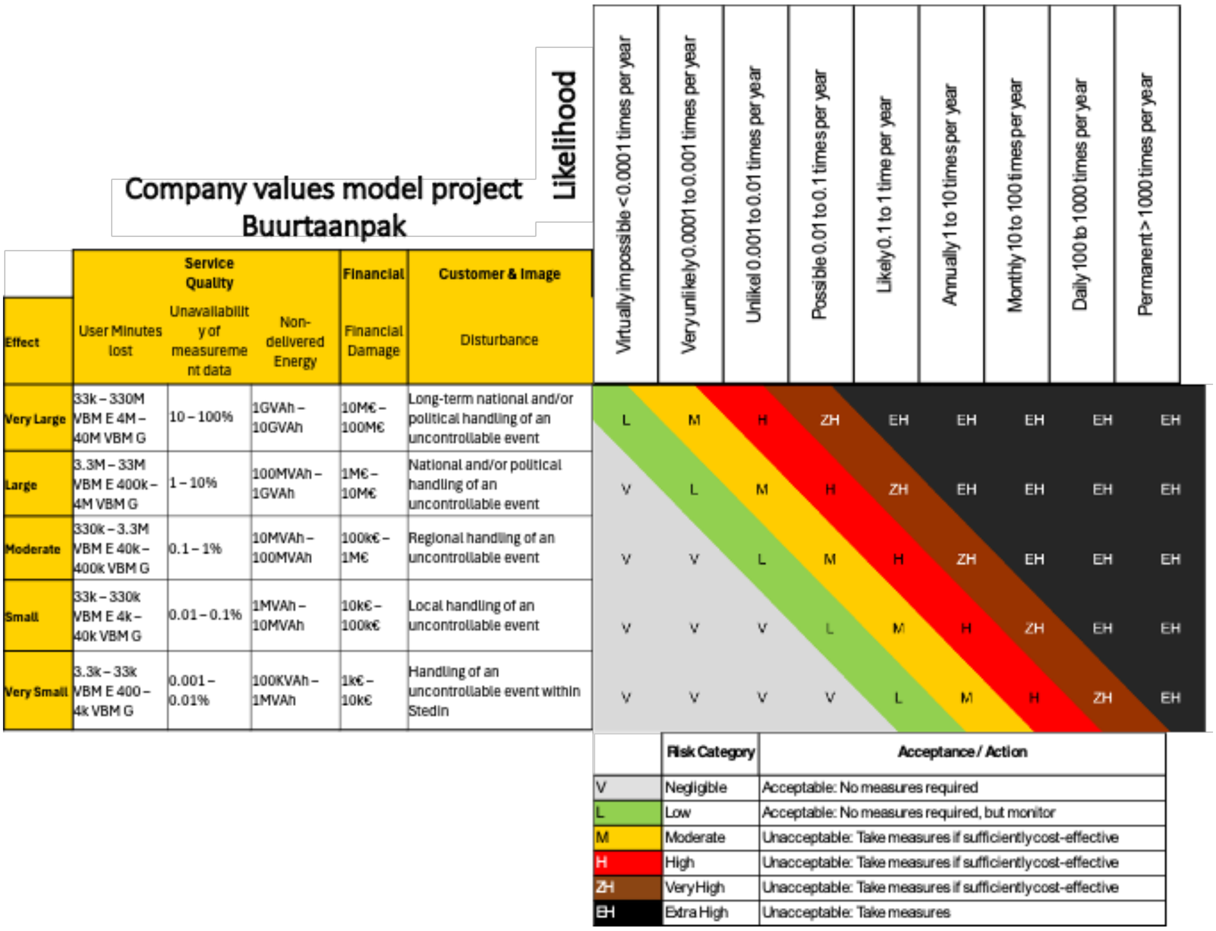
Question 4: What is the reason that for the project Buurtaanpak only impacts on the core values financial performance, quality of service and customer satisfaction and image are included in the decision making?

Question 5: How are the values used in the core company value model quantified?

When answering question 1, Interviewee 1 explained that Stedin's strategy for the project Buurtaanpak, recently switched from a reactive strategy to a proactive strategy. The reactive strategy consisted of upgrading specific grid components in neighborhoods only when issues started to emerge. The current proactive strategy that Stedin employs consist of systematically upgrading entire high-risk neighborhoods one by one, making them future proof for the coming forty years. This strategic change was driven by the regulatory reform in 2019 by ACM, which provides grid operators more leniency in recovering investments made to ensure sufficient capacity in the future.

When answering question 2, Interviewee 3 explained that the basis of the risk-based prioritization method is Stedin's business value model, which includes the company's core values. When answering question 3, Interviewee 7 answered that the core company values are formulated high up in the organization in line with the overall strategy of the company. The process of designing the core company value included many discussions high up in the organization. Interviewee 7 mentions that it is important to note that these core company values apply for the entire company and are thus not specific to the investments in LV grids.

When answering question 4, Interviewee 8 answers: To make the risk analysis more manageable only core company values are considered that are actually at risk in the project Buurtaanpak. Since financial performance, quality of service, and customer satisfaction and image are the values most impacted by risks related to LV-grids in neighborhoods, these are the ones included in the risk assessment. Interviewee 8 adds that over the whole company rarely risks emerge that impact all core company values. Figure 8. Shows the risk matrix and core company value model that is used for assessing risks in the LV-grids of neighborhoods. When answering question 5, Interviewee 7 explains that defining the values in the core company model is a challenging process. Stedin tries to monetize values that are often inherently difficult to express in financial terms. This quantification relies on data from academic sources that, for example, discussing how much a life is worth, or the value of a lost minute of electricity. Interviewee 7 emphasizes that, although this quantification is based on academic sources and expert opinions, significant subjectivity remains. When asked why Stedin quantifies the values this way, considering the uncertainty it introduces, Interviewee 3 explains that this method, while imperfect, is essential to create this common unit to enable the comparison of diverse criteria.



Company values model project Buurtaanpak

	Service Quality			Financial	Customer & Image	Likelihood								
Effect	User Minutes lost	Unavailability of measurement data	Non-delivered Energy	Financial Damage	Disturbance	Virtually impossible < 0.0001 times per year	Very unlikely 0.0001 to 0.001 times per year	Unlikel 0.001 to 0.01 times per year	Possible 0.01 to 0.1 times per year	Likely 0.1 to 1 time per year	Annually 1 to 10 times per year	Monthly 10 to 100 times per year	Daily 100 to 1000 times per year	Permanent > 1000 times per year
Very Large	33k – 330M VBM E 4M – 40M VBM G	10 – 100%	1GVAh – 10GVAh	10M€ – 100M€	Long-term national and/or political handling of an uncontrollable event	L	M	H	ZH	EH	EH	EH	EH	EH
Large	3.3M – 33M VBM E 400k – 4M VBM G	1 – 10%	100MVAh – 1GVAh	1M€ – 10M€	National and/or political handling of an uncontrollable event	V	L	M	H	ZH	EH	EH	EH	EH
Moderate	330k – 3.3M VBM E 40k – 400k VBM G	0.1 – 1%	10MVAh – 100MVAh	100k€ – 1M€	Regional handling of an uncontrollable event	V	V	L	M	H	ZH	EH	EH	EH
Small	33k – 330k VBM E 4k – 40k VBM G	0.01 – 0.1%	1MVAh – 10MVAh	10k€ – 100k€	Local handling of an uncontrollable event	V	V	V	L	M	H	ZH	EH	EH
Very Small	3.3k – 33k VBM E 400 – 4k VBM G	0.001 – 0.01%	100KVAh – 1MVAh	1k€ – 10k€	Handling of an uncontrollable event within Stedin	V	V	V	V	L	M	H	ZH	EH

	Risk Category	Acceptance / Action
V	Negligible	Acceptable: No measures required
L	Low	Acceptable: No measures required, but monitor
M	Moderate	Unacceptable: Take measures if sufficiently cost-effective
H	High	Unacceptable: Take measures if sufficiently cost-effective
ZH	Very High	Unacceptable: Take measures if sufficiently cost-effective
EH	Extra High	Unacceptable: Take measures

Figure 8. Adapted core company model showing values considered in project Buurtaanpak (Adapted from Stedin, 2024)

5.2.2 IDENTIFYING CAPACITY BOTTLENECKS

To get a deeper understanding of Stedin's approach to identifying bottlenecks in the grids of existing neighborhoods, the following questions were asked:

Question 2: Where does the prioritization of projects in the LV grids in neighborhoods start?

Question 6: What three bottlenecks are considered and what do they include?

Question 7: Which of these bottlenecks is the most pressing and why?

Question 8: How are these bottlenecks identified?

Question 9: How does the Stedin Energy Transition Assessment Model (SETIAM) work?

Question 10: What are the main challenges with this process (regarding SETIAM)?

Question 11: How does Stedin regionalizes the implementation of new technologies?

When answering question 2, Interviewee 1 answers that this process starts with identifying three different capacity bottlenecks that can be experienced in the LV distribution grids. When answering question 6, Interviewees 1 and 3 answer that the three bottlenecks that are considered by Stedin for LV grids are:

- Overvoltage: Causes PV inverters to shut off and hinders clients from being able to feed their produced solar energy back to the grid.
- Undervoltage: Causes malfunctioning and, in some cases, damaging of residential electrical appliances.
- Overloading of MV/LV transformers: Can cause power outages.

When answering question 7, interviewee 3 explains how the overloading of transformers has the most severe societal impact, as entire sections of neighborhoods can have blackouts due to failures of the transformers. Overvoltage is considered the least pressing as the impacts are limited to owners of PV and undervoltage is considered more pressing as it can impact larger groups of people. When answering question 8, interviewee 3 answered that for overvoltage and undervoltage smart meter data from 1.6 million customers is used. These smart meters register undervoltage and overvoltage events. Combining the numbers of these events for all impacted homes in a neighborhood gives a good overview of which neighborhoods are experiencing long-term and frequent events. For the overloading of transformers, the process is more complex as it requires simulations of the future electricity loads.

The initial results of the future scenarios are primarily qualitative, which limits the ability to directly use them for grid simulations and the identification of capacity bottlenecks. To be able to use the qualitative data, experts at Stedin further quantify the scenario assumptions by estimating the growth of each technology relevant to the energy transition. This process includes making considered estimates for each technology that plays a role in the energy transition. This results in an overview of the expected growth of these technologies over time.

This quantified data is then used as input for the Stedin Energy Transition Assessment model (SETIAM). When answering question 9, Interviewee 8 answers that Stedin uses this SETIAM to assess the impact of the energy transition on the capacity of the distribution grids. The model distributes the projected demands and supply across the Stedin network and simulates the expected load of specific components.

When answering question 10, interviewee 7 explained that it is hard to estimate in what neighborhood exactly an increase of demand will happen as Stedin is not directly involved in purchasing the technology. This can result in significant deviations from the average expected electrification rate in specific neighborhoods.

When answering question 11, Interviewee 8 Answers: To make better estimations for specific neighborhoods the SETIAM model uses a stochastic approach to determine what neighborhoods are most likely to have new technologies implemented. SETIAM uses Artificial intelligence to analyze patterns based on customer data and data on already installed technologies in neighborhoods. By learning these patterns, the model can better estimate which areas are more likely to see additional electrification. The main insights that are gained from the simulations with SETIAM are an overview of the distribution of demand and supply across the Stedin network, including the impact on specific parts of the grid that risk getting overloaded. For each hour until 2050, SETIAM provides the expected load through transformers. By comparing this to the rated power of transformers, SETIAM provides the moment in time when the rated power of Stedin's 21.000 transformers is exceeded.

5.2.4 RISK ASSESSMENT OF BOTTLENECKS

To get a better understanding of how Stedin assesses bottlenecks the following questions were asked:

<u>Question 12</u>: How does Stedin determine the risk appetite?

<u>Question 13</u>: What risk-level does Stedin use in the prioritization of neighborhoods for project Buurtaanpak?

<u>Question 14</u>: Why are the risk levels set to these relatively high levels?

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Figure 9. Plot showing development of risk levels over time (Stedin, 2024)

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5.2.5 PRIORITIZATION OF PROJECTS

To get a better understanding of the continued prioritization process of the identified set of neighborhoods, the following questions are asked:

Question 15: Which scenario does Stedin consider as the most plausible and how is it applied in further calculations and decision-making for neighborhood upgrades?

<u>Question 16</u>: Is this resulting prioritization always leading for the investment decisions?

<u>Question 17</u>: What conditions have to be met by municipalities?

<u>Question 18</u>: What are the consequences of indecisions or not cooperating by municipalities?

<u>Question 19</u>: Are there any additional conditions that have to be met by municipalities?

<u>Question 20</u>: Is it challenging to find sufficient space?

<u>Question 21</u>: Are the any other reasons to deviate from the sequence resulting from the prioritization approach?

<u>Question 22</u>: What happens if the resulting set of neighborhoods requiring upgrades per year still exceed the Stedin's implementation capacity?

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When answering question 21, Interviewee 8 explains that there are some strategic choices that Stedin can make to improve overall efficiency. These strategic choices are mainly related to the locations of the neighborhoods. If, for example, the resulting sequence includes the entire city center of Rotterdam, Stedin will make adjustments to prevent the city from getting completely jammed by the amount of work being done in the streets. Another reason to make strategic adjustments is to ensure that neighborhoods are being selected that have workforce capacity located nearby. Stedin wants to prevent that the implementing engineers and contractors have to travel many hours from where they are located to improve efficiency. A final reason to deviate from the prioritization method is when project can be combined for increased overall efficiency. An example of this can be that a neighborhood with a slightly lower risk level than prioritized borders a neighborhood that is prioritized. Stedin considers combining these projects if significant efficiency gains can be made.

When answering question 22, Interviewee 3 explains that for the resulting set of neighborhoods, a final prioritization round is conducted before definite decisions are made. In this step, Stedin determines for each neighborhood how the project costs compare to the overall risk reduction. Neighborhoods expected to yield the highest risk reduction per euro spent are prioritized, ensuring that the most cost-efficient measures are implemented first. Neighborhoods that have a low-risk reduction per euro spent and fall outside of the implementation capacity are delayed till next the coming year.

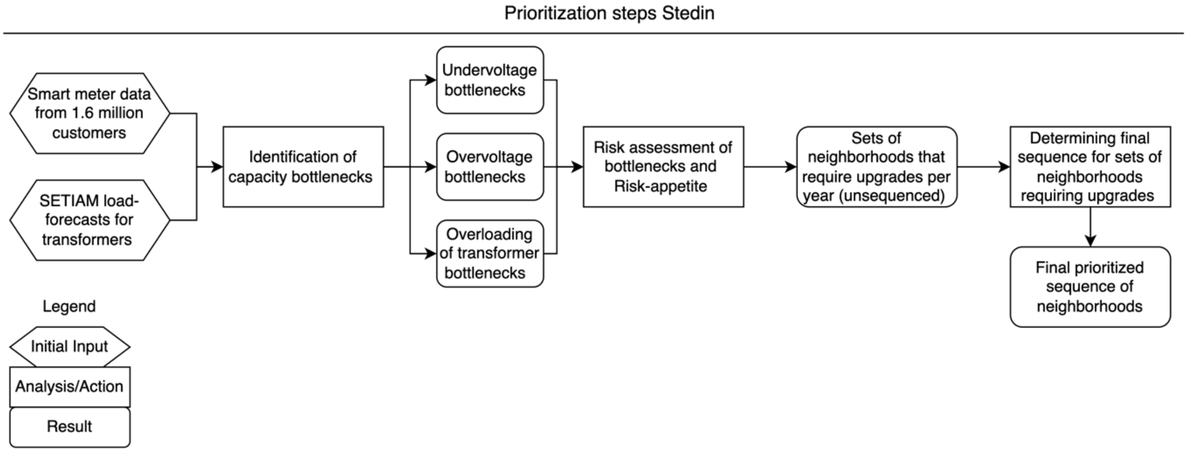

Figure 10. Prioritization process of Stedin.

5.2.6 CHALLENGES

To get a better understanding of the challenges that have to be dealt with by Stedin in their prioritization approach the following question is asked:

Question 23: What are the main challenges with the current prioritization method?

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5.3 RISK AND UNCERTAINTY

This section discusses important risks and uncertainties governing investment decisions in LV grids in neighborhoods. This section aims to contribute to answering sub-question 2 How does Stedin prioritize investments in the LV distribution grid? By examining which uncertainties and risks are currently considered in Stedin's prioritization method and identifying those that are not yet included or underrepresented. To get a deeper understanding of these uncertainties and risks, the answers to the following questions are discussed:

Question 24: What are the main uncertainties and risks that have to be considered when investing in LV grids?

Question 25: What do you think of material scarcity as an uncertainty for investment decisions in the LV grids?

Question 26: Are long waiting times for components an important risk that Stedin considers?

5.3.1 FUTURE CAPACITY REQUIREMENTS

When answering question 24, Interviewees 1-6 all mention that the future expected capacity requirements are one of the main uncertainties that emerge from external factors. Interviewee 1 goes as far as stating that grid operators can struggle to predict the usage of specific LV grids two years from now. Interviewee 1 also mentions that swerving government policies causes uncertainty for residents. Examples of these swerving government policies are the abolishment of the Salderingsregeling and whether heat pumps will be obligatory. These indecisions by the government can make residents hesitant to invest and potentially slow down electrification. Interviewee 3 agrees with this and adds that constant updates to climate policies, new laws, and regulations cause uncertainty regarding future capacity. These updated policies and regulations result in the prioritization of neighborhoods needing to be updated regularly. Interviewee 3 mentions that the scenarios with which the future capacity requirements are modeled are likely not to be completely accurate. Interviewees 3 and 5 agree with this statement and mention the fact that, although the scenarios are compiled with a lot of care, predicting the required capacity many years from now is susceptible to many external factors and remains highly uncertain.

Interviewee 1 mentions developments in the new tariff structure as an interesting uncertainty that could impact capacity requirements. Interviewee 5 is convinced that a future new tariff structure can effectively reduce the peaks. However, implementing such a structure can take a few years. During this time, Interviewee 5 suggested making the impact of variable electricity pricing more noticeable for residents. An interesting finding is that Interviewee 5 expects that in 3 to 4 years, the uncertainty regarding required capacity will drastically decrease. The interviewee foresees more intelligence built into the LV grid, resulting in much better capabilities for determining future capacity requirements.

5.3.2 PROJECT COMPLETION TIME

When answering question 24, Interviewee 4 identifies the availability of area needed for reinforcements as one of the most impactful uncertainties. Especially in densely populated neighborhoods, much reluctance towards new transformers is experienced. Not having enough space for infrastructure can put projects on hold, which causes delays. Interviewee 6 adds to this by stating that there is a serious risk of not being able to provide sufficient capacity for the neighborhoods if residents keep complaining about the look of transformers and preferring parking space over energy infrastructure. Interviewee 1-5,8 identify the availability of qualified personnel as an important uncertainty that has significant impact on Stedin's investment decisions. To successfully reinforce the LV grids, a lot of extra contractor and engineering capacity is needed according to Interviewee 2. This uncertainty could cause either the success or the failure of the Buurtaanpak project. Interviewee 3 agrees that finding enough personnel is a big challenge for DSOs as they all compete for the same professionals. Interviewees 1,4,5 emphasize the inability or reluctance of local municipalities as a major uncertainty potentially causing delays. Interviewee 1 states that municipalities can remain indecisive on important decisions they must make. Interviewee 3 agrees that the collaboration between municipalities and DSOs can improve in some cases. When answering question 25, interviewees 2,3,4 agreed that the scarcity of materials currently has a relatively small impact on project completion time due to the personnel scarcity being much more constraining. However, when DSOs are scaling up their implementation capacity, the scarcity of materials must be monitored closely. When answering question 26, Interviewee 3 answered that for LV grids, waiting times for components do not really impact the projects much currently as LV grid components are not that complicated to manufacture.

5.4 SUMMARY OF CHAPTER

The interviews that are discussed in this chapter provided a deeper understanding into both Stedin's prioritization method, and the uncertainties and risks considered in the prioritization process, addressing the internal and external components of the research problem. From the interviews regarding Stedin's prioritization method it became evident that simulating the electricity loads over the grids is extremely challenging as uncertain data and numerous assumptions have to be included. The interviews highlighted the critical importance of the scenarios developed by Netbeheer Nederland, which significantly influence multiple stages of the prioritization method. While Chapter 4 already revealed that these scenarios are used by Dutch grid operators as a starting point for the load simulations, the interviews showed that in a later stage of the prioritization the scenarios again play a significant role in determining the risk appetite. Another key insight that emerged from the interviews is that municipalities must meet specific requirements before projects can begin.

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From the interviews regarding the prioritization method of Stedin revealed minimal disagreements among experts about the steps involved in the prioritization process. The experts explained the different steps that Stedin takes to prioritize neighborhoods and there seemed to be little disagreement among them. This is likely, due to their extensive experience with the method and familiarity with current procedures. However, when discussing the main challenges with the current approach some differing opinions were found.

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From the interviews regarding uncertainties and risks that Stedin several interesting observations can be made. There was a general agreement among the interviewees that accurately estimating the future capacity requirements of the grids is significantly uncertainty. Interviewees mentioned several important reasons making this uncertainty unpredictable, including, swerving government policies, and changing regulations. When discussing how, Stedin manages this uncertainty interviewees mentioned that many uncertainties are included in the scenarios by Netbeheer Nederland. Some interviewees regarded this as sufficient while others doubted the degree to which the scenarios account for emerging uncertainties. This difference in opinion is again likely due to biases that originate from the interviewees' roles within Stedin. For instance, Interviewee 2, whose role includes the application of the scenario results, found the scenarios adequate for managing capacity requirements. In contrast, interviewees 3,4, and 5, whose roles include a more critical stance on the scenarios, doubted the extent to which the scenarios effectively manage emerging uncertainties. This bias towards the importance of certain uncertainties was observed frequently in the interviews. Interviewee 6, who's role includes collaborating and meeting with municipalities on a daily basis, found municipalities not collaborating less of a risk, then Interviewee 1, 4, and 5 who described municipalities as a major risk. Regarding the availability of qualified personnel, interviewees were likeminded and explained that finding enough personnel is a significant uncertainty that impacts the prioritization method.

Overall, the interviews showed that experts mostly agree on risks and uncertainties that impact the future prioritization. However, the relative importance assigned to these factors often depended on the interviewees' roles, highlighting the influence of professional biases on their perspectives. The findings from this chapter will be extensively discussed in Chapter 7.

CHAPTER 6 MAPPING RISK AND UNCERTAINTY

In this chapter, desk research is performed with the aim of mapping uncertainties and risks that may emerge in the near future. This chapter aims to answer sub-question 3: *What uncertainties can emerge from expected regulatory, policy, and market developments?* This chapter addresses the external component of the research problem by identifying uncertainties that can emerge that influence the prioritization method. By mapping these potential uncertainties, the robustness of Stedin's prioritization method against emerging uncertainties can be analyzed.

6.1 DESK RESEARCH METHODOLOGY

The desk research in this chapter mainly consists of gathering data from a range of publicly available sources. These sources mainly include European Union reports, Dutch government policy documents, and Dutch strategic plans regarding the energy transition.

6.2 EUROPEAN REGULATORY AND POLICY DEVELOPMENTS

In this section, European reports and regulatory documents are extensively analyzed to identify uncertainties and risks that can be considered when prioritizing LV grid upgrades.

6.2.1 EUROPEAN REGULATORY AND POLICY DEVELOPMENTS

The challenge of becoming climate-neutral by 2050 requires regulatory and policy developments that transform the way energy is produced, distributed, and consumed. In the Netherlands, these developments primarily stem from two main sources: EU directives and legislation and national laws and initiatives. Many of the domestic policies are formulated in alignment with the European Climate Law and additional European directives. Both European and domestic regulation and policy developments will be analyzed to identify uncertainties that potentially influence the prioritization of grid investments. To start, European sources of regulatory developments that potentially influence LV grid investment prioritization are discussed.

Most of the European guidelines and targets for emission reduction are described in the European Green Deal. This deal can be seen as a roadmap to making Europe the first climate-neutral continent. Union-wide laws, regulations, and directives have been implemented to make the guidelines binding for the member states. These laws, regulations, and directives help guide member states in designing national regulations and policies in their transition towards climate neutrality. In the following sections, European laws, regulations, and directives that have a potential influence on LV grids are discussed. After that, specific regulations are highlighted, including their impact on LV grids and potential emerging uncertainties. All initiatives that are included in the European Green Deal have been studied but only the ones with potential impact on LV grid investments will be discussed. The initiatives that will be discussed are:

- European Climate law

- EU Emission Trading System (EU ETS)
- Effort Sharing Regulation (ESR)
- Emission Trading System 2 (ETS2)
- Land Use, Land-Use Change and Forestry (LULUFC)
- Energy Efficiency Directive (EED)
- Renewable Energy Directive (RED)
- REPowerEU

6.2.1.1 European Climate Law

The European Climate Law writes into law the goals set out in the European Green Deal (European Parliament and the Council, 2021). To ensure the contribution of all EU member states and to ensure that all sectors of the economy and society take their responsibility. The European climate policy architecture is characterized by three main pillars: each setting targets for emissions reduction across various sectors. These three main pillars are Emission Trading System (EU ETS), Effort Sharing Regulation (ESR), and Land Us, Land Use Change and Forestry (LULUCF).

6.2.1.2 European Emission Trading System (EU ETS)

The European Emission Trading System (EU ETS) is a cap-and-trade scheme aimed to lower GHG emissions from electricity generation, large industry, aviation, and the maritime sector. A cap, expressed in emission allowances, is set on the total amount of GHGs emitted by the different sectors (European Parliament and the Council, 2003). This cap is reduced annually, resulting in a decrease in emissions, which is in line with European targets. To be able to emit 1 tonne of carbon dioxide equivalents, one allowance credit must be used. Emitting companies might receive some free credits but must buy additional allowance credits on the EU carbon market or trade them with other companies. The increasing scarcity resulting from the annual reduction leads to higher allowance prices, which might motivate companies to make their business process less polluting. The selling of carbon credits has resulted in 152 billion euros in revenue from EU ETS since 2013 (European Commission, 2023). The capital that is raised is used by member states to invest in renewable innovations to reduce emissions further. Since 2005, EU ETS has helped reduce emissions from the companies within the system by 44%. The target of EU ETS is to further increase this reduction to 62% in 2030 compared to 2005. This binding reduction increase will likely influence the LV grid by increasing the incentive to electrify. Specific regulations from EU ETS that can influence the LV grid are shown in Appendix D.1

6.2.1.3 Effort Regulation Sharing (ESR) and ETS2

The ESR was adopted in 2018 and mandates national emission reduction targets for road transport, heating of buildings, agriculture, small industrial installations, and waste management. These sectors currently generate about 60% of EU GHG emissions (European Commission, 2021). The main target of the ESR is to reduce this by at least 40% by 2030. It is important to note that the target for specific member states is set based on their GDP per capita. Resulting in a 48% reduction target for the Netherlands by 2030 compared to 2005.

To assist in achieving this target, a secondary emission trading system, ETS2, will be introduced in 2027. ETS2 will cover CO2 emissions from small industries, road transports, buildings, and additional sectors that are currently not included in EU ETS (European Parliament and the Council, 2023). The aim of the ETS2 cap will lead to reducing emissions from these sectors by 42% in 2030 compared to 2005. Revenues generated from auctioning 150 million allowance credits will be used to supply the new Social Climate Fund (SCF). This SCF will be used to help vulnerable groups with investments in energy efficiency of old buildings, heating, and cooling solutions. Because there are many small emitters that fall under ETS2, it is impossible to regulate the emissions of the end user. Instead, the point of regulation will be higher in the supply stream for the fuel suppliers. The costs for ETS2 will thus not be for end consumers like car owners. However, it is likely that costs at the pump will increase, leading to an incentive to switch to EVs. Developments in ETS2 and ESR can significantly impact the capacity that is needed in specific neighborhoods. Specific regulations from ESR and ETS2 that could affect the LV grid are shown in Appendix D.2.

6.2.1.4 Land Use, Land-Use Change and Forestry (LULUFC)

The land use sector is seen by the European Commission as an important sector in reducing emissions (European Parliament and the Council, 2018). To help reach climate neutrality in 2050, it is important that forests, wetlands, and grasslands absorb enough carbon from the atmosphere. To manage, protect, and boost carbon removal from these ecosystems, the European Commission has in 2023 upgraded LULUFC regulations. At first, land use change and forestry regulations appear to have little impact on the investment in LV grid reinforcements in neighborhoods. However, the amount of land area that is needed for additional grid infrastructure near and in neighborhoods cannot be underestimated. For the city of The Hague, experts within Stedin expect multiple football fields worth of area to accommodate the required LV grid reinforcements. Therefore, it is important to investigate whether the upgraded LULUFC regulations should be kept in mind when prioritizing grid investments.

6.2.1.5 Energy Efficiency Directive (EED)

The EED is a directive with the main goal of lowering emissions emitted by EU member states by decreasing the union’s final energy consumption. In the directive binding energy reduction targets for EU member states are imposed (European Parliament and the Council, 2023). The EED also focuses on alleviating energy poverty, aiming to assist with energy efficiency upgrades of the worst-performing homes. Additionally, renewable heating and cooling applications are extensively discussed. Improving energy efficiency will likely significantly impact the LV grid, which will involve increased electrification. Specific regulations from EED that can influence the LV grid are shown in Appendix D.3.

6.2.1.6 Renewable Energy Directive (RED)

The RED was introduced in 2009 to accelerate the development of renewables, increase the share of renewables in the EU's energy consumption, and set binding targets for the renewable energy share. In 2023, the RED directive was revised, and an overall renewable energy target of at least 42.5% was set (European Parliament and the Council, 2023). The increasing share of renewable energy is likely to put pressure on the LV grids due to the increased electrification that comes with shifting away from fossil fuels. Specific regulations that can influence LV grids are shown in Appendix D.4.

6.3 DUTCH REGULATORY AND POLICY DEVELOPMENTS

In this section, Dutch policy reports and regulatory documents are analyzed to identify uncertainty and risk that can be considered when prioritizing LV grid upgrades in neighborhoods.

6.3.2 REGULATIONS AND POLICY ON THE DUTCH NATIONAL LEVEL

Many of the Dutch national laws regarding energy systems are based on in section 6.2 discussed binding EU regulations and directives. From these, the following national policies and regulations are formed that will be studied:

- New proposed energy law
- Additional climate package
- National Plan Energy System (NPES)
- National Grid Congestion Action Program (LAN)
- Multi-year program climate fund
- IBO climate

6.3.2.1 Additional Climate Package

The additional climate package in the Netherlands was announced in 2023 to ensure that the EU carbon emission reduction target from 55% in 2030 compared to 2005 is achieved. This additional package of regulations is supposed to result in an additional carbon reduction of around 22 megaton CO2-eq (Jetten, 2023). The package consists of regulations and policy proposals for various sectors, including electricity. Many of these regulations have a significant impact on the way energy is used in the Netherlands. This climate package will accelerate the electrification and, if not properly managed, worsen the problems DSOs experience in neighborhoods. Specific regulations and policies from the additional climate package are shown in Appendix D.5.

6.3.2.2 New Proposed Energy Law

Towards the end of 2017, the Dutch Gas Law and the Dutch Electricity Law merger was proposed. This proposed energy law includes regulations for transporting and delivering electricity and gas. The aim of this proposal is to develop a reliable and affordable low-emission energy system (Tweede Kamer der Staten-Generaal, 2023). The new law seeks to simplify and to clarify existing regulations to accelerate the energy transition. Additionally, the proposed law gives DSOs more freedom to manage congestion problems by allowing DSOs to manage existing grid capacity. Another interesting development in this proposal is that it will provide opportunities for households and companies to become an active player on the energy market.

6.3.2.3 National Plan Energy System (NPES)

The NPES outlines the long-term vision of the Dutch government for energy system development up to 2050 (Ministerie van Economische Zaken en Klimaat, 2023). Key components of the NPES are that the government commits fully on maximizing renewable supply, saving energy, and smart deployment of existing energy infrastructure. As mentioned before, measures like these put additional pressure on the LV grid, making it relevant to research policy and regulatory developments resulting from this plan.

6.3.2.4 National grid congestion action plan (LAN)

LAN is an action program proposed in 2022 with the aim of accelerating the construction of grid expansions (Ministerie van Economische Zaken en Klimaat, 2022). The program has three main targets. Realizing grid expansions more quickly, focusing on better use of available grid capacity, and increasing flexible capacity. These targets are likely to have a significant impact on LV grids. On the positive side, measures that speed up the approval process for grid reinforcement can be beneficial. However, there may be negative consequences if, for example, the accelerated grid expansion causes a scarcity of materials and personnel. Specific regulations from LAN that impact the LV grid are shown in Appendix D.6.

6.3.2.5 IBO climate

The IBO climate is the result of interdepartmental policy research aimed at providing the government with additional policy recommendations to achieve 2030 emission targets. The IBO report proposes aiming for a 60% reduction of emissions in 2030, compared to the 55% proposed by the European Climate Law (Rijksoverheid, 2023). The report provides policy recommendations for all key sectors of the Dutch economy. The policy recommendations that could affect LV grids are shown in appendix D.7.

6.3.2.6 Multi-year program climate fund

The climate fund is intended for additional measures to achieve the emission reduction targets while ensuring a fair transition for the entire society (Ministerie van Economische Zaken en Klimaat, 2024). This is accomplished by funding renewable energy supplies, energy efficiency developments in the business sector, and renewable energy and energy efficiency in the housing sector. The multi-year program outlines the allocation of funds up to 2030. These funds can significantly impact the electricity capacity needs in certain neighborhoods. Specific policies

6.4 MARKET DEVELOPMENTS

In this section potential developments on the Dutch electricity market are discussed. These developments are discussed because they can have a significant impact on the prioritization.

6.4.1 DEMAND SIDE RESPONSE

Experts and professionals within the electricity distribution field are increasingly highlighting the potential of market developments to deal with congestion issues. One of the developments that is much discussed is demand-side response (DSR). DSR are actions that can be taken in order to change the normal consumption patterns of consumers with the aim of shaving peak load consumptions. This can be achieved by various measures, such as incentivizing shifting consumption out of peak hours or directly controlling flexible loads. DSR measures that are currently discussed for implementation in the Netherlands will be discussed in the following sections.

6.4.2 DYNAMIC TARIFFS

Currently, in the Netherlands, a flat tariff for connection to the grid is used independent of the amount and time of use for small consumers. The main functions of these tariffs are to maintain the grid network and to recoup investment costs of infrastructure investments. A form of demand-side response that is currently being discussed to help flatten peak loads and relieve some of the pressure on upgrading grids is dynamic tariff prices. These dynamic tariff prices provide consumers with a financial incentive to shift their consumption to off-peak periods (Abdelmotteleb, 2023). There are multiple ways of implementing dynamic electricity tariffs. These consist of time-of-use (TOU), critical peak pricing (CPP), variable peak pricing (VPP), and real-time pricing (RTP). A TOU tariff works by separating a day into several periods, each with different prices. The time blocks and their prices are based on historical conditions and are announced significantly in advance. CPP is a tariff structure where prices significantly increase during certain forecasted hours of the year. These hours can be caused by extreme heat or cold conditions. Consumers are incentivized to shift away from these peaks by significantly lowering tariffs during non-critical hours. VPP is comparable to TOU except that the peak period prices frequently alternate to match real-time conditions rather than relying on historical data. RTP tariff includes prices varying often throughout the day to reflect fluctuating costs.

Recently ACM announced three changes to the tariff structure that affect large-scale consumers directly connected to the national HV TenneT grid. These changes introduce a discount for large-scale consumers if they lower their demand during peak hours. Additionally, it is made possible for grid operators to give contracts to large-scale consumers that exclude them from using their connection to the grid during peak hours in exchange for higher discounts. The structure that will be implemented is most like a TOU. This means that large consumers can lower their tariff costs by shifting their demand to less expensive times of the day. This is an essential first step towards using the Dutch distribution grid more efficiently by making it more flexible.

Together with three announced changes to the tariff structure, ACM (2024) has published several points of interest for the future of the tariff structure in the Netherlands, which are in line with the rules of the EU. These principal points to be considered in a future tariff structure are cost reflectivity, system efficiency, transparency, and non-discrimination. Cost reflectivity relates to the need for a new tariff structure to represent costs related to grid usage accurately. If a new tariff structure accurately represents grid usage costs, users can be incentivized to reduce their usage during peak hours. Principal point two, system efficiency, relates to the desire to transport as much energy through the system as possible for the installed capacity. This point aims to ensure a new tariff structure contributes to increasing the system's efficiency in the long and short term. This is a crucial point, as increasing the grid's efficiency can reduce the needed grid reinforcements. The point transparency relates to the desire that grid users must be well-informed about the tariff structures and the consequences. This ensures that users can make informed decisions regarding their grid usage. The final point, non-discrimination is aimed at ensuring that all current and future users are treated equally.

A new tariff structure needs to balance these principal points. Currently, ACM and Netbeheer Nederland are researching the effect of implementing a dynamic tariff structure for small consumers. Netbeheer Nederland (2023) expects that introducing dynamic tariff prices will stimulate flexible electricity usage, making the overall grid more efficient and lower costs. An additional advantage of demand response is that it helps reduce the use of carbon-intensive generators, which are typically employed during peak hours. By lowering peak demands, demand response not only reduces the capacity needed on the distribution grid but also decreases overall carbon emissions due to a cleaner energy mix. (Guo and Weeks, 2022). Considering the many advantages dynamic tariff prices offer, it is likely that in the future a dynamic tariff structure will be implemented in the Netherlands for small consumers.

However, introducing dynamic tariffs presents several challenges. For dynamic tariffs to be effectively implemented, smart meters must be installed on a large scale (Guo and Weeks, 2022). These smart meters must at least be able to record energy consumption during the chosen periods for different tariffs and communicate them with the grid operators so that the tariff can be calculated. This adds complexity to the system as it requires additional data management (Pereyra-Zamora et al., 2019). Dutch DSOs are already installing smart meters in households in the Netherlands, and Netbeheer Nederland expects the implementation of smart meters to be completed by 2026. An advantage of having increasingly more smart meters within the system is that DSOs can better monitor and predict demand growth trends. Another challenge of introducing dynamic tariffs is that the effectiveness of a new tariff structure depends on a change in the behavior of consumers. Consumers need to change their energy usage habits, which can require some adaption time. There are also concerns for consumers with lower incomes (Signh et al., 2021). They are likely to have less flexible consumption patterns due to not having modern technology, which would allow them to shift their consumption. This can lead to this group being disproportionately affected by higher prices during peak hours, which is not in line with principal point four by ACM. Another challenge emerging from introducing dynamic tariffs is revenue stability. Dynamic prices can lead to unpredictable revenue streams and insufficient remuneration. This uncertainty can complicate financial planning and investment planning. Thereby comes that the costs for implementing and maintaining a dynamic pricing tariff need to be recovered.

6.4.3 DIRECT CONTROL OF FLEXIBLE LOADS

Another form of demand-side response that is considered in the Netherlands to deal with congestion is direct control of flexible loads by grid operators (Hennig et al., 2023). This form of demand-side response works by the grid operators, turning off the appliances of end users during peaks without significantly impacting their comfort or productivity. For example, charging EVs during the night instead of during peak hours or curtailing a portion of PV production during sunny days. Having direct control of appliances by grid operators can offer significant benefits. Firstly, lowering peak demand reduces the risk of grid overloading, enhancing cost efficiency by reducing the need for grid investments and expensive peaking power plants. Thereby comes that a higher integration of locally generated renewable energy is possible with direct control. This results from grid operators being enabled to better balance renewable energy variability by actively matching demand and supply. Stedin recently suggested in the media that the government should consider switching public EV charging points off from 16:00 until 21:00 (Koster, 2024). However, this was met with much critique. Opponents raise awareness for the fact that owners of EVs should always have the ability to charge their cars and that statements like these can have a deterring effect on people considering buying an EV. There are more challenges related to direct control of flexible loads. To start, a lot of investment is needed to make the appliances “smarter” to enable them to be controlled remotely. Additionally, concerns exist regarding the privacy and fairness of using direct control (Haque et al., 2019). To ensure a fair and secure implementation of direct control, a clear regulatory framework needs to be designed, and a lot of investment is needed.

6.5 OVERVIEW OF UNCERTAINTY AND RISK EMERGING FROM EXTERNAL DEVELOPMENTS

In this section an overview is presented which shows the risks and uncertainties that are identified In this chapter.

Studying the external developments results in numerous uncertainties that have to be considered when deciding on investing in low voltage grid reinforcements in neighborhoods. The uncertainties impacting the decision-making process are divided into three categories. Table 6. shows these categories: Expected future capacity requirements, Project completion time, and Costs.

#	Uncertainty	Risks	Damage/consequence	Sources
1.	**Expected future capacity requirements.**	Overinvestment in grid infrastructure Underinvestment in grid infrastructure	Overinvestment can lead to grid infrastructure not being fully utilized, resulting in inefficient use of financial and material resources. Overinvestment can cause additional costs for society due to increased tariff costs. Resources spent on unnecessary grid upgrades could have been more effectively spent elsewhere. Underinvestment can lead to the LV grid becoming overloaded, reducing reliability, potentially causing power outages, and requiring expensive unplanned emergency upgrades. Frequent overloads and outages of the grid due to the reduced reliability harm the DSO's reputation.	Klimaatpakket 2023 NPES
1.1	Future number of EVs and EV charging points.	Varying EV adoption rates influenced by regulatory and policy changes, complicates planning and forecasting neighborhood demand. Increased peak demand due to the potential high adoption rate of EVs and fast charging facilities. Low EV adoption rates can limit the flexibility a neighborhood can provide the grid.	Inaccurate forecasting and planning due to varying EV adoption rates can result in overinvestment or underinvestment in specific neighborhoods. Increased peak demand puts stress on infrastructure components. Limited demand flexibility can necessitate additional investments to manage peak loads.	ESR Aanvullend klimaat pakket 2023

1.2	Future volume of PV.	Varying PV integration rates influenced by regulatory and policy changes complicate planning and forecasting neighborhood demand. Grid stability issues due to the intermittent nature of PV production. Increased reverse power flow due to high integration of PV in neighborhoods.	Inaccurate forecasting and planning due to varying PV integration rates can result in overinvestment or underinvestment in specific neighborhoods. Fluctuations in demand and supply require more capacity. Reverse power flow can cause voltage levels to rise, potentially overloading transformers.	article 30d(6a,6b) ESR REPowereEU plan Klimaatpakket 2023 NPES
1.3	Future amount of energy efficiency upgrades.	Energy efficiency upgrades increase peak demand as a result of electrification	More capacity on the LV grid required.	Article 10.3 EU ETS Article 30c.1 ESR article 30d(6a,6b) ESR
1.4	Future implementation of district heating	Indecisions in neighborhoods on the energy carrier for heat supply complicate the planning of the grid investments.	Delayed and inefficient grid planning causing potential disruptions and mis investments	Article 10.3 EU ETS Multi year programm
1.5	Future number of heat pumps installed.	High numbers of heat pumps can cause increased electricity demands during winter months.	The adoption rate of heat pumps can vary widely per neighborhood, affecting the predictability of demand and grid planning. High numbers of heat pumps causing stress on infrastructure components	Article 10.3 EU ETS REPowerEU
1.6	The unpredictability of the timing and implementation of dynamic tariffs for small consumers.	If dynamic tariffs implementation is delayed or canceled (after being announced), additional grid investments will be required to manage peak loads and maintain reliability.	If planning of grid infrastructure depends on future dynamic tariffs, delays can cause capacity problems.	Article 10d,2 EU ETS Additional climate package

1.7	The unpredictability of how consumers will respond to a dynamic tariff system, and how much they will reduce electricity usage during peak hours.	If the behavior of consumers does not adapt as expected, the intended benefits of dynamic pricing may not materialize.	Continued high peak loads due to inadequate peak load reduction causing stress on grid infrastructure and potentially requiring emergency upgrades.	Article 10d,2 EU ETS Additional climate package
1.8	The unpredictability of the implementation and timing of direct control of flexible loads.	If direct control of flexible loads implementation is delayed or canceled (after being announced), additional grid investments will be required to manage peak loads and maintain reliability.	If planning of grid infrastructure depends on future direct control of flexible loads, delays can cause capacity problems.	Koster, 2024
1.9	The extent to which consumers will allow DSOs to control their appliances	If consumer participation is lower than expected, intended benefits of direct control may not materialize.	Continued high peak loads require other means of managing peak loads oro additional infrastructure	Koster, 2024
2.	**Project completion time**	Delays in project completion can intensify the capacity problems that are experienced.	Intensified capacity problems can cause failures, safety issues and potentially damage the DSOs reputation.	LAN
2.1	Availability of qualified personnel	Limited availability of qualified personnel could cause project delays or result in reduced quality of delivered projects. Projects could become more expensive.	Project delays as a result of limited availability of personnel can delay future projects and impact the entire planning of DSOs.	LAN
2.2	Availability of needed materials	Scarcity of needed materials can delay projects.	Project delays as a result of limited availability of materials can delay future projects and the entire planning of DSOs.	LAN
2.3	Availability of needed space	Local municipalities not providing the necessary space for infrastructure upgrades in by the engineers desired locations.	Project delays. Infrastructure placed in suboptimal locations causing a reduced efficiency of the grid.	LAN

2.4	Waiting times for the production of infrastructure components by third-party suppliers.	Rising waiting times for components can lead to extra delays and require more careful planning.	Delaying future projects	LAN
3	**Costs**	Increasing costs can lead to less projects fitting within the budgets of DSOs.	Less projects fitting within the yearly budget can cause more intense capacity problems in other neighborhoods	Additional climate package 2023
3.1	Scarcity of materials	Scarcity of materials can drive up prices.	Less projects fitting in the budget.	Additional climate package 2023
3.2	Scarcity of qualified personnel.	Wages of personnel can increase due to there being a high demand for qualified personnel	Less projects fitting in the budget.	Additional climate package 2023
3.3	Increasing production costs of components.	Increasing production costs can drive up prices.	Less projects fitting in the budget.	EU ETS

Table 6. Overview of uncertainties identified from desk research

6.6 CONCLUSION OF CHAPTER

The desk research into uncertainties and risks emerging from outside factors was conducted with the aim of answering the sub-research question: *What uncertainties and risks can emerge from regulatory, policy, and market developments that impact the prioritization of neighborhoods?* From the desk research multiple uncertainties and risks were highlighted that impact the prioritization of neighborhoods. It was found that the uncertainties could be categorized under three main uncertainties: Expected future capacity requirements, Project completion time, And costs. The complete overview of the identified risks and uncertainties can be found in section 6.5. The identified uncertainties will be compared to the uncertainties included in Stedin's prioritization method in chapter 7 with the aim of identifying uncertainties that may be underestimated in Stedin's approach.

CHAPTER 7 DISCUSSION

7.1 INTRODUCTION

The purpose of this chapter is to synthesize the findings from the sub-questions and work toward answering the main research question: *"How can the Dutch distribution grid operator Stedin ensure the effectiveness of grid investment prioritization, considering emerging uncertainties from different regulatory, policy, and market developments?"*

Initial research and conversations with experts at Stedin indicated that answering this research question requires both an examination of prioritization methods and strategies, and an analysis of emerging uncertainties and risks from regulatory, policy and market developments. To guide this study the following three sub-research questions were formulated:

1. *What are the current methods for the prioritization of investments in large infrastructure projects?*
2. *How do Dutch grid operators prioritize grid expansion projects?*
3. *What uncertainties and risks can emerge from regulatory, policy, and market developments that impact the prioritization of neighborhoods?*

To answer these sub-research questions an exploratory research approach was employed. First, a literature review was conducted to understand prioritization methods and strategies used in large infrastructure projects, that are discussed in the academic literature. This was followed by desk research focusing on the prioritization methods of other Dutch grid operators providing insights into how these companies handle challenges similar to those face by Stedin as a result of the energy transition. Through in-depth semi-structured interviews, a detailed understanding of the prioritization method employed by Stedin to define a sequence of neighborhoods needing LV grid upgrades most critically was achieved. Additionally, the interviews gave an insight into uncertainties and risks that Stedin considers in the prioritization process. This was followed by additional desk research into potentially emerging uncertainties and risks from European and Dutch regulations and policies, and market developments. With this desk research an overview of these risks and uncertainties was obtained. To answer the main research question this chapter integrates the findings from the three sub-research questions.

To integrate the findings of the sub-research questions, this chapter will compare the main findings and answers to each sub-research question. First, a comparison is made between Stedin's prioritization method, and the prioritization strategies employed in large infrastructure projects. This comparison will allow for the identification of differences and similarities between these methods, potentially providing usable insights for Stedin. Additionally, by analyzing the strengths, weaknesses, and key takeaways of these methods, recommendations for the future of Stedin's prioritization method can be made. Secondly, the prioritization method of Stedin is compared to the prioritization methods employed by the other Dutch grid operators. This comparison will provide insights into the practices of Dutch grid operators and reveal points of interest for Stedin. Finally, the risks and uncertainties that are included in the prioritization method of Stedin are compared to the risks and uncertainties identified in chapter 6. This comparison aims to identify any under-represented risks and uncertainties in Stedin's prioritization method. Based on this comparison, recommendations will be provided on how Stedin might be able to mitigate these factors or include them in the future decision-making.

7.3 INTEGRATING FINDINGS FROM SUB-RESEARCH QUESTIONS

7.3.1 DESIGN OF RISK MATRIX

When comparing Stedin's prioritization method for investments in LV grids and the academic literature on prioritization methods for investments in large infrastructure, several interesting observations can be made. An overall observation is that the method of Stedin contains elements of many of the methods identified in the literature. Specifically, Stedin uses a risk-based method, including a risk matrix, to visualize risks and calculate risk scores. In a later step, Stedin performs a CBA to prioritize remaining neighborhoods based on the amount of risk reduced per euro spent. Notably, Stedin has also adopted a large-scale proactive strategy, systematically upgrading entire neighborhoods that critically need upgrades. A closer analysis reveals further insights, including potential areas where Stedin's model could benefit from incremental adjustments based on the academic literature.

Starting with the risk assessment part of Stedin's prioritization method. When analyzing the risk matrix developed by Stedin, it becomes evident that many of the rules for designing a useful risk-matrix have been followed. Firstly, both likelihood and impact are on a logarithmic scale, which helps maintain a constant relative uncertainty across different orders of magnitude. Secondly, the matrix is designed such that decision-makers are indifferent to risks falling in within the same category. Thirdly, the matrix bases the risk levels on expected values where possible and are also displayed logarithmically. However, the fourth rule for designing a useful matrix suggest that the number of categories for severity and impact should match the number of risk levels, which Stedin's matrix does not implement. Stedin's matrix (Appendix C.1.) includes five categories for severity, nine likelihood categories, and six risk levels. According to the findings from the literature review, this can cause the matrix to oversimplify risks or fail to differentiate risks properly. The added value of having nine categories of likelihood seems limited. Additionally, having six risk categories from which three require identical actions seems unnecessary. To ensure that Stedin's matrix does not oversimplify risks or fails to differentiate risks properly the following recommendation is made.

Recommendation 1: To avoid oversimplification or inadequately differentiating risks, consider reducing the risk matrix to having five categories each for severity, likelihood and risk levels.

When comparing Stedin's risk matrix to the matrix of the large grid operator Liander (Appendix C.2.) it is notable that Liander does follow all four design rules identified in the literature review. This suggests that effective risk assessment in the LV grids can be achieved with the recommended streamlined risk matrix.

7.3.2 QUANTIFICATION OF QUALITATIVE VALUES

Another key finding from the literature review is that multiple sources warn about the significant uncertainty and potential bias that is introduced by monetizing non-financial values, such as injuries or environmental impacts. There are several reasons why academics caution against this approach. First, assigning a monetary value on complex values like life or environmental impact is inherently subjective. Different stakeholders may have very conflicting perspectives on how to value these factors depending on their context. For example, the financial impact of minutes lost may differ significantly between a neighborhood or an industrial complex. Additionally, the literature highlights the substantial uncertainty that arises when reducing complex qualitative factors down to a single quantified value. This uncertainty can distort the accuracy of the prioritization method, potentially leading to inaccurate results.

Expert interviews revealed that Stedin does quantify complex values within the core company model and the risk matrix into financial terms. When discussing the flaws of this approach, it became clear that experts are aware of these flaws but choose to use this approach anyway. The need for a common factor to compare the different criteria appears to outweigh the downsides of this approach, leading to Stedin accepting the associated trade-offs. While alternative methods that were discussed in the literature review, like MCA and AHP, offer structured approaches to weigh qualitative criteria, their practical application to Stedin's approach appears limited. Due to the nature of AHP, which includes pairwise comparisons of criteria and alternatives, comparing over 3,000 neighborhoods is practically impossible, as it would result in an unmanageable volume of comparisons. For MCA, a similar observation can be made. MCA also often includes pairwise comparisons of alternatives by stakeholders, which is also unfeasible on such a large scale. Although these methods, in theory, can result in more accurate results, the lack of scalability and the impracticality of comparing thousands of alternatives limits their applicability for Stedin's prioritization method.

Comparing Stedin's quantification approach to other Dutch grid operators reveals insightful differences. Both Liander and Enexis follow a similar risk-based approach to Stedin in which a similar approach to quantify the impacts of risks is employed. This suggests that Liander and Enexis make a similar trade-off between the need for a common factor enabling comparisons and the increased uncertainty. However, the difference in values assigned to the same impacts are striking. For instance, Stedin assigns a value of €0,33 per consumer minute lost, while Enexis values it at €0,20, and Liander at €1,00. This means that Enexis and Liander evaluate the same user minute lost with a factor five differently. Similar differences in the evaluation of impacts exists across other categories of the risk matrices. The significant difference in how the three grid operators evaluate the same user minute lost seems to support the earlier notion that monetizing qualitative values causes significant uncertainty.

Based on the findings of this research, it can be concluded that there are limited options available to improve the quantification of qualitative risk impacts. Therefore, it seems that given the limitations, monetizing qualitative value remains the best practice in the industry for now. From these findings several recommendations can be made.

Recommendation 2: Maintain the current approach for monetizing qualitative risk impacts while actively incorporating awareness of the uncertainties this method introduces into the final decision-making.

This is recommended as, from this research, it turned out that there is a lack of a better method to obtain a common term that enables comparing the values. This research highlights the clear uncertainty that this method introduces, as initially observed from academic sources and later identified in practice through comparisons between grid operators. Therefore, while experts seem to be aware of the limitations accompanying this method, it is found essential that decision-makers and users of this method are actively aware of the uncertainties, and explicitly consider them during key decision moments. This awareness can be created by incorporating sensitivity analyses into the quantified impacts in the risk matrices to show how varying assumptions could alter the prioritization outcomes. Such a sensitivity analysis could include for example the differing values for user minutes lost (e.g., €0.20, €0.33, €1.00) to demonstrate the variability in outcomes caused by this uncertainty. By demonstrating these different possible outcomes the variability caused by uncertainties becomes more evident and visible for decision-makers, allowing them to make a more considered decision.

A second recommendation can be made based on the findings regarding the monetization of qualitative values. From the comparison with other regional grid operators, it became evident that, although the prioritization approaches are similar across Dutch grid operators, significantly different quantifications of qualitative values resulted. This big variation beg the question of how this is possible.

Recommendation 3: Convene with Liander and Enexis to explore the underlying reasons for the varying valuations of qualitative values. Consider collaborating with Liander and Enexis to achieve a more consistent quantification of qualitative values.

This is recommended as the substantial differences how qualitative impacts are valued suggest that improvements can be made. Identifying the causes behind the variations could help reduce uncertainty of the methods. Working together and exchanging methodologies is suggested as it can be mutually beneficial for all parties, enhancing the accuracy and reliability of each operator's prioritization model.

7.3.3 PROACTIVE STRATEGY

The literature highlights the absolute importance of maintaining a proactive large-scale strategy in managing LV distribution grids. In recent research on the LV grids in the Netherlands, it was estimated that a proactive approach can halve the number of necessary projects over the duration of project Buurtaanpak compared to a reactive approach. Systematically addressing grid needs before issues arise helps avoiding outages, failures and ad hoc repair projects. This proactive approach if implemented effectively can lead to significant efficiency gains for Stedin that contribute to the success of project Buurtaanpak.

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Recommendation 4: INTENTIONALLY LEFT BLANK DUE TO CONFIDENTIALLITY

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From the interviews it initially appears that municipal indecisions stem from an inability or unwillingness to act by municipalities. However, this view is too short-sighted. Similar to Stedin, municipalities operate within a pressure field shaped by diverse and often conflicting stakeholder priorities. Municipalities must manage conflicting priorities between several stakeholders which can make it challenging to promptly comply with conditions imposed by Stedin. For instance, municipalities must abide by policies imposed by the Dutch government regarding spatial planning. Spatial planning policies include guidelines for sustainable development and land use, and can include binding plans, and non-binding plans that municipalities must consider. The interpretation of these national spatial plans is often done by regional governments (provinces), which act as intermediaries between the national government and municipalities. The interpretation of these policies and guidelines often conflicts with grid operators' infrastructure plans, placing municipalities in a difficult position of choosing between compliance with spatial policies or meeting grid operator requirements.

Recommendation 5: Collaborate with municipalities, regional governments, and the regulator to align spatial planning plans with the requirements of Stedin.

This recommendation is an addition to recommendation 4. The fact that spatial planning and grid operators' plans often conflict calls for more collaboration between the affected stakeholders. Simply expecting municipalities to solve these problems independently, while they face competing dependencies and limited resources, is likely to cause delays. If grid operators were to collaborate more with municipalities and regional governments, to align spatial planning with grid infrastructure requirements, delays can be prevented or minimalized. This alignment helps Stedin maintain its desired proactive approach, ensures smoother project implementation and enhances overall efficiency of project Buurtaanpak.

7.3.4 DEPENDENCY ON SCENARIOS BY NETBEHEER NEDERLAND

Comparing the uncertainties identified in the desk research and those included in Stedin's prioritization method reveals several noteworthy insights. Initially it seems that a significant portion of the uncertainties that have been identified in the desk research are well represented in the Stedin's prioritization method. According to expert interviews, many of the uncertainties related to the future capacity of the grid are included in the scenarios by Netbeheer Nederland, which are used as input in SETIAM. These include assumptions on, the future adoption of EVs, the future amount of PV in the built environment, additional electrification in the built environment, and the number of heat pumps. The scenarios are updated whenever there are significant developments that impact the energy transition. This allows Stedin to keep the prioritization method aligned with new developments and ensures that the method is adaptive to changes in regulatory policy and market changes regarding these uncertainties.

However, when closely examining the scenarios developed by Netbeheer Nederland, several issues arise. While these scenarios attempt to account for uncertainties regarding future requirements of the grid, a closer look reveals significant limitations. The energy transition is an incredibly complex process influenced by numerous interconnected variables, yet these scenarios describe this complexity into a handful of assumptions across only four long-term storylines. This approach excludes a wide range of factors that could significantly influence the trajectory of the energy transition.

Thereby comes that the four long-term scenarios are based on deterministic storylines. For instance, in the International Trade scenario, it is assumed that the Netherlands becomes a global energy hub and that industry repositions outside the Netherlands. Such definitive correlations are found in all four scenarios, however these correlations fail to reflect the true uncertainty of these developments. The scenarios treat these correlations as fixed outcomes while these correlations are not inevitable.

The only conclusion that can be drawn from this is that the scenarios oversimplify the energy transition. Although they offer a general idea of what might happen, they definitely do not represent the full spectrum of possible trajectories of the energy transition. Netbeheer Nederland explicitly states in the scenario report that "The scenarios are an accurate description of several realistic future development paths. The scenarios are not a forecast of the future but describe several future developments." (Netbeheer Nederland, 2023). From this it seems that Netbeheer Nederland is well aware of the fact that the scenarios oversimplify the energy transition. Yet Dutch grid operators use these scenarios as the foundation for their most critical decisions, including the prioritization of investments in neighborhood grids. This causes significant risk as the entire prioritization strategy assumes these scenarios to be accurate. However, there is considerable uncertainty about whether any of the scenarios by Netbeheer Nederland materialize as expected.

When discussing these significant flaws in the scenarios during the interviews, it became clear that experts on the prioritization method are aware of the heavy reliance on the future scenarios. Interviewee 9 expressed concerns about the dependency on the scenarios, but concluded that with the current limited amount of data that is available for prioritizing neighborhoods, although imperfect, the scenarios remain the best method for determining a sequence of investments.

Recommendation 6: Where possible, reduce the dependency on the scenarios by Netbeheer Nederland.

This recommendation is made because the oversimplifications and limited number of scenarios make the scenarios a fragile foundation for long-term planning and prioritizing neighborhoods. This study is well aware of the fact that currently, the dependency on the scenarios is inevitable due to the limited data. Therefore, it is recommended that, to reduce this dependency, the implementation of smart meters in the grid is continued, and if possible accelerated. These smart meters provide real-time insight into electricity patterns of households and neighborhoods, which can be used to make better estimations of future demands.

7.3.5. MANAGING ADDITIONAL UNCERTAINTIES FROM REGULATORY, POLICY AND MARKET DEVELOPMENTS

Additional uncertainties that were identified from the desk research included uncertainties impacting the completion time of projects. These include the availability of qualified personnel, necessary materials, adequate space, and the waiting times of infrastructure components. From the expert interviews, it was evident that Stedin is aware of these uncertainties and has different methods of dealing with them. Currently, the most constraining factors limiting project implementation are the availability of personnel and materials. To address this, Stedin is actively scaling up the entire operation to become less constrained in implementation capacity in the future. Stedin deals with uncertainties regarding space by setting a strict requirement for municipalities. This requirement entails that Stedin does not start the implementation of projects before suitable space for the infrastructure is granted. Additionally, Stedin is exploring the option of purchasing land to deal with uncertainties regarding space. This approach not only ensures space for upgrades, but it also prevents municipalities requesting them to relocate infrastructure. The final uncertainty that was identified in the desk research regarding project completion time was the waiting time on infrastructure components. From the interviews it became evident that this uncertainty has rarely been a constraining because till now suppliers have been able to match the demand. Still, Stedin monitors the availability of components closely and maintains its relationships with suppliers.

Another set of uncertainties that was identified in the desk research included uncertainties regarding costs. However, the expert interviews revealed that currently, the availability of qualified personnel and materials is a lot more of a constraining factor compared to the costs. The interviews highlighted that with the current constraining factors in personnel and material, the method of Stedin is relatively resilient against fluctuations in prices. Therefore, it is unlikely that costs are a significant risk in the foreseeable future. Since such a large part of the identified uncertainties is effectively included in the prioritization method of Stedin the following is recommended.

Recommendation 7: Continue the current approach for including and managing emerging uncertainties regarding project completion time, and costs uncertainties, while focusing on monitoring and adapting to potential new emerging uncertainties.

This recommendation acknowledges the current strong approach to include these uncertainties in the operation of Stedin. However, rapid developments occur during the energy transition, and it is essential for Stedin to actively monitor uncertainties and risks to ensure impacting developments are identified and incorporated into the method timely.

The desk research revealed several uncertainties regarding the potential implementation of demand-side response (DSR) initiatives. The initiatives that are discussed in the desk research are dynamic tariffs and direct control of flexible loads. These initiatives could theoretically reduce peak load demands and alleviate risks of existing grids, and thus significantly reduce urgence of grid upgrades. Although the potential benefits for the LV grids are significant, there are still several issues that require more research before a decision is made on the implementation of these initiatives. From the interviews it appears that not much thought is given to these initiatives in the prioritization method, likely because they have not been adopted yet. However, considering their potential significance in the future, further evaluation of these initiatives could be beneficial.

Recommendation 8: Consider evaluating the future impact of DSR initiatives on the prioritization of neighborhoods. Additionally, it can be considered to advocate for these initiatives as their implementation can provide Stedin with significant benefits.

7.3 LIMITATIONS OF RESEARCH

During this research several limitations were encountered that should be acknowledged. First, a notable limitation that was identified was that this study was conducted in close collaboration with Stedin. While this provides advantages such as access to otherwise confidential information, several limitations were experienced. Stedin influenced the direction of the research significantly at various stages. On multiple occasions, it seemed that Stedin tried to direct the research away from findings that could be perceived as unfavorable. This influence by Stedin limited the ability to perform completely independent academic research.

Another limitation that originated from the close collaboration with Stedin is the fact that many of the findings may include biases from Stedin's perspective. Many of the interviews included experts from

Stedin, which may have introduced a perspective influenced by the organization's viewpoints and biases.

An additional potential limitation of this study is the fact that most recommendations were tailored specifically to Stedin. As a result the generalizability of these findings to other Dutch regional grid operators, or international grid operators may be limited.

Finally, this study aimed to address the effectiveness of grid prioritization methods in the context of the energy transition. However, measuring the true success of such methods presents a significant challenge. The results of current grid prioritization decisions will only materialize over the next 10 to 20 years, as upgrades of the LV grids in neighborhoods are completed. This long-term nature of outcomes underlines the importance of ensuring that current prioritization methods are designed as robust to external changes as possible. Nevertheless, the inability to evaluate the impact of recommendations done in this study limits the ability to validate results.

7.4 SUGGESTIONS FOR FUTURE RESEARCH

This thesis was written out of the perspective of Dutch regional grid operators. However, for future research it can be interesting to devote time to researching the dependencies, priorities, and pressures faced by the other key stakeholders in the LV distribution grid. For example, investigating the barriers and conflicting priorities municipalities face in collaborating with grid operators could provide valuable insights. Additionally, research could explore how municipal planning processes can be better aligned with the needs of grid. While these aspects lied outside of the scope of this thesis, gaining a deeper understanding of these dynamics could reveal new insights in the system and potentially generate actionable recommendations for Stedin to consider.

A complementary study to this thesis which is conducted entirely independent of any stakeholders in this system could provide new insights. Removing the influence of a single stakeholder could provide a more neutral view on the challenges within the system and generate unbiased recommendations for improving the system efficiency. However, it is important to recognize that this approach may result in less detailed data on prioritization methods due to confidentiality constraints. Nevertheless, studying the system from a more detached, helicopter view likely results in different insights. Comparing these findings with those of this thesis would provide valuable insights into the extent to which conducting this research within Stedin may have influenced the results and introduced biases.

This study identified several areas within the prioritization method where current approaches and practices are suboptimal yet utilized due to the absence of better alternatives. These key points where significant room for improvement exists, present valuable opportunities for future research. Key-points found that required improvements included, the quantification of qualitative measures, and the oversimplification by the scenarios defined by Netbeheer Nederland. Studying how the dependency on the scenarios can be reduced could have significant value for Dutch grid operators. This study recommended that the implementation of smart meters is continued or accelerated. Future research could explore how this real-time data can specifically be used to complement the scenarios in forecasting grid load flows. The quantification of qualitative risks remains a difficult challenge. Future research into improving this process could include exploring new methodologies that could potentially capture the values of the risks more accurately.

This study found that while regulatory changes by ACM provide grid operators more leniency in recouping proactive investments, the regulatory process of obtaining approval for proactive investments remains time-consuming. Conducting an institutional study aimed at improving this regulatory process could yield significant benefits for Dutch grid operators .

Additionally, the scope of this study was limited to analyzing and comparing methods employed by grid operators within the Netherlands. Future research could expand this comparision to include grid operators active in other countries that face similar energy transition challenges. Such a broader study could uncover additional insights and offer recommendations for enhancing current prioritization methods.

This study identified the future implementation of DSR initiatives as a significant uncertainty influencing future capacity requirements. However, the potential implementation of these initiatives is currently absent in the prioritization methods. Future research could examine the impact of these initiatives on LV distribution grids in neighborhoods and explore how they could complement the ongoing efforts to upgrade grid capacity. Such a study could include a case study in which load simulations similar to the ones performed currently by regional grid operators are performed. By comparing simulations that incorporate DSR initiatives to current simulations that assume no implantations, valuable insights can be generated. If the results demonstrate significant benefits, these findings could help advocate for the implementation of DSR initiatives.

CHAPTER 8 CONCLUSION

The exploratory stage of this thesis showed the absolute importance of answering the main research question. For decades, regulations that prioritized cost-efficiency over future capacity investments have effectively prohibited regional grid operators from making proactive upgrades. Coupled with the rapid electrification driven by the energy transition, this has now led to an overwhelming number of LV grids in neighborhoods requiring urgent capacity upgrades. Following an important regulatory change in 2019 by ACM, Dutch grid operators have been making significant efforts to proactively upgrade grids in neighborhoods with severe risks of capacity issues, while managing significant resource limitations. To address these resource limitations Dutch grid operators have adopted relatively novel prioritization methods to determine a sequence of neighborhoods that should receive upgrades. The success of the grid operators to upgrade neighborhood LV grids timely to enable the energy transition hinges on the effectiveness of these prioritization methods. The risk of ineffective prioritization is significant. If the wrong neighborhoods receive upgrades grid operators face an increased risk of failures and outages. These issues can lead to expensive ad hoc repair investments and slow the progress of the energy transition. At the same time, Dutch grid operators operate within a complex system undergoing a rapid energy transition, shaped by numerous uncertainties arising from regulatory, policy, and market developments. This begs the following main research question:

"How can the Dutch distribution grid operator Stedin ensure the effectiveness of LV grid investment prioritization, considering emerging uncertainties from different regulatory, policy, and market developments?"

To answer this question, this study aimed to identify the key aspects of ensuring the effectiveness of Stedin's prioritization method of LV grid investments in neighborhoods, within a rapidly evolving energy landscape. Identifying these key aspects was done by examining the best practices regarding prioritization strategies from academic literature, studying the approaches and strategies by other Dutch grid operators, and identifying emerging uncertainties from external developments. By analyzing these key factors, this study was able to provide insights and recommendations that can be considered by Stedin to maintain a proactive and effective prioritization approach.

The literature review showed that there are several prioritization methods that can be used to prioritize investments in large infrastructure projects. A recurring theme that was identified was that combining methods can improve the accuracy of results. One of the most significant findings was the importance of adopting a proactive large-scale strategy. When studying Stedin's prioritization method it became clear that several methods and strategies that were identified in the literature review are implemented in Stedin's method to prioritize neighborhoods for LV grid upgrades. It was found that Stedin employs a proactive large-scale strategy for upgrading the LV grids in neighborhoods. Additionally, it was found that Stedin's prioritization method is fundamentally a risk-based assessment in which the strengths of a risk matrix are used. This risk matrix enables Stedin to calculate risks scores for each neighborhood, which after combining them with a risk appetite results in a set of neighborhoods that exceed risk thresholds per year. Following this risk-based assessment a cost benefit analysis is applied to ensure the most cost reduction is achieved per euro spent. Furthermore, through mapping uncertainties emerging from regulatory, policy, and market developments, several categories of uncertainty were defined potentially impacting the effectiveness of the prioritization method. This study found that most of these uncertainties regarding costs and project completion time are adequately managed by Stedin through the inclusion in the prioritization method or by actively monitoring them. However, it was found that the prioritization method by Stedin is significantly dependent on scenarios developed by Netbeheer Nederland in which capacity requirement uncertainties are included. While these scenarios form the foundation of the prioritization method they introduce significant uncertainty dye to their oversimplified representation of the energy transition's complexity.

Answering the main research question

The main findings of this research indicate that maintaining a proactive large-scale approach, combining several models and methods for prioritization, and managing and adapting to emerging uncertainties are of critical importance. Applied to Stedin the following conclusions can be drawn.

This research shows that Stedin's current prioritization method incorporates essential elements to ensure effective prioritization of LV grid investments in neighborhoods. First, Stedin has adopted a proactive large-scale strategy aligning with best practices identified in the literature. Additionally, Stedin's method integrates multiple proven prioritization approaches creating a comprehensive method. Furthermore, this study showed that Stedin well aware of relevant identified uncertainties manages most of these well. However, the dependency on the scenarios defined by Netbeheer Nederland presents a challenge for the robustness of the method.

In summary, Stedin's method provides a solid foundation for effective prioritization of LV investments given the current available data, however, reducing the dependency on the scenarios should be considered. Additionally, this study provided several specific incremental recommendations that can help ensure the effectiveness of Stedin's prioritization method in a transitioning energy world. These recommendations include:

- Streamlining the risk matrix to avoid oversimplification or inadequately differentiating risks.
- Incorporating a sensitivity analysis into the quantification of qualitative factors.
- Encouraging collaboration with other regional grid operators to achieve a more consistent quantification of qualitative values.
- Maintain proactive strategy as much as possible.

- Collaborate with municipalities, regional governments, and the regulator to align spatial planning plans with requirements of Stedin.
- Advocate for DSR initiatives.

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Appendix A.1 Comparison table

Source	Infrastructure	Prioritization methods discussed	Key findings
Novak et al., 2012	roadway projects	Network trip robustness BCA MCA	All methodologies for prioritizing transportation infrastructure projects are only as good as the input data and the performance metrics that are used BCA is particularly challenging due to the difficulty related to obtaining accurate cost information. However federally funded transportation investments in the USA always include BCA. Project prioritization generally occurs after the financial feasibility, environmental costs, and land-use impacts have been considered. The reasons for prioritization are 1. providing an objective reason for choosing one project over another. 2. facilitating fair and effective resource allocation. 3. selecting the best project to maintain transportation system. 4. identifying the most critical projects The projects are ranked, with the projects that yield the greatest overall system improvement in travel time ranked highest. Results show that the ranking of transportation networks can be non-intuitive in terms of impact of individual projects.
Woldemariam 2020	Roadway projects	Goal programming	This paper presents a goal programming framework that prioritizes investments by considering network accessibility performance and the total cost of road infrastructure projects or project bundles. Transportation investment decisions focus on solving corridor-level transportation problems such as traffic congestion air pollution or travel time reduction. In the evaluation criteria that were used included travel time, vehicle operating cost, safety and economic efficiency. Transportation investment decision are often made, focusing on specific ocrridors without considering the relationship between road corridors and the overall impact on the transportation network. In this article a goal programming framework is proposed that allows decision makers to include performance measures and incorporates stakeholders preferences to performance measures. GP is a mathematical programming method that is very useful to solve problems considering multiple performance criteria. In this study project cost and network accessibility are used as performance criteria
Woldemariam 2021	Roadway projects	Incremental benefit-cost analysis	This paper presents an incremental benefit-cost analysis (IBCA) methodology which considers network accessibility benefits and project costs. The framework can be used to prioritize transport infrastructure investments. In the IBCA the costs are considered to be 2.5 M$ per mile. The value of travel time is calculated to be 24.67$ /h. With these values the benefit/cost ratio can be calculated. All projects with a BCR lower than 1.0 are not longer considered as the

			benefits do not outweigh the costs. Projects are prioritized for the highest BCR. This framework allows decision makers to identify which project or bundle of projects should be implemented to improve accessibility of the road network.
Guhnemann et al 2012.	Transportation projects	Combination of CBA and MCA	An important advantage of MCA over CBA is that in MCA, impacts that cannot be quantified on a monetary scale can be included. The aim of this study is to identify routes or sections of a route suitable for investment. The objectives for upgrading the road network are determined by national guidelines. And consist of improvement of enviornment, safety, economy, accessibility, and integration. The scoring system of an MCA is more transparent and straightforward if it is symmetrical. In this method the criteria are subdivided in monetised elements and non-monetised elements. The argument for including monetesized elements is that for criteria for which reliable estimates for monetary value can be made they are a good reflection of impact. The strength of MCA is that it uses a set of consistent preferences from decision markets to prioritize alternatives. However unlike CBA it does not give an indication as to whether a project offers value.
Quadros 2015	Transportation projects	MCA and AHP	Traditionally, decisions on transportation investment use the CBA to achieve the goal of profit maximization or cost minimization. Using three assessment criteria NPV BCR and IRR. Investment in transportation infrastructure requires the involvement of more complex variables and the use of multiple criteria. In this paper, AHP is chosen as the method to prioritize because of three features: Uses of decision on several levels, allows assessing the consistency of judgements, and it is considered in a large number of scientific publications. The four main aspects that are considered in the AHP of this article include: Economic/financial aspect Transportation/logistics Social and environmental. The AHP results in the following: The main factor to be considered in the prioritization of investments is the reduction of transportation costs. After that projects should be prioritized based on their best economic feasibilities. Less important criteria are the reduction of environmental interfaces and the reduction of GHG emissions.

Meiwu and Craig 2010	Roadway network		In this paper a CBA based approach is performed to prioritize new highway capacity projects. The benefits are divided into user benefits and non user benefits. User benefits = value of personal time savings + vehicles operation cost savings + travel time reliability savings + logistics benefits. Nonuser benefits = environmental benefits = total VHT savings x pollutants / VHT x Dollars/pollutants. Costs include: design, utility, right-of-way acquisition, and construction costs. Prioritization of projects is done by ordering projects based on their CBR with the highest CBRs most favorable.
Roigé et al 2020	Water network	Mives methodology	An increasing gap between available budget and investment needs increasingly challenges Spanish Utility companies. To deal with this, utility companies are developing methodologies to ensure systematic decision-making taking economic, social, and environmental grounds into account. In this paper prioritization of water network projects is done with the Mives methodology. This method was chosen as the authors argue that the method responds to three challenging end purposes.1. The unique index value that Mives framework defines, the prioritisation index for pipeline renewal (PIPR). 2. The way that the unique index is established through quantitative and qualitative values. 3. Meeting stakeholder expectations and encouraging them to participate in the decision making process. Mives considers ecological, financial, and social dimensions in the prioritisation processes. The weights for these dimensions are determined by performing an AHP. The economic criterion is calculated using the interal rate of return mix (IRRM). The social requirement is calculated with 3 indicators. 1. Continuity service improvement 2. Water organoleptic perception improvement. 3. Mobility disruptions The environmental requirement is calculated by the water loss (m3), water loss per lineal metre (m3/m), energy loss (kWh), and Energy loss per lineal metre (kWh/m).
Kim et al 2016	Water networks		In this paper the risks of multi-regional water pipelines were calculated and used to prioritize renewal projects. The risks in this paper are calculated with the formula Risk =PoF x CoF

Tlili and Nafi 2012	Water networks	Preference ranking organization method for enrichment evaluation (PROMETHEE)	This paper argues water pipe renewal projects need implementation of proactive failure prediction. The prioritization criteria classified in 4 groups. Hydraulic criteria, Economic criteria, Social criteria, Structural criteria. THe PROMETHEE is based on pairwise comparison of alternatives. the alternatives are evaluated according to different criteria that are either maximized or minimized.
Halfawy et al., 2008	Sewer network	Risk assessment model	Across the world, municipalities are aiming to improve sewer asset management. To do this an integrated approach for optimal renewal planning of sewer networks is needed. Assessing the risk of failure is essential for prioritizing sewers for renewal. Risk of failure is measured based on the consequences of failure multiplied by the probability of failure. This paper uses a risk assessment model in which the risk is defined as ranging between 1 and 5, with. The risk index is calculated by multiplying the risk factor * the likelihood of failure index. Projects are prioritized using a prioritization scheme. This scheme prioritizes asset replacement based on the maximum return on renewal investment in terms of improving the overall network condition and reducing the risk of failure. This approach uses sewer condition and risk indices as the main criteria for prioritization.
Chi and Bunker 2021	Transport infrastructure	CBA	This article provides a perspective on the use and efficiency of CBA in transport infrastructure investment. Overcoming limitations of CBA can be done by using it as a part of MCA. Environmental impacts are challenging to monetize. There is also not a common understanding of what environmental impacts and externalities should be included in CBA.
Erbrink et al 2023	LV grids	CBA, reactive, proactive	Reactive approach is currently used Prioritization methods options: **Proactive:** What is the optimal time to start an investment and will future problems also be solved in advance **Scale:** Only help the customer with a specific complaint or simultaneously tackle bottlenecks in the surrounding area. **Future proof:** Prevent rework for a longer period of time? CBA is used Outcomes: proactive investment strategies lower the costs. Most grid reinforcements are expected in the coming twenty years. Comparing the NPV of the 3 strategy alternatives does not give a very distinctive difference however, the actual cost of proactive investment is slightly lowered compared to reactive investment. Also efficiency of projects is higher due to better scheduling which

			allows for combining work and sharing project overhead costs. Combining projects leads to decreasing of engineering costs, installation costs and project management costs. If these advantages are added up it results in large-scale proactive investment strategies resulting in significantly lower costs than the reactive small scale investment strategies. Stepwise proactive strategy results in more overhead costs. However, it gives the opportunity to prioritze problems that arise within multiple neighbourhoods at the same time. Additional outcomes; Large scale proactive investment strategies turn out to be more efficient, saving time, manpower and materials. This is mainly attributed to the fact that reactive and small-scale investment strategies are forecasted to result in more than double the number of projects when compared to the proactive large scale strategy. This is a result of looking 40 years ahead in the proactive strategy preventing reworks at certain location. Proactive strategy uses a “no-regret” solution resulting in a slightly oversized grid design. This means that this strategy has a high risk of misinvestment. Mixed strategy Designing an optimal approach for the LV grids ask for weighing different interests. 1. Size of work requires increase of planning, engineering and construction capacity, 2. National energy transition targets need to be facilitated in time. 3. Voltage constraints in LV grids need to be identified, prioritized and mitigated by proactive strategy. Mix of strategies is needed to cover the period in which large scale reinforcement is not yet possible. Proactive strategy takes advantage of scale by combining comparable activities into one working package. Resulting in a smooth continuous process moving from one neighbourhood to the next, Proactive strategy suggests that typically the amount of MV/LV distribution stations will be doubled. Prioritization process: Most effective to invest when a neighborhood experiences large scale problems and not incidents. grids are prioritized by the following weighting factors; 1. Actual capacity: outage or high load has high priority 2. Actual voltage: strongly deviating voltages indicate weak spots or too long cable lengths in the LV grids 3. Future load: calculated grid performance with forecasted load. 4. Secondary indicators: age or condition Uncertainties mentioned: 1. Number of heat-pumps 2. PV installations 3. EVs 4. Scarce resources and materials 5. Availability of skilled workforce 6. Large customers settling in the area Risks mentioned 1. Increased peak loads on LV cables and MV/LV-transformers

			2. Misinvesting Conclusion: Main difference between the approaches is the timing of individual reinforcements. Looking 40 years ahead results in less workforce needed and reduced social impact. Fully proactive strategy is on paper the most efficient but large-scale realization in thousands of LV grids within the next few years is not possible.
van Soest et al. (2014)	LV grid		Gradual replacement of aging assets will no longer be sufficient to ensure distribution grids reliability. New developments impact electricity demand from households in turn impacting investment in the LV grid. Uncertainties mentioned 1. Growth of the number of EVS. Which can double the current peak load of a household. 1. Charging power of charging stations has a big impact. Model used shows that when 10kW charging power is implemented instead of 3kW double the investments are needed for DSO. 2. Increasing number of heat pumps. 3. The use of µ-CHP unit 4. The increasing number of solar panels(according to the model only slightly impacting the required investments.) Upcoming technologies that can deal with increasing demand and decrease the number of required investments: 1. Demand side management 2. Smart charging of EV 3. Smart storage of electricity
Dos Santos		AHP	AHP method is used to evaluate alternatives in a MCDA Key indicators that are used are 1. System average interruption duration index (SAIDI) 2. System average interruption frequency index (SAIFI) 3. Number of sustained interruptions 4. Number of customers 5. Distribution system usage rate (EUSD) AHP consists of structuring the decision problem into different hierarchical levels, as 1. Main objective 2. criteria 3. alternatives Followed by a pairwise comparison at each level.
Wu et al 2019		MCDA AHP	If investment decisions are made based on a single project, it will result in suboptimal, time consuming, and labor-intensive projects. Therefore it is useful to carry out multiple projects simultaneously, requiring to decide on the investment order of many projects. Maximizing improvement of the overall level of the power grid under the conditions of economical and sustainable development. Evaluation method 1. Preliminary screening of the project, based on the results of grid power demand and transformation needs. Basically investigating the economic rationality, technical feasibility and construction necessity of power grid investment construction. 2. The power demand degree of the project. 3. Optimize portfolio decision making research.

			Optimization method: MCDA with AHP Focussed on technology, economy, environmental benefits, and social impact.
Coumans et al. (2015)	LV grids		This paper quantifies the developments of PV systems and heat pumps in the residential sector. Also distributed energy storage within LV grids is discussed. Using historical electricity demand data as a method to predict future demand is inapplicable due to the introduction of new technologies. Implementing storage systems can help DSO to reduce the peak loading by performing peak shaving and valley filling and thus be an alternative for classic network investments. Uncertainties mentioned: 1. Penetration degree of PV systems 2. Penetration degree of Heat pumps 3. PV systems
Celli and Chowdhury 2018	Distribution grid	MCDA CBA	Traditionally planning options for energy infrastructure was done based on economic based tools like CBA Traditional fit and forget approach is no longer effective. Modern grid planning should be based on multi-objective approaches. Current distribution grid planning usually includes conflicting objectives such as, maximizing capacity, reduce energy losses, improve service quality, reduce CAPEX and reducing OPEX. To find the best fit for a planning solution a MCDA is used in literature. A fuzzy analytic hierarchy process is used to rank a set of four smart grid planning alternatives The optimal solution needs to achieve an acceptable level of performance on several conflicting criteria. An advantage of using MCDA over CBA is that MCDA involves stakeholder point of views directly. Moreover it allows considering the impact directly and uncertainties related to monetary conversion are avoided. use of the tools can be joined together to combine their strengths. Optimization methodology of this paper is an MADM approach which aims to find the best alternatives among a large set of options. The methodology is based on AHP. The methodology consists of 3 steps 1. Automatized scoring stage 2. Overall score evaluation for each possible weight scheme 3. The final score evaluation for each alternative In the first step of the AHP the decision maker has to express his preference by a pairwise comparison of alternatives.

			9 objectives that are used for multi-objective optimization. 1. Network investment 2. Energy losses 3. Reactive power exchange with the TSO 4. Black start support 5. Cost of the energy storage system 6. duration of interruptions 7. Frequency of interruptions 8. Voltage regulation 9. Voltage dips Conclusion: The proposed methodology allows for optimal planning of distribution networks. This methodology helps finding the design option that fits best with expectations of the stakeholders.
Wijnia and Herder, 2005	Energy infrastructure	CBA	All asset managers try to postpone investment, reduce operating cost and improve the performance of the network. Which are conflicting targets. Two approaches can be followed regarding the investment opportunities. 1. Optimize the individual opportunity. 2. Optimize the portfolio of investment opportunities. All asset managers have introduced some sort of a multi criteria analysis in their decision making. Investment decisions in electricity infrastructures are different from regular financial investment decisions. Financial investments should in the future deliver cash flows which are preferably higher than the costs meaning a positive NPV. Investment in energy infrastructure cannot be based on such a simple rule. There are 3 causes for this 1. It is difficult to allocate future cash inflows to specific network elements. Most needed investments do not necessarily induce new income. 2. As a result of the monopolistic characteristics, DSOs are obliged to provide a connection for everyone requesting one even though the new connection might have a negative NPV. 3. Investments are often done with non-financial benefits in mind like reliability, safety, or sustainability. Investment in electricity infrastructure is essentially risk management.
Troncia et al 2018		MCA and CBA	This paper presents a joined Multi Criteria - Cost benefit analysis to be able to consider monetary and non-monetary impacts in investment decisions. By combining these tools the weaknesses of both are mitigated. The framework can be used to identify the best solution from a set of planning alternatives. The CBA

Grond et al 2013	LV grids	MCA	Problem with decision support optimization tools is that they are rarely tools that are rarely used in practice. This is due to the fact that network operators still mainly hold on to the regular network planning process. This is the result of large networks being problematic to optimize. From academic literature there have been multiple suggestions to optimize grid investments however solving the increasingly complex distribution system a long term time period
Esmaeeli et al (2016)	LV grids	Risk based method	A risk based method for placement of transformers in LV networks is proposed in which three different DSO strategies are discussed. The strategies that are discussed are: risk seeker, risk-neutral, risk averse. Uncertainties mentioned: Load growth Failure rate Failure duration Energy price variation

Appendix B.1 Interview protocol

Introductory questions
1. Could you briefly explain your role within the company, and how long you have been involved in this field? Do you have any prior experiences in related fields?
2. Could you describe how your role relates to investment decisions for low-voltage grid reinforcements, if at all?

Part on the external part of the component, uncertainties and risks that need to be considered in the prioritization of neighborhoods needing grid upgrades
Identifying additional uncertainties and risks
3. What kind of uncertainties can you think of that need to be considered when investment decisions are made for neighborhood reinforcement projects?
    1. provide examples if needed
4. Can you identify risks that might arise from these uncertainties?
5. What kind measures are taken to mitigate these risks?
6. Are there specific external factors that introduce these uncertainties and risks? Think of market reforms, policies, and regulations.
7. How is the investment decision making process affected by these uncertainties and risks?

Example questions on the internal component of the research proble,
8. Can you tell me something about how Stedin prioritizes neighborhoods?
9. Can you tell me what kind of models and approaches Stedin uses to assist this process?
10. How are the company values used in the prioritization of investments?
11. What kind of challenges are related to the current way of prioritizing LV grid upgrades?
12. what are strong point of the current prioritization method?

13 Is there anything else you want to add regarding uncertainties and risks in the LV grid investments?
14 When you consider everything we have discussed in this interview, is there anyone who would be interesting for me to interview as well?

Appendix B.2 Summary of Interview 1

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Appendix B.3 Summary of interview 2

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Appendix B.4 Summary of interview 3

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Appendix B.5. Summary of interview 4

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Appendix B.6. Summary of interview 5

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Appendix B.7. Summary of interview 6

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Appendix B.8. Summary of interview 7

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Appendix B.9. Summary of interview 8

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Appendix B.10. Summary of interview 9

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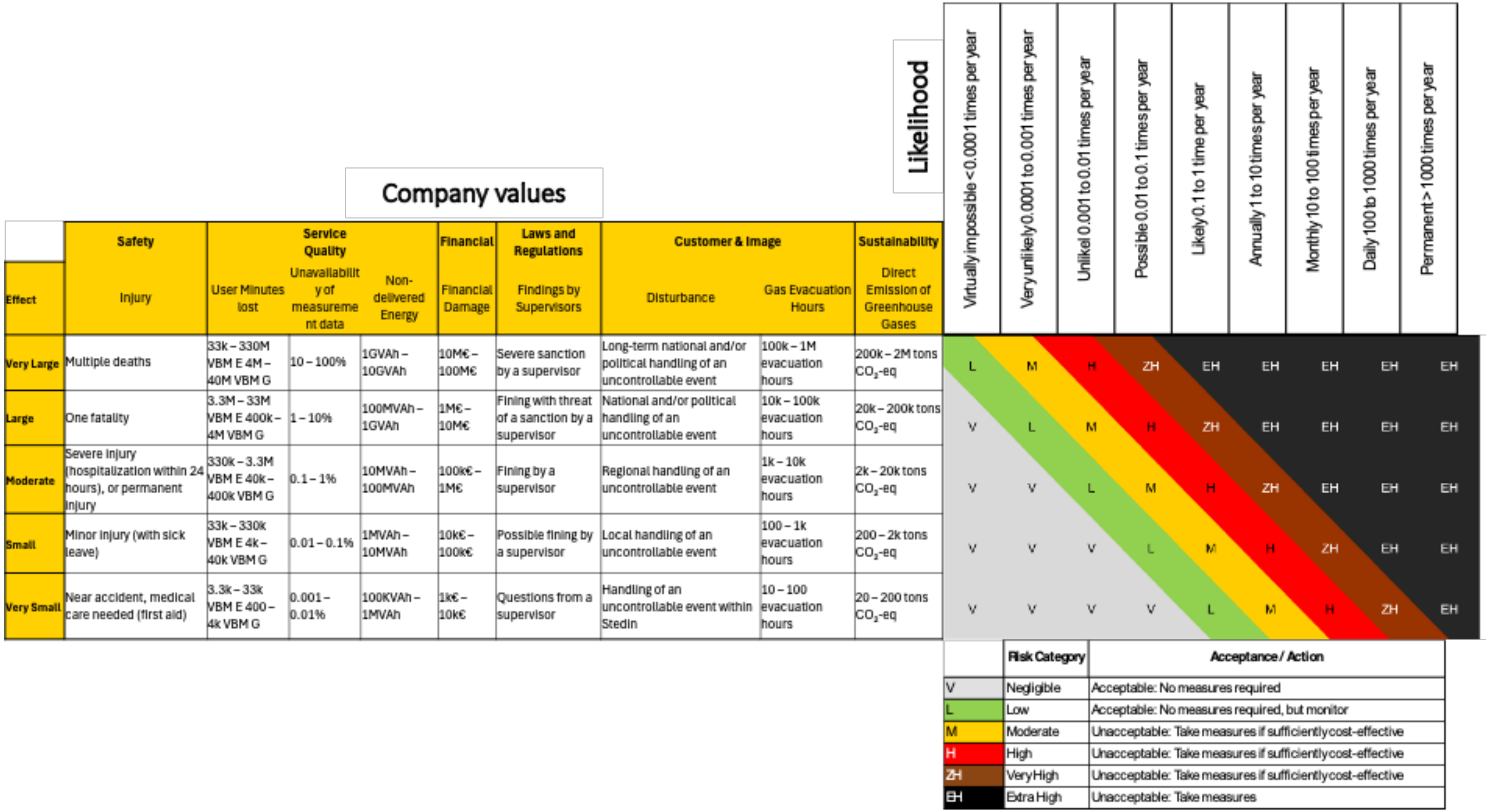
Appendix C.1 Risk matrix Stedin (adapted from Stedin, 2024)



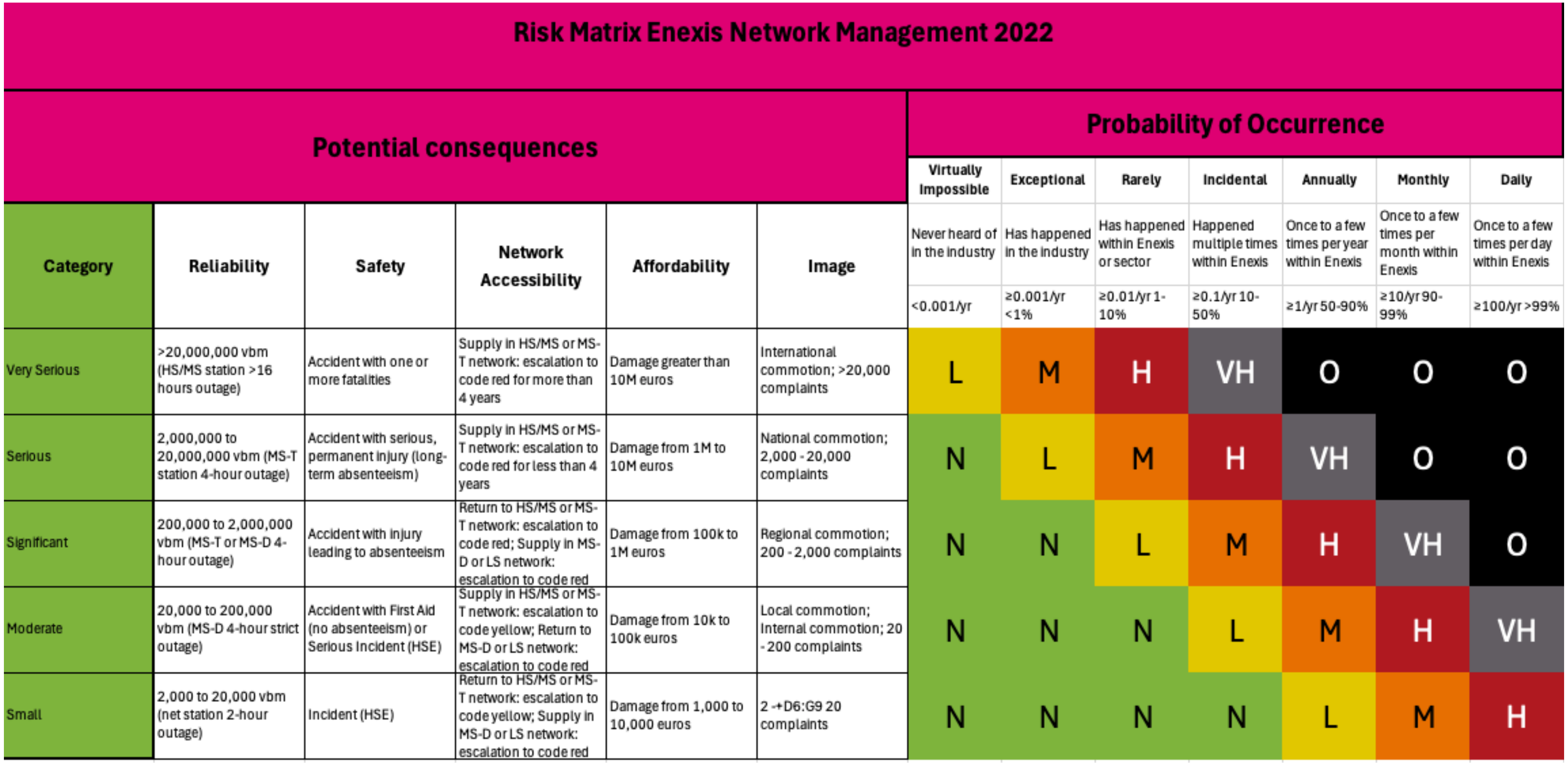
Company values

Likelihood

	Safety	Service Quality			Financial	Laws and Regulations	Customer & Image		Sustainability									
Effect	Injury	User Minutes lost	Unavailability of measurement data	Non-delivered Energy	Financial Damage	Findings by Supervisors	Disturbance	Gas Evacuation Hours	Direct Emission of Greenhouse Gases	Virtually impossible < 0.0001 times per year	Very unlikely 0.0001 to 0.001 times per year	Unlikel 0.001 to 0.01 times per year	Possible 0.01 to 0.1 times per year	Likely 0.1 to 1 time per year	Annually 1 to 10 times per year	Monthly 10 to 100 times per year	Daily 100 to 1000 times per year	Permanent > 1000 times per year
Very Large	Multiple deaths	33k – 330M VBM E 4M – 40M VBM G	10 – 100%	1GVAh – 10GVAh	10M€ – 100M€	Severe sanction by a supervisor	Long-term national and/or political handling of an uncontrollable event	100k – 1M evacuation hours	200k – 2M tons CO_2-eq	L	M	H	ZH	EH	EH	EH	EH	EH
Large	One fatality	3.3M – 33M VBM E 400k – 4M VBM G	1 – 10%	100MVAh – 1GVAh	1M€ – 10M€	Fining with threat of a sanction by a supervisor	National and/or political handling of an uncontrollable event	10k – 100k evacuation hours	20k – 200k tons CO_2-eq	V	L	M	H	ZH	EH	EH	EH	EH
Moderate	Severe injury (hospitalization within 24 hours), or permanent injury	330k – 3.3M VBM E 40k – 400k VBM G	0.1 – 1%	10MVAh – 100MVAh	100k€ – 1M€	Fining by a supervisor	Regional handling of an uncontrollable event	1k – 10k evacuation hours	2k – 20k tons CO_2-eq	V	V	L	M	H	ZH	EH	EH	EH
Small	Minor injury (with sick leave)	33k – 330k VBM E 4k – 40k VBM G	0.01 – 0.1%	1MVAh – 10MVAh	10k€ – 100k€	Possible fining by a supervisor	Local handling of an uncontrollable event	100 – 1k evacuation hours	200 – 2k tons CO_2-eq	V	V	V	L	M	H	ZH	EH	EH
Very Small	Near accident, medical care needed (first aid)	3.3k – 33k VBM E 400 – 4k VBM G	0.001 – 0.01%	100KVAh – 1MVAh	1k€ – 10k€	Questions from a supervisor	Handling of an uncontrollable event within Stedin	10 – 100 evacuation hours	20 – 200 tons CO_2-eq	V	V	V	V	L	M	H	ZH	EH

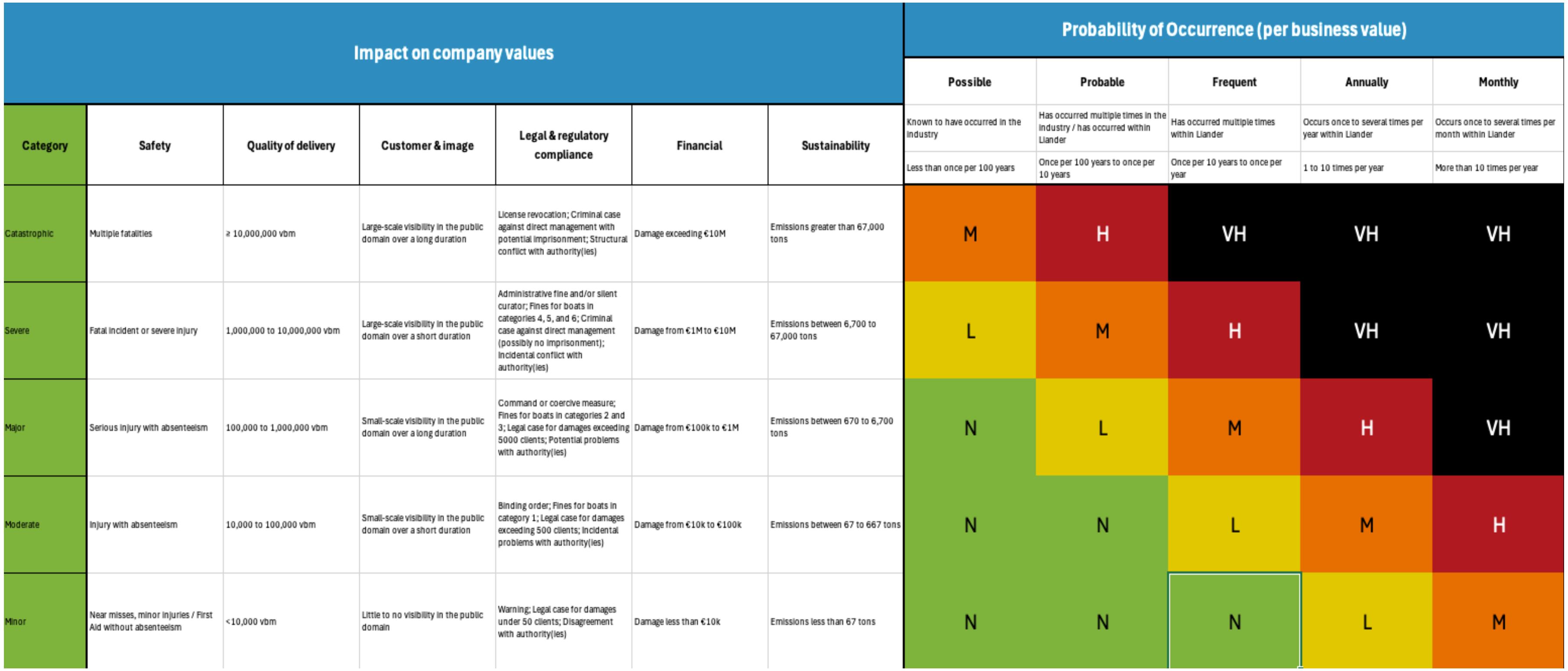
	Risk Category	Acceptance / Action
V	Negligible	Acceptable: No measures required
L	Low	Acceptable: No measures required, but monitor
M	Moderate	Unacceptable: Take measures if sufficiently cost-effective
H	High	Unacceptable: Take measures if sufficiently cost-effective
ZH	Very High	Unacceptable: Take measures if sufficiently cost-effective
EH	Extra High	Unacceptable: Take measures

Appendix C.2 Risk matrix Enexis (adapted from Enexis, 2024)



Risk Matrix Enexis Network Management 2022												
Potential consequences						Probability of Occurrence						
						Virtually Impossible	Exceptional	Rarely	Incidental	Annually	Monthly	Daily
						Never heard of in the industry	Has happened in the industry	Has happened within Enexis or sector	Happened multiple times within Enexis	Once to a few times per year within Enexis	Once to a few times per month within Enexis	Once to a few times per day within Enexis
Category	Reliability	Safety	Network Accessibility	Affordability	Image	<0.001/yr	≥0.001/yr <1%	≥0.01/yr 1-10%	≥0.1/yr 10-50%	≥1/yr 50-90%	≥10/yr 90-99%	≥100/yr >99%
Very Serious	>20,000,000 vbm (HS/MS station >16 hours outage)	Accident with one or more fatalities	Supply in HS/MS or MS-T network: escalation to code red for more than 4 years	Damage greater than 10M euros	International commotion; >20,000 complaints	L	M	H	VH	O	O	O
Serious	2,000,000 to 20,000,000 vbm (MS-T station 4-hour outage)	Accident with serious, permanent injury (long-term absenteeism)	Supply in HS/MS or MS-T network: escalation to code red for less than 4 years	Damage from 1M to 10M euros	National commotion; 2,000 - 20,000 complaints	N	L	M	H	VH	O	O
Significant	200,000 to 2,000,000 vbm (MS-T or MS-D 4-hour outage)	Accident with injury leading to absenteeism	Return to HS/MS or MS-T network: escalation to code red; Supply in MS-D or LS network: escalation to code red	Damage from 100k to 1M euros	Regional commotion; 200 - 2,000 complaints	N	N	L	M	H	VH	O
Moderate	20,000 to 200,000 vbm (MS-D 4-hour strict outage)	Accident with First Aid (no absenteeism) or Serious Incident (HSE)	Supply in HS/MS or MS-T network: escalation to code yellow; Return to MS-D or LS network: escalation to code red	Damage from 10k to 100k euros	Local commotion; Internal commotion; 20 - 200 complaints	N	N	N	L	M	H	VH
Small	2,000 to 20,000 vbm (net station 2-hour outage)	Incident (HSE)	Return to HS/MS or MS-T network: escalation to code yellow; Supply in MS-D or LS network: escalation to code red	Damage from 1,000 to 10,000 euros	2 -+D6:G9 20 complaints	N	N	N	N	L	M	H

Appendix C.3 Risk matrix Liander (Adapted from Liander, 2024)



Impact on company values							Probability of Occurrence (per business value)				
							Possible	Probable	Frequent	Annually	Monthly
							Known to have occurred in the industry	Has occurred multiple times in the industry / has occurred within Liander	Has occurred multiple times within Liander	Occurs once to several times per year within Liander	Occurs once to several times per month within Liander
Category	**Safety**	**Quality of delivery**	**Customer & image**	**Legal & regulatory compliance**	**Financial**	**Sustainability**	Less than once per 100 years	Once per 100 years to once per 10 years	Once per 10 years to once per year	1 to 10 times per year	More than 10 times per year
Catastrophic	Multiple fatalities	≥ 10,000,000 vbm	Large-scale visibility in the public domain over a long duration	License revocation; Criminal case against direct management with potential imprisonment; Structural conflict with authority(ies)	Damage exceeding €10M	Emissions greater than 67,000 tons	M	H	VH	VH	VH
Severe	Fatal incident or severe injury	1,000,000 to 10,000,000 vbm	Large-scale visibility in the public domain over a short duration	Administrative fine and/or silent curator; Fines for boats in categories 4, 5, and 6; Criminal case against direct management (possibly no imprisonment); Incidental conflict with authority(ies)	Damage from €1M to €10M	Emissions between 6,700 to 67,000 tons	L	M	H	VH	VH
Major	Serious injury with absenteeism	100,000 to 1,000,000 vbm	Small-scale visibility in the public domain over a long duration	Command or coercive measure; Fines for boats in categories 2 and 3; Legal case for damages exceeding 5000 clients; Potential problems with authority(ies)	Damage from €100k to €1M	Emissions between 670 to 6,700 tons	N	L	M	H	VH
Moderate	Injury with absenteeism	10,000 to 100,000 vbm	Small-scale visibility in the public domain over a short duration	Binding order; Fines for boats in category 1; Legal case for damages exceeding 500 clients; Incidental problems with authority(ies)	Damage from €10k to €100k	Emissions between 67 to 667 tons	N	N	L	M	H
Minor	Near misses, minor injuries / First Aid without absenteeism	<10,000 vbm	Little to no visibility in the public domain	Warning; Legal case for damages under 50 clients; Disagreement with authority(ies)	Damage less than €10k	Emissions less than 67 tons	N	N	N	L	M

Appendix D.1. EU ETS regulations

#	Regulation	Impact on LV distribution grid	Uncertainty	Source
1	Member states shall ensure that from january 2005, no installation or activity that falls under ETS1 shall emit GHG unless its operator holds a valid permit.	Companies producing the components and materials for LV grid upgrades might have increased production costs as a result of needing to buy allowance credits to account for their emissions.	Price of components and materials needed for reinforcements of the LV grids might fluctuate.	Article 4 EU ETS
2	Linear fall factor of total emissions shall be 4,3% from 2024 to 2027 an 4,4% from 2028	The increasing fall of total emissions by activities included in the ETS1 is likely to lead to an increased urge to become more sustainable. This incentive to become more sustainable will lead to additional transport capacity needed on as well the transmission grids as the distribution grids. Increasing the scarcity of material and personnel needed for investment in project buurtaanpak.	Availability of qualified personnel and material. Prioritisation neighborhoods vs renewability of large emitters.	Article 9 EU ETS
3	Member states shall use revenues generated from auctioning of allowances for one or more of the following: 1. Reduce GHG emissions. 2. Develop renewable energies and grids for electricity transmission. 3. Measures intended to improve energy efficiency, district heating systems, efficient and renewable heating and cooling, renovation of buildings.	Additional budget that is available for developing renewable energy might lead to increased pressure on grids. Again leading to additional investment needed in transmission grid capacity. Improving energy efficiency of buildings, district heating, renewable heating and cooling significantly impacts the electricity needs of neighborhoods. Improving energy efficiency and district heating systems could increase the transportation capacity that is needed in a neighborhood and thus making them more urgently in need for capacity investments.	Availability of qualified personnel and material. Which neighborhood gets a budget for improving the efficiency of buildings? Which neighborhood gets district heating? Which neighborhood gets renewable heating and cooling?	Article 10.3 EU ETS

		Renewable heating and cooling might increase the pressure on the LV grid as more electricity is required.	How many heat pumps will there be in certain neighborhoods?	
4	Modernization fund supporting small scale investment projects to modernize energy systems shall be established for the period from 2021 to 2030. 80% of revenue from allowances referred to in article 10(1) shall be used to support. a. Generation and use of electricity from renewable sources. b. Heating and cooling from renewable sources. c. Energy storage and the modernization of energy networks, including demand-side management, district heating pipelines, grids for electricity transmission.	Modernization of energy networks might include improvements in grid technologies and ways of using the grids. For example, accommodating bi-directional energy flows from DERs or demand side management both potentially enhancing reliability of the grid. Energy storage solutions can play an important role in balancing demand and supply within the entire system. Having energy storage facilities in neighborhoods could decrease peak demand and peak supply, resulting in less capacity needed.	How fast will technologies evolve? To what extent do residents engage in demand side management? Will there be variable prices? Will smart grid technologies be available on a large scale? Will there be energy storage solutions in neighborhoods or is it something that will only be used in higher layers of the grid system?	Article 10d,2 EU ETS

Appendix D.2. Effort Sharing Regulation (ESR) and ETS2

Number	Regulation	Impact on LV distribution grid	Uncertainty	Source
1	Reducing 40% EU-wide reduction in GHG emission from ESR sectors by 2030 compared to 2005. Starting from 2025	Increased incentive to drive an EV due to the potential increase of prices at fuel stations.	How many extra EVs and charging points are expected in certain neighborhoods?	ESR

		Increased incentive to make buildings more sustainable, leading to on the one hand to a reduced electricity needs by potentially having DERs on buildings. On the other hand, an increase of heat pumps and electrification of buildings increases energy needs	Which buildings will have PV installed? Which buildings will increase their electrification and how quick?	
2	Union-wide quantity of allowances shall decrease in a linear manner each year after 2024.	A yearly decrease of available allowances incentivizes an accelerated implementation of sustainable measures. Potentially resulting in more pressure on transmission and distribution grids.	Which neighborhoods are implementing sustainable measures immediately.	article 30c.1
3	Revenues shall be used for among others: 1. Decarbonization of buildings. 2. measures to provide financial support for low-income households in worst-performing buildings 3. Measures to accelerate the uptake of zero-emission vehicles.	Decarbonization of buildings could lead to extra pressure on the LV grid due to an increased electricity demand. Improving the worst-performing buildings can decrease energy demand due to increased efficiency. An increase in EV requires an increase in charging facilities which can significantly increase electricity demands for neighborhoods However if smart loading facilities are adopted, the batteries of the EVs can serve to dampen peak demands in the LV grids	Which buildings will be decarbonized first. Which technologies will buildings get? What worst-performing buildings are prioritized for efficiency upgrades. How many EVs will there be for a specific neighborhood? Will there be smart charging facilities?	article 30d(6a,6b)

Appendix C3. EED

#	Regulation	Impact on LV distribution grid	Uncertainty	Source

1	Member states have to collectively realise a reduction of 11,7% of the union's energy consumption in 2030 compared to the 2020 reference scenario.	This regulation causes an increase in electrification in order to improve overall energy efficiency.	How much more capacity do specific neighborhoods require?	DIRECTIVE (EU) 2023/1791 article 4.1
2	EED obliges public sector to a yearly 1,9% reduction of energy use consumption	This regulation causes an increase in electrification in order to improve overall energy efficiency.	How much more capacity do specific neighborhoods require?	DIRECTIVE (EU) 2023/1791 article 5.1
3	Every year at least 3% of total floor area of government owned buildings have to be renovated to energy neutral buildings.	Renovating a building towards an energy neutral building requires PV on the roof and efficiency upgrades.	The fluctuation of generation from PV can lead to grid instability. The electrification of the building could on cloudy days lead to an increased electricity demand from the grid.	DIRECTIVE (EU) 2023/1791 article 6.1

Appendix C4. RED

Number	Regulation	Impact on LV distribution grid	Uncertainty	Source
1	Renewable energy up to 45% by 2030	An increase in renewable energy contributes to an increased electrification.	Increased electrification causes uncertainty by not knowing the rates of electrification of specific neighborhoods.	RED
2	Increase total capacity PV by 320 GW by 2025 and 600 GW by 2030	Increased capacity of PV leads to more transport capacity needed in both transmission and distribution grids.	Where will the PV capacity be located? Will the installation have a storage facility? Is the PV capacity going to be event spread over the country or will it consists of a relatively low number of big PV installations.	RED
3	Double to current deployment of	An increase in deployment of individual heat pumps leads to an	Which neighborhoods will have relatively many heat pumps?	RED

	individual heat pumps.	increased electricity demand.	Will the target amount of heat pumps be installed?	

Appendix D5. Policy aims from additional climate package 2023 and National Plan Energy System (NPES).

#	Policy	Impact on LV distribution grid	Uncertainty	Source
	Electricity sector climate neutral in 2035	Generation of electricity will likely be very intermittent.	Will there be sufficient energy storage facilities? What happens when the yields from solar and wind energy disappoint due to unfavourable weather circumstances? Are the grids robust enough to deal with highly fluctuating electricity generation.	Additional climate package 2023 NPES
	2 additional nuclear reactors operational for electricity production by 2035.	Steady base load available which helps decrease fluctuation in load.	Will the reactors be completed without delays? Will the reactors provide baseload for the entire country or will the benefits be mostly experienced regionally?	Additional climate package 2023 NPES
	Stimulate production of green hydrogen at sea.	Lowering the fluctuations in electricity supply due to the availability to convert electrical energy to thermal energy and store it. Less frequent supply peaks.	How much electrolyser capacity will be deployed?	Additional climate package 2023

		Ability to convert hydrogen to electricity in times of unfavorable weather circumstances to avoid voltage drops.		
	Stimulate Demand Side Response for end users.	Demand Side Response helps balancing the demand on the distribution grids by encouraging customers to shift demand to times when total demand is lower or when more supply is available	Will demand side response be incentivized for end users? Will there be variable pricing? To what extent will consumers participate in demand side response? To what extent will DSR lead to peak load reduction.	Additional climate package 2023
	Additional energy storage and additional policy on balancing the electricity demand	Additional storage facilities reduce the impact of generation intermittency on the grids. It can be expected that additional policy on balancing the electricity demand leads to more balance on the grid and less fluctuations.	How much additional storage capacity is the government aiming for? When will this storage capacity be operational? What policy will be implemented and when will this be implemented?	Additional climate package 2023
	Expansion of national electricity and hydrogen network and improvement of interconnectivity	Expansion of the national electricity grid could mean that less personnel, material and budget is available for reinforcement of low voltage grids in neighborhoods. Expansion of the electricity grid and interconnectivity can result in enhanced grid stability.	To what extent does the focus on expanding the entire grid hamper low voltage grid reinforcements?	Additional climate package 2023
	Additional focus on implementing PV on buildings.	Implementing PV on roofs of buildings can decrease the	What buildings will be fitted with PV?	Additional climate

	Government has made a 222,5 M€ budget available for this measure.	capacity needed from the low voltage grids.	Will the buildings supply electricity to the grid in case of more generation than use?	package 2023
	Realization of 3 GW of solar energy on sea in 2030. 44,5 M€ budget has been made available for this.	Increase of intermittent nature of the generation capacity.	To what extent will the intermittency from solar on sea be experienced in LV grids in neighborhoods?	Additional climate package 2023
	Additional PV on rental houses. A 100M€ budget has been made available for this.	Demand fluctuations of neighborhoods increase. Grid reinforcements are needed to deal with reverse power flow in times of excess solar generation.	In which neighborhoods will PV on rental houses be adopted? To what extent is the load profile altered by the introduction of more PV in neighborhoods?	Additional climate package 2023
	Energy saving obligations for large consumers will be expanded.	Energy savings lead to less capacity needed for these large consumers.	How much energy will be saved by these large consumers? Will this be done by electrification or by other means for example improving insulation of buildings?	Additional climate package 2023
	More possibilities to obtain loans for improving the sustainability of housing with an E F or G label.	Less energy needed in neighborhoods where improvements are made.	Will sustainability improvements lead to more or less capacity needed from the low voltage distribution grid?	Additional climate package 2023
	Scaling up of the use of local heat sources.	Local heat sources can either increase the electricity needs of neighborhoods or decrease the electricity needs depending on which technology is implemented.	Which technologies will be used in which neighborhoods?	Additional climate package 2023
	Accelerate growth of emission free private cars by increasing CO2 reduction targets for work related personal mobility.	Increase in EV will cause an increased demand for charging facilities. Which requires reinforced LV grids in neighborhoods.	How many EVs and charging points are expected per neighborhood?	Additional climate package 2023

	Subsidizing purchase of second hand EVs	Increase of affordability allows lower income households to switch to EV, resulting in total EV increase.	How many EVs and charging points are expected per neighborhood?	Additional climate package 2023
	Government invests 403,8M€ in charging facilities for EVs	More charging facilities require reinforced LV grids	Which neighborhoods will get the charging facilities and how many?	Additional climate package 2023
	Phase-out of tax benefits for fossil fuels	Phasing out of tax benefits for fossil fuels incentivizes electrification further. Potentially increasing the adoption of EVs, electrical heating and PV.	With what percentage will the adoption of the mentioned technologies increase if it does? How will this increase be distributed over different neighborhoods?	Additional climate package 2023
	Energy tax will be adapted so that increasing sustainability will be more beneficial	Increased incentive to become more sustainable can lead to increased speed of electrification.	How much will the speed of the electrification increase?	Additional climate package 2023
	Phasing out of non-residential buildings with bad energy-labels	Improving energy labels requires improving energy efficiency of the buildings which likely includes electrifying the building.	How much extra transport capacity is needed for these non-residential buildings?	Additional climate package 2023
	Encouraging more sustainable travel behavior.	Promoting sustainable travel can lead to an increase of EV adoption requiring more charging facilities.	Which neighborhoods will get the charging facilities and how many?	Additional climate package 2023

Appendix D.6. Policy from Landelijk actieprogramma netcongestie (LAN)

#	Policy	Impact on LV distribution grid	Uncertainty	Source
	Increase flexible capacity	Increase of flexible capacity decreases the amount of voltage fluctuation as a result of intermittency on the distribution grids which can mean that neighborhoods are less urgently in need of reinforcements.	When will the flexible capacity be realised?	LAN
	Accelerate preparation process of grid	Accelerating the preparation process can lead to accelerated reinforcement projects in neighborhoods.	Is there enough personnel and material available to	LAN

	extension projects		perform the projects?	

Appendix D.7. Regulations Meerjarenprogramma

#	Regulation	Impact on LV distribution grid	Uncertainty	Source
	National subsidy scheme for district heating networks worth 1000M€	District heating supplies an alternative to electric heating which can reduce the overall electricity demand in the grid, making neighborhoods with district heating potentially less urgent in need of grid reinforcements.	It is not sure which neighborhoods will get a district heating system. If a neighborhood gets a connection to a district heating net it is uncertain when it will be operational.	Meerjarenprogramma
	Nationally 1 million installed hybrid heat pumps and 500.000 new connections to the district heating net in 2030.	A neighborhood which is connected to a district heating net is likely less urgent in need of grid reinforcements while neighborhoods with a relatively high number of hybrid heat pumps is likely more urgently in need of grid reinforcements.	It is not sure which neighborhoods will get a district heating system. It is uncertain which neighborhoods will adopt hybrid heat pumps more swiftly.	Meerjarenprogramma
	Insulating 2.5 million residential houses by 2030	Insulating houses leads to a more consistent energy demand. If the houses are fitted with electrical heating, electricity demand will go down.		Meerjarenprogramma
	Install all electric heat pumps for a budget of 190M€			

Appendix D.8. IBO policy

#	Policy	Impact on LV distribution grid	Uncertainty	Source
	Make use of natural gas more expensive and make us of electricity cheaper	Incentive to use more electricity is likely to lead to more electricity demands in neighborhoods.	How much more capacity do specific neighborhoods require?	IBO
	Increase of tax for fossil fuel powered cars and trucks.	Incentive to switch to EV	Which neighborhood require what amount of charging facilities and capacity.	IBO

#	Regulation	Impact on LV distribution grid	Uncertainty	Source
	Commercial building owners need to improve the 25% of their worst performing buildings before 2030	This regulation causes an increase in electrification in order to improve overall energy efficiency.	How much more capacity do specific neighborhoods require?	Voorjaarsbesluitvorming klimaat 2023
	Rental homes with an EFG label may no longer be rented out from 2029	Improving the energy label of a rental home can lead to electrification of the home which leads to more electricity demand	How much more capacity is required when owners improve their labels	Voorjaarsbesluitvorming klimaat 2023
	In 2050 Dutch traffic and transport no longer emit CO2	Everyone who wants to travel needs to do so with either EV or non emitting cars on other fuels	How much more charging for EVs is needed per neighborhood?	Voorjaarsbesluitvorming klimaat 2023