Quantifying costs and benefits of flexibility for DSOs

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Quantifying costs and benefits of flexibility for DSOs

by

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Preface

Before you lies my thesis on "Quantifying costs and benefits of flexibility for DSOs", my research on quantifying the application of flexibility in a techno-economic context. This thesis is the result of my work at Stedin from March to October and represents the last step in obtaining my Master's degree in Sustainable Energy Technologies at the TU Delft.

I want to thank Daniël Booms as my daily supervisor for this project, not only for the discussions on the subjects of this project but also for sharing his thoughts and expertise on various areas related and unrelated to this topic. Furthermore, I thank Milos Cvetkovic as my supervisor from the TU Delft, for his valuable comments and guidance in this project.

Due to the versatility of the subject, I had the pleasure of meeting, and involving, a lot of colleagues and departments in this project. I'd like to thank the many colleagues who have contributed by actively and enthusiastically sharing their expertise, providing feedback, and involving me in their topical and relevant challenges and projects. Besides the support from my colleagues and fellow students, I want to thank my family and friends. For their support and encouragement, but also for getting me out of my attic room for the moments of much-needed distraction.

This project gave me the opportunity to delve further into the challenges of the energy transition. I have met many enthusiastic colleagues and fellow students with the same motivation who are committed to making this transition possible. Many great theories and ideas have crossed the tables, the lecture halls, and Teams meetings. I'm looking forward to taking this theory into practice and putting these ideas to the test.

Mark Boere
Cabauw, October 2021

Abstract

The energy transition is expected to increase the peak loading of the grid, requiring Distribution System Operators (DSOs) like Stedin to invest an increasing amount of capital and labour in the reinforcement of their network. Flexible resources can be used to decrease the peak loading of the grid through better matching consumption and generation. DSOs can defer or avoid reinforcement by using flexible power to realize sufficient capacity at the lowest possible cost. This thesis provides the means for quantifying the ability of flexible power to act as an alternative to investment in grid reinforcement.

The problems expected to arise as a function of the energy transition are identified by literature research. It was found that of the identified problems, 'Power quality: Voltage dips and swells'- and 'Capacity: Thermal capacity'-problems are most likely to be solvable through the application of flexible resources. To assess the intensity of the problems in Stedin's service area and research possible means of categorization, a projection of the energy transition scenarios of Netbeheer Nederland on Stedin's grid is used. This projection is implemented in Stedin's grid analytic tools through a newly developed script and used to model one Medium Voltage (MV) distribution grid and twenty underlying Low Voltage (LV) grids. These simulations show problems arising mainly from cumulative integration of typical energy transition technologies, like Photovoltaic power generation (PV), Heat pumps (HPs) and Electric Vehicles (EVs). The proposed indicator for categorization, the Address Density (AD), was found to show only little correlation with the experienced problems. The most noticeable correlation was found to originate from the MV grid. Furthermore, for both the MV as the LV grid, the voltage and capacity problems are highly related to active power flows, where the influence of reactive power flows is comparatively low.

Through a proposed revision of the 'Reinforce unless'-framework, the means are provided to determine the feasibility of solving encountered problems and bottlenecks through flexible resources. This revised framework starts with assessing the required impact necessary to solve both capacity and voltage bottlenecks by applying the Jacobian matrix of the power flow analysis. This is combined with the potential impact of the available flexible resources to determine their technical ability to solve the bottleneck. The application of flexible resources as an alternative to investment reduces the certainty of supply through the possibility of insufficient flexible capacity to mitigate the bottleneck. The resulting risk can be quantified through the 'not delivered'-energy.

Several potential barriers and discussions arise through describing the potential flexible resources in the distribution grid. The main discussion is based on the lack of insight and controllability in the distribution grid, reducing the overall applicability, and the trade-off between applying flexibility or facilitating flexibility. This discussion is actually broader than solely the discussion of flexibility for capacity or flexibility for power (balancing). This trade-off requires DSOs to determine where to facilitate and where to use flexibility.

The financial feasibility of applying flexibility as an alternative to investment is discussed on both the procurement as the comparative feasibility towards reinforcement. Based on the review of services currently contracted by the Transmission System Operator (TSO) and literature research, a most likely approach to contract sufficient flexible resources at reasonable costs is described. The resulting method counteracts gaming, guarantees sufficient flexible power for mitigating bottlenecks at reasonable prices, and allows for market operation to provide the lowest possible costs.

This thesis reviews the operational problems that DSOs can expect and the role flexible resources can play to solve them. The framework of 'Reinforce unless' is adapted to fit this wider range of bottlenecks and to include specific methods to assess and substantiate the sufficiency of flexible power to solve the bottleneck.

Contents

Glossary

Address Density The local address density in addresses/km^2 which acts as a measure of urbanity. The Dutch translation is omgevingsadressendichtheid, abbreviated to OAD.

Carbon Capture and Storage A process that captures CO_2 from air and stores it, inhibiting it from entering the atmosphere.

Climate Agreement 2019 The Dutch plan for adhering to the Paris Agreement.

Climate Agreement-scenario One of Stedin's future energy scenario's for assessing the impact of the energy transition.

Combined Heat and Power-plant A generating unit providing both heat and electric power resulting in a high overall efficiency.

Customer Average Interuption Duration Index A measure of reliability used by grid operators .

Energy Transition Technologies A collective term for technologies strongly associated with the energy transition.

European Article Numbering, A numbering system used for identification of grid connections.

Green Gasses A term for gaseous energy carriers mostly produced through digestion of organic biomass or organic byproducts.

Grid Operators Platform for Congestion Solutions A platform set up by grid operators where system users can offer their flexibility.

Integral Infrastructure-outlook 2030-2050 An outlook on the development of the energy system for 2030-2050 set up in cooperation between Dutch energy system operators.

International Ambitions-scenario One of Stedin's future energy scenario's for assessing the impact of the energy transition.

Investment plan 2022 Investment plan for 2022-2030 set up in cooperation between Dutch energy system operators.

Management View-scenario One of Stedin's future energy scenario's for assessing the impact of the energy transition.

Maximum Power Point Tracking A control algorithm of a power electronic devices aimed at maximizing power output.

Multi Energy System A system where energy in different forms is provided through the optimal interaction of multiple energy systems.

National Drive-scenario One of Stedin's future energy scenario's for assessing the impact of the energy transition.

Netbeheerder kosten-batenanalyse The Dutch translation of grid operator cost-benefit analysis, a way of comparing the costs and benefits of an investment introduced by Overlegtafel Energievoorziening.

Overlegtafel Energievoorziening A collective consisting of stakeholders in the electrical energy-chain.

Power-to-Gas A process where electrical power is converted to/stored in a gaseous energy carrier.

Power-to-Heat A process where electrical power is converted to heat for the storage of energy or addressing heat demand.

Regional Energy Strategies A plan entailing information about the future energy system for a certain RES-region.

Requirements for Generators European legislation on the requirements for grid-connected generators.

Stedin Energy Transition Impact Assessment Model Stedin's in-house-developed tool to asses the impact of the energy transition on its grid.

System Average Interuption Frequency Index A measure of reliability used by grid operators which equals the average frequency of interruptions per connection per year.

Total Harmonic Distortion A measure of the harmonic distortion of a signal expressed as a percentage of the magnitude of the main frequency.

Transport Indication A document provided by the grid operator specifying that at the moment of the request, sufficient grid capacity is or isn't available. This is a necessary step for a subsidy-application.

Verification and Validation The process of checking if a model does as it is specified/documented and sufficiently captures reality.

Acronyms

ACM Autoriteit Consument en Markt.

AD Address Density, *Glossary:* Address Density.

AM.2021 Management View-scenario, *Glossary:* Management View-scenario.

BRP Balance Responsible Party.

CA2019 Climate Agreement 2019, *Glossary:* Climate Agreement 2019.

CAIDI Customer Average Interruption Duration Index, *Glossary:* Customer Average Interuption Duration Index.

CAPEX Capital Expenditure.

CCS Carbon Capture and Storage, *Glossary:* Carbon Capture and Storage.

CE-CHP Combustion Engine Combined Heat and Power.

CEP Clean Energy Package.

CHP Combined Heat and Power, *Glossary:* Combined Heat and Power-plant.

DG Distributed Generation.

DH District Heating.

DRG Distributed Renewable Generation.

DSO Distribution System Operator.

EAN European Article Numbering, *Glossary:* European Article Numbering,.

EC Electric Cooking.

ETM Energy Transition Model.

ETTs Energy Transition Technologies, *Glossary:* Energy Transition Technologies.

EV Electric Vehicle.

GAW Gestandaardiseerde Activa Waarde (standardized asset value).

GOPACS Grid Operators Platform for Congestion Solutions, *Glossary:* Grid Operators Platform for Congestion Solutions.

HP Heat pump.

HV High Voltage.

HVAC Heating, ventilation, and air conditioning.

IA International Ambitions-scenario, *Glossary:* International Ambitions-scenario.

ICT Information and Communications Technology.

II3050 Integral Infrastructure-outlook 2030-2050, *Glossary:* Integral Infrastructure-outlook 2030-2050.

IP2022 Investment plan 2022, *Glossary:* Investment plan 2022.

IV Intermediate Voltage.

KA Climate Agreement-scenario, *Glossary:* Climate Agreement-scenario.

LV Low Voltage.

LWRA Least Worst Regret-assessment.

MES Multi Energy System, *Glossary:* Multi Energy System.

MPPT Maximum Power Point Tracking, *Glossary:* Maximum Power Point Tracking.

MV Medium Voltage.

ND National Drive-scenario, *Glossary:* National Drive-scenario.

NKBA Netbeheerder Kosten-batenanalyse, *Glossary:* Netbeheerder kosten-batenanalyse.

NPV Net Present Value.

OPEX Operational Expenditure.

OTE Overlegtafel Energievoorziening, *Glossary:* Overlegtafel Energievoorziening.

P2G Power-to-Gas, *Glossary:* .

P2H Power-to-Heat, *Glossary:* .

PEID Power Electronics Interfaced Devices.

PV Photovoltaic power generation.

RDO Region of Diverse Operation.

RES Regional Energy Strategies, *Glossary:* Regional Energy Strategies.

RfG Requirements for Generators, *Glossary:* Requirements for Generators.

RSO Region of Secure Operation.

SAIFI System Average Interruption Frequency Index, *Glossary:* System Average Interuption Frequency Index.

SETIAM Stedin Energy Transition Impact Assessment Model, *Glossary:* Stedin Energy Transition Impact Assessment Model.

SoC State of Charge.

THD Total Harmonic Distortion, *Glossary:* Total Harmonic Distortion.

TSO Transmission System Operator.

V2G Vehicle-to-Grid.

V&V Verification and Validation, *Glossary:* Verification and Validation.

WACC Weighted Average Cost of Capital.

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1 Introduction

This chapter provides the motivation, scope, and objective of this thesis. It starts with describing the topic's relevance in the context of the current energy system and the challenges ahead. Following, the existing literature on the subject of this thesis is described. Using this information, the objective and methodology of this thesis are defined and placed in the context of the current literature. Finally, this chapter finishes with the outline of the report.

1.1. Motivation

In this thesis, flexibility is regarded as "The ability to shift or adjust levels of generation or consumption based on a variety of incentives" [1]. By utilizing flexibility, Distribution System Operators (DSOs) can balance local consumption and generation to keep the overall system-state of the grid inside the allowable limits. This way, the use of flexibility can act as a (temporary) alternative to reinforcement.

The reinforcement of grid infrastructure requires large investments. Stedin, as one of the three largest DSOs in the Netherlands, expects to need 750 million to 1 billion in extra capital in the coming years [2]. These costs are eventually going to come back to the consumers.

Stedin is aware of the existing research on flexibility and its potential for delaying or avoiding operational problems like congestion. The principles of operation of these methods seem promising. However, apart from a few exceptions, Stedin has not found a way to quantify the effects of these methods for realistic cases, inhibiting large-scale implementation. Stedin wants to identify the most promising methods and quantify the applications of these methods in their potential for reducing investment and network expansion.

The world is transitioning towards a sustainable future. A transition that, among others, includes a lot of changes to the electrical power system. Targets set for the future include an overall decrease in greenhouse-gas emissions resulting from electrifying previously fossil fueled-processes and providing this electric power through renewable generation (*see:* fig. 1.1).

The accelerated energy transition causes power flows in electrical networks to change. In the Climate Agreement 2019 (CA2019), the Dutch plan for adhering to the Paris Agreement ('het Klimaatakkoord'), an installed capacity of 3.7 GW of wind power on land and 14.3 GW of Photovoltaic power generation (PV) is estimated at the current pace [4]. To meet the actual target, this needs to be even higher. The distributed generation and increased consumption are connected at various grid levels, leading the power flows to change in direction and the distribution of voltages to shift [5]. The increased intermittency of often weather-dependent Distributed Renewable Generation (DRG) and the integration of large consumers with a high level of simultaneity as Electric Vehicle (EV)-chargers and Heat pumps (HPs) also lead to higher power peaks, deeming the current capacity of the grid insufficient.

System operators are tasked with facilitating the users and the market by guaranteeing the three market freedoms: freedom of capacity, freedom of transaction, and freedom of dispatch. These market freedoms are commonly called the copper plate principle, which translates to an approach in which

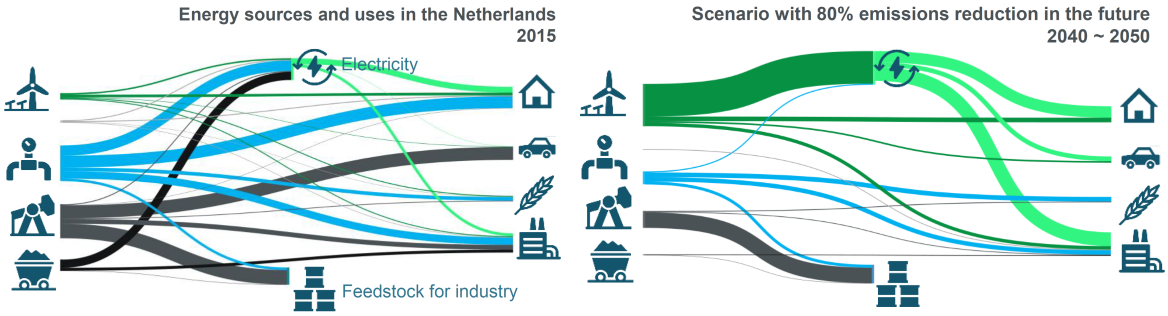


Figure 1.1: A simplified Sankey-diagram of the energy flows in 2015 and 2040-2060 [3]. This figure shows the challenge for the distribution grid to accommodate the growth in both distributed generation as electrical consumption. Generation is shifting from conventional sources like gas, oil, and coal, to renewable generation. Consumption from heating, mobility, and industry is increasingly electrified. An electricity system built for, and struggling with, the green flows on the left needs to accommodate the green flows at the right.

virtually any desired transfer of electricity between market parties can be performed [6]. As such, it relies on the assumption that physical constraints do not restrict the flow of electricity. This requires DSOs to invest in their grid when a shortage of capacity is forthcoming, endangering these freedoms.

As this DRG is often realised faster than the infrastructure can cope with, DRG's introduction and large-scale integration lead to a more dynamic and unpredictable need for capacity. This leads to new challenges for the system operator to determine sufficient capacity levels and provide this capacity in a reasonable time. When the need for capacity is higher than can be provided by the network, this is called congestion. At the moment of writing, and probably for several years to come, congestion is a serious problem in the Netherlands.

Although investments in the grid infrastructure will realise sufficient capacity, the question arises if this is always the most socially beneficial solution. This is because the investments are primarily needed to accommodate the peaks, while a lot of capacity still remains underutilised. Also, the amount of bottlenecks, the required space, and the work associated with it is large, while the resources to carry it out and the locations to build the reinforcements are both in short supply.

The costs that the DSOs incur are socialised through the network tariffs, which are determined by Autoriteit Consument en Markt (ACM), the organization responsible for the regulation of DSOs and Transmission System Operators (TSOs), at the start of a new regulation period. It is one of the tasks of the ACM to ensure that these tariffs remain reasonable. ACM calculates these tariffs based on the incurred costs, the market share, the performance, and the efficiency of the DSO over the previous regulation period. Higher efficiency is characterised by realizing sufficient capacity for lower total costs, where the overall availability of the grid measures performance.

By using alternative methods such as available flexibility from connected system users, DSOs may be able to balance local consumption and generation to keep the overall system state of the grid inside the allowable limits. This way, the use of flexibility may act as a more efficient alternative to reinforcement.

If sufficient capacity can be realised through the application of flexibility without an overall degradation of market freedoms or the grid's performance, it can act as a temporary, but possibly also as an indefinite alternative.

1.2. Literature review

A lot of research has been performed on the use of flexibility in the grid. A distinction can be made between different forms of flex: flexibility for energy (e.g., for addressing seasonal variability), flexibility for power (system level), flexibility for capacity (local level, congestion), and flexibility for voltage (also local level) [7, 8].

Most of the available research has focused on flexibility for power, applying flexibility for balancing on a national scale, and for a good reason. As mentioned, in the conventional grid operation methodology, the consumers and their demand were leading, where large-scale conventional generators balance out any occurring mismatches. Thus, the total required flexibility in this system could be provided by the conventional generation (see fig. 1.2). These mismatches were either solved by the portfolio of the Balance Responsible Party (BRP) themselves or through the balancing market of the TSO.

As levels of integration rise, the new and relatively cheap energy from DRG effectively out-competition that of conventional generation. However, the intermittent DRG leads to high variability in generation, decreasing the overall flexibility that the supply side can provide. Without this flexibility to balance generation and consumption, BRPs and TSOs will face increasing difficulty in respectfully maintaining their agreed position of exchange and maintaining a balanced and stable grid. As a collective term for different forms, the lack of flexibility is therefore often indicated as a barrier for the integration of DRG [1, 9–11].

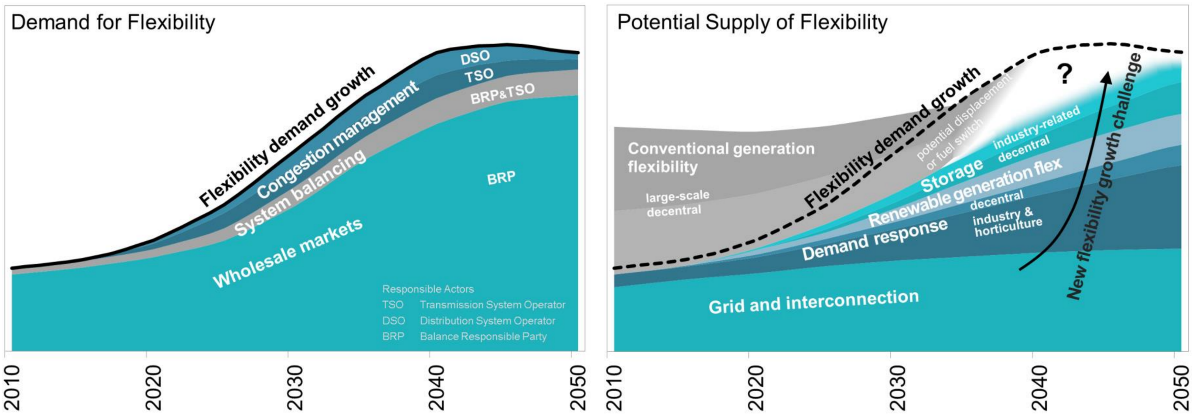


Figure 1.2: Demand and potential supply for flexibility from 2010 to 2050 [3]. The displacement of conventional generation through intermittent distributed generation leaves a flexibility gap.

On a distribution grid-scale, flexibility is effectively used with the same goal; to (locally) balance consumption and generation to retain stable operation of the grid. This way, operational problems in the grid that would typically be solved by expansion can be mitigated or avoided. Such problems could be the overloading of assets as cables or transformers but could also include corrections in the voltage distribution of the network. The voltage distribution is influenced by both the active as the reactive power flows in the network. Therefore, locally balancing consumption and generation applies to active power flows and reactive power flows [9].

A lot of the research on flexibility for power can effectively be transferred to an application of flexibility for capacity and voltage. This includes research on unlocking potential sources of flexibility, barriers to applying flexibility, and relevant processes, including its actors and stakeholders.

1.2.1. Barriers towards feasibility

To assess the feasibility of applying flexibility as an alternative to reinforcement, it is important to identify the barriers towards applying flexibility. The provided definition of flexibility can highlight several of the barriers towards the use of flexibility.

"The ability to shift or adjust levels of generation or consumption based on a variety of incentives"

The use of flexibility requires participation from system users with the ability to provide flexibility. This requires system users, of various sizes and services, to deviate from their normal behaviour. For example, for residential system users, it could require a decrease in their overall comfort or a decrease in revenue due to curtailed residential PV. For large system users, it could mean shifting a business process or shifting to another means of energy input. This is the first barrier towards integration of flexibility; **system user participation**.

Lund et al. [12] and Junker et al. [13] suggest that sufficient flexibility is already widely available; it just needs to be unlocked. Other than the common flexible resources as Combined Heat and Power

(CHP) and generators, these sources model the effect of novel potential flexible resources. Based on their results, they argue that the system users of these flexible resources just need to be shown the proper incentives for them to realise the benefits [14, 15]. These novel resources can range from simple households with deferrable equipment (equipment whose usage can be deferred or advanced without a large impact on the users [16, 17]) as dishwashers or laundry machines to large industrial processes operating below constant utilization. Other sources warn for assessing potential flexible resources as such without sufficient research into the after-effects [1, 18, 19]. As an example, a lot of attention is pointed towards heating and cooling as a source of flexibility. The wider range of temperatures, however, leads to increased temperature differences and overall higher consumption. Such an effect, often related to a higher difference in potential, is known as a rebound or payback effect [18, 19].

Overall, a large role is imposed on the flexibility of demand, often called demand response. As generation is becoming more and more dispersed, variable, and ‘uncontrollable’, loads and consumers are becoming more intelligently connected and controllable [18]. As a result, the roles are changing, and several sources suggest it is now upon demand to take on the role of balancing the grid [13, 20].

Shariatzadeh et al. [21] distinguish two types of activation, dispatchable and non-dispatchable. Dispatchable demand response means performing actions on command. This primarily includes system users allowing system operators to activate flexible resources. Participation is compensated according to an agreement made beforehand.

Non-dispatchable demand response is based on variable tariffs that reflect the scarcity or surplus of electricity. This can reflect both an energy scarcity (high market prices) and a local scarcity of capacity. D-Cision and Ecorys [22] write that a pure form of the latter has not been applied to their knowledge. This is, however, the part that is relevant for DSOs to reflect their costs.

Nevertheless, overall flexible demand is highly dispersed, increasing the complexity of the required control. This introduces the second barrier, **sufficient communication infrastructure**.

Insufficient Information and Communications Technology (ICT) infrastructure is indicated as one of the main barriers to the integration of flexibility. For many bottlenecks in the grid, insufficient information is available to identify the ”when, where, and how much” of the needed flexibility. ICT infrastructure therefore not only translates to the controllability but also the monitoring of power flows and asset conditions (commonly summarised as smart-metering) [11, 12, 18]. This also applies to the providers of flexibility. Therefore, not only will consumers need to be informed about the proper incentive so they can respond and confirm their participation (allocation), their participation also needs to be monitored for the proper reconciliation.

A third barrier is connected to the provision of incentives. At the moment, the **market for non-conventional flexibility** is slowly rising out of its infancy. Several projects have been set up to unlock flexibility. These mainly originate from cases of congestion, where the DSOs aim to mitigate the effects of congestion through the use of flexible resources. Examples are the platform of Grid Operators Platform for Congestion Solutions (GOPACS), a platform set up by grid operators where system users can offer their flexibility [23], and Stedin and Liander’s application of flexibility on Zuidplaspolder [24].

Because the market is still developing, the market cannot yet be described as fair and functioning. The demand from DSOs experiencing congestion is relatively high, while the supply from flexible resources remains low. This demonstrates itself in the abundance of Dutch grids where congestion management could not solve experienced congestion. For the market to sufficiently develop, both the levels and stakeholders in supply and demand for flexibility should increase. This also relates to the barrier of system user participation and unlocking sufficient providers.

A fourth barrier lies in the transport **tariff-structure** that is currently used. Large consumers pay a fixed tariff for the availability of the connection and a variable tariff based on the maximum consumption per time period. The current tariff structure originates from a cause-of-costs-perspective, the understanding that maximum consumption (peaks) contribute to the need for expansion and thus lead to extra costs. With the application of flexibility, this also leads to ’punishing’ consumers that, through excess consumption, contribute to the decrease of congestion caused by a large amount of DRG. In contrary to the cause of congestion, as DRG is exempted from transport tariffs.

Part of the barriers of market development and participation relate to a fifth barrier that is specific towards the use of flexibility by DSOs. As mentioned, flexibility for power is indicated as **a necessity for the integration of DRG on a national scale** because of the decrease in controllability of the generation-side. As shown in fig. 1.2, the market players with a demand for flexibility are therefore DSOs, TSOs, and BRPs.

Flexibility can be used locally by TSOs and DSOs as an alternative for reinforcement or on a system level by TSOs and BRPs for balancing the grid. If flexibility is extensively used in local balancing and as an alternative for reinforcement, it effectively drops this flexible power from the national pool. The grid's capacity is then insufficient to facilitate the transfer of this flexibility to the system level. However, the national pool might also benefit from the additional demand, as it is likely to unlock more supply.

Netbeheer Nederland [8] therefore describes this as a task for DSOs; facilitating flexibility. The DSO's relation is therefore twofold, first facilitating flexibility for both its own use as for other market parties and the use of the facilitated flexibility for effectual grid operation. This is supported by the ACM [25], arguing that maintaining the provision of capacity at the lowest possible cost requires the unlocking of small-scale, flexible potential. Overall, this requires a trade-off between local or congestion flex and system or balancing flex.

1.2.2. Reinforce unless

DSOs are required to realise sufficient capacity to ensure the market-freedoms of their system users at the lowest possible costs. Overlegtafel Energievoorziening (OTE), a collective consisting of stakeholders in the electrical energy-chain, its paper 'Reinforce unless' [26] extends on the current analysis DSOs use, which focuses on reinforcement and expansion-alternatives, and also includes alternative approaches towards realizing this capacity, like flexibility.

DSOs are encouraged to invest in their grids through a reward for high performance. This performance is determined by the down-time of the grid, measured in Customer Average Interruption Duration Index (CAIDI) and System Average Interruption Frequency Index (SAIFI). Lower CAIDI and SAIFI indicate higher reliability. ACM argues that lower reliability should result in a lower income.

Aside from performance, DSOs are evaluated by their efficiency in comparison to the overall DSO benchmark. This efficiency takes both Capital Expenditure (CAPEX) as Operational Expenditure (OPEX) into account, which are added in the Total Expenditure (TOTEX). As the income through tariffs is set at the start of the regulation period, a higher cost-efficiency (for instance, using alternative methods to grid-reinforcement) results in higher profits for the DSO. Realizing sufficient capacity with lower TOTEX thus leads to higher relative productivity.

OTE's workgroup argues that utilizing its framework leads to more efficient solutions, lower social costs, lower time to realise than reinforcements (both as a full and as a temporary alternative), and aids in unlocking potential new sources of flexibility.

1.2.3. Summary

To summarise, the previous research on flexibility focuses mainly on different types of flexibility and its necessity in integrating renewable energy sources on a national scale. Literature that quantitatively describes what demand response can do to avoid or delay congestion in the distribution grid and maintain the copper plate principle is scarcer but available. Especially in the most recent papers, this balance starts to shift. Also, a large portion of the literature for application on a national scale can be applied to the use of flexibility on the distribution grid.

This thesis aims to contribute to the current literature by using the available information on flexibility and applying it to the use of flexibility to solve operational problems in the distribution grid. It does this by providing the means to assess the fitness of these operational problems for being solved by flexibility and the fitness of different forms of flexibility to aid in general. Following, it provides the means to quantify the need for flexibility and the associated costs and benefits through OTE's 'Reinforce unless'.

1.3. Research objectives

1.3.1. Main question

The research focuses on quantifying flexibility methods to avoid or delay congestion and investment in grid capacity expansion. This is summarised in the following research question:

What ‘flexibility’-methods can DSO’s like Stedin pursue or contract to solve or delay congestion and retain stable operation of its grid over the course of the accelerated energy transition?

1.3.2. Sub-questions

The research is subdivided into five research questions:

1. What are operational problems that arise in the distribution grid due to the accelerated energy transition?
2. What are the root causes behind operational problems in the distribution grid and how can these be used to categorise the problems in the context of applying flexibility?
3. How can the feasibility of solving or delaying specific operational problems through flexibility be determined?
4. What solutions in the form of flexibility can be applied to solve or delay operational problems?
5. How can the value of flexibility for DSO’s like Stedin be determined and quantified?

1.4. Methodology and milestones

The research questions are answered through a series of objectives.

1. The first objective of this research is to determine what problems might arise due to the energy transition. This is done through researching current literature on the energy transition and bottlenecks in the grid. This objective is described in Chapter 2 and answers Sub-question 1 through defining *”stable operation of a grid”* and providing an overview of the encountered problems that might endanger this.
2. The second objective is to determine the extent of these problems on Stedin’s grid and identify possible indicators through which the problems and possible solutions can be categorised. This is done through the modeling of several grids under different scenarios for the year 2030. To assess the impact on the grid in 2030, a prognosis for future developments is needed. This is provided through four scenarios of Netbeheer Nederland [27]. The scenarios are described in Chapter 3, the models, their application, and the results are described in Chapter 4. This objective answers Sub-question 2 by showing the expected impact of the energy transition on Stedin’s grid and aims to further categorise these problems along with outcomes of simulation.
3. This objective focuses on the overall feasibility of solving operational problems through flexible resources. Chapter 5 provides a method to quantify the required flexibility for solving a specific case of congestion, answering Sub-question 3. For this, the Quick Scan of OTE’s ’Reinforce unless’-framework is actualised and supplemented.
4. Possible flexible resources are described in Chapter 6. This identifies possible flexible resources through literature research and earlier projects and thus answers Sub-question 4. It also expands on the ’Reinforce unless’ framework by providing the means of determining the security of supply of (a combination of) flexible resources.
5. The fifth objective is to provide a method to determine what flexibility is worth for the DSO. For this, the remainder of OTE’s ’Reinforce unless’-framework is actualised and specified in Chapter 7. These chapters answer Sub-question 5 and result in a renewed version of the framework.

1.5. Outline

Chapter 1 introduces the subject, evaluates current literature, and translates these into the research objective of this thesis. The second chapter of this research defines the background on the operation of the distribution grid and determines what aspects define “stable operation of its grid”. It concludes with an overview of the expected problems in the grid due to the energy transition. The third chapter describes the scenarios on which Dutch DSOs base their assessments for the future, their origin, and important details. Chapter 4 describes the development of a model that uses the scenarios and Stedin’s grid analytic tools to determine the conditions to which the identified problems will demonstrate themselves. Chapter 5 quantifies the feasibility of problems in being solved through flexibility by utilizing and adapting the ’Reinforce unless’ framework. Chapter 6 follows up by evaluating several potential flexible resources and derives several barriers and implications. Chapter 7 discusses the means for DSOs to assess the financial feasibility of flexibility as an alternative. Chapter 8 concludes this thesis and provides recommendations for further research in the field of this thesis and towards Stedin.

2

Determining operational problems

The first part of this research defines the background on the operation of the distribution grid and determines what aspects define the *"stable operation of its grid"*. Using this definition, it establishes the problems in the distribution grid that could arise as part of the energy transition. Operational problems under the responsibility of a TSO or which can arise on a transmission grid- or national scale will not be considered. This chapter aims to answer the following research question:

What are operational problems that arise in the distribution grid due to the accelerated energy transition?

The approach to answer this question through literature research was chosen to maintain a broad view on the subject. Aside from the problems that would have been found by analyzing historical data or models of future grids, there might exist other effects that present themselves in later simulations or experiences. Also, by modeling the grid in the search for operational problems, the researchers' bias would shift the focus towards the problems that will and can be demonstrated by the used model.

This chapter will first propose a definition of stable grid operation, resulting in three key categories of operational problems. Next, a small introduction is given in the representation of the distribution grid to provide a background on grid operation. Following this definition, these key aspects are used as categories for the operational problems that were found to be linked to the energy transition by current literature.

The next chapter will further expand on the results of this chapter and reference the results to the problems found by the analyses of Stedin its distribution grid following from the scenarios.

2.1. The task of the distribution grid

Nijhuis, Gibescu, and Cobben [28] suggest that to determine the impact of a specific technology on the operation of the distribution grid, the task of the distribution grid first has to be clearly defined. It states:

"The function of the distribution network is to provide access to safe electrical power of an adequate quality at the lowest possible cost" [28]

The aspects where operational problems may arise can be categorised along this definition: access to **electrical power (capacity)**, **safety**, and **power quality**. The aspects will be evaluated on their dependency on specific causes related to the energy transition, the integration of DRG, and increased electrification through Energy Transition Technologies (ETTs). Section 2.2 provides a representation of the grid, which is used in the following sections to determine if flexibility can positively impact these aspects. This will be presented through the use of table 2.1, which will be filled throughout section 2.3 to section 2.5. Finally, section 2.6 summarises the results of this chapter

	Causes								
	DRG		EV				HP	EC	Flex
	Residential PV/small DRG	Commercial/large DRG	Private small	Public small	Charging plazas	High power chargers	HP	EC	Flexibility as a solution
Effects									
Capacity									
Thermal									
Topological									
Power Quality									
Voltage dips and swells									
Harmonics and distortion									
Voltage asymmetry									
DC components									
Safety									
Shock hazard protection									
Reverse power flows									
Unintended Islanding									
Fault currents									
Cybersecurity									

Negative effect   Impossible   Improbable   Probable

Table 2.1: The table used for the representation of the results of this chapter

Where possible, the aspects will be supported by relevant legislation, as, for instance, the ”Netcode elektriciteit” (Dutch for grid code, from here referred to as the Netcode) [29]. Nijhuis, Gibescu, and Cobben [28] also demonstrated an approach on challenging the grid to its definition using the Four A’s approach. Due to the criticism of this approach [30, 31], this method will not be used.

2.2. Representation of the distribution grid

This section is based on Phase To Phase its ”Netten voor de distributie van elektriciteit” [32]. It provides a general simplified representation of a distribution grid. This section is used in the following sections to describe the expected problems and the potentially mitigating role of flexible resources.

The distribution grid is represented as a symmetrical three-phase network consisting of different nodes connected by branches. As an example, the MV distribution grid shown in fig. 2.1 consists of an HV/MV station with two MV busbars (nodes), different MV/LV substations with a single (node), client substations with a busbar (node), and interconnecting power cables (branches). Branches are fitted with breakers that can open and close, as shown in the ring opening. In normal operation, the breaker near the middle of the ring is opened, and the distribution grid is operated radially.

The ring structure shown in fig. 2.1 creates a level of redundancy in the grid. When a cable or station fails, the fault can be isolated using the breakers, and normal operation can largely be restored. According to relevant legislation on grid operation as the ”Netcode” [29] and the ”Elektriciteitswet 1998” (Electricity-law) [33], DSOs are not obligated to maintain redundancy in the grid. However, in mitigating

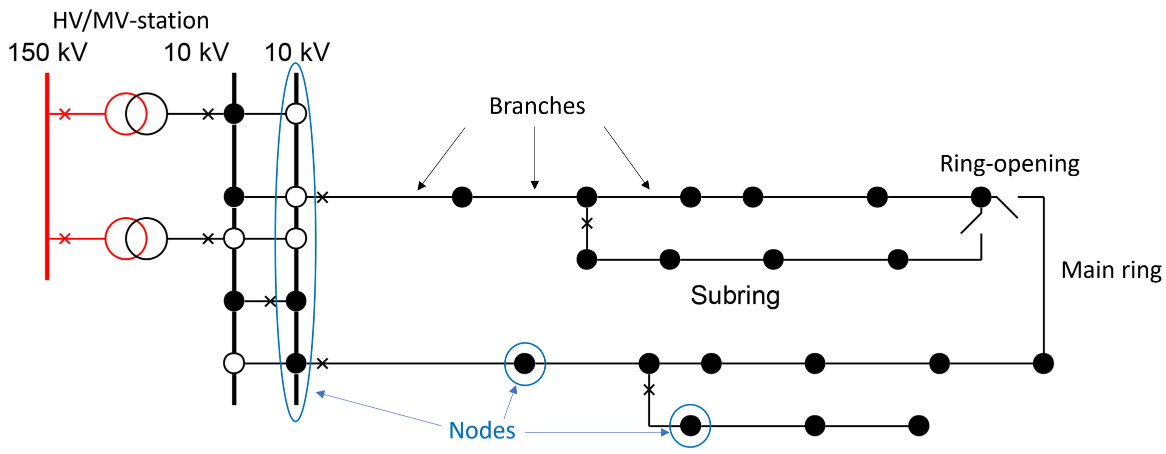


Figure 2.1: A representation of an MV grid as nodes and branches [32]

the risks associated with loss of load and downtime, operating the grid at this redundancy is seen as the most economically efficient choice.

On the IV and HV levels, and for transformers connecting these levels to the MV grid, redundancy is applied in a manner such that, under normal conditions, no outage takes place in the event of a single component failure. This type of redundancy is called "N-1" redundancy. In the medium voltage grid, the redundancy is mainly applied in the form of switchable operation, for instance, through changing the ring opening.

To ensure the loading of the assets does not exceed its nominal rating, also in the event of a failure, the assets in the grid are generally operated at half their capacity (sometimes somewhat higher, depending on the overloading capabilities of the asset). In general, the redundancy is rarely addressed, and assets barely operate over half, let alone at or near their nominal capacity. Thus, it seems counter-intuitive to evaluate reinforcement to resolve a bottleneck that only occurs in fault conditions. However, just as in normal operation, the unconditional redundant operation is regarded as the most economically efficient choice.

The MV network is connected to the HV (or IV) network through a transformer, which acts as a special branch. This branch does not connect the two nodes (the HV or IV node of the upstream grid and the MV node of the MV network) directly but connects the nodes through a transfer ratio equal to the turns ratio of the transformer.

At each of these nodes, equipment as loads or generators can be connected. This equipment can be represented in several ways, depending on what information is known. A generator can deliver active power based on its main driver and during which, maintain a constant voltage (U control) or maintain a constant reactive power as a function of its active power ($\cos\varphi$ control). A load can draw a constant amount of active power under different bus voltages (e.g., a power converter) or an amount that varies with the voltage (e.g., a resistive heating element). The following holds in general. The equipment connected at a node:

- can impose a certain current or maintain a certain apparent power which, through the impedance of the network, results in a certain voltage at the node (PQ, as in, active and reactive power are specified);
- can impose a certain voltage which, through the impedance of the network, results in a certain current injection (Uf, as in voltage and frequency are specified);
- can have an impedance (load) which, as a function of the voltage of the node, draws a certain current which in turn also influences the voltage through the impedance of the network.

In general, the upstream grid is seen as a node of the second representation—one with a constant voltage, a constant frequency, and a phase angle equal to zero. This is called the slack-node, the node of which its voltage is a phasor with a phase angle $\delta = 0$ and a magnitude of 1 p.u. The phasors of the voltages of the other nodes will be expressed as relative towards this node. The upstream grid will supply any active or reactive power drawn but not locally supplied in the MV grid.

Generators are represented as either imposing a certain apparent power phasor (PQ, as active power is specified and reactive power is specified through a reactive power- or $\cos\varphi$-setpoint) or imposing a certain active power and a certain voltage magnitude (Pv, as in, active power and voltage are specified).

Loads are generally represented as imposing a certain apparent power phasor (PQ) or as a combination of one share that imposes a certain apparent power phasor and a smaller share that has a certain impedance.

The definition of flexibility, which was provided in the introduction, is repeated here below:

" The ability to shift or adjust levels of generation or consumption based on a variety of incentives"

Applying this definition to the representation of the grid, the shifting of adjusting of levels of generation or consumption is further defined as adjusting the apparent power phasor of generators and loads (PQ) over time (shifting/sizing).

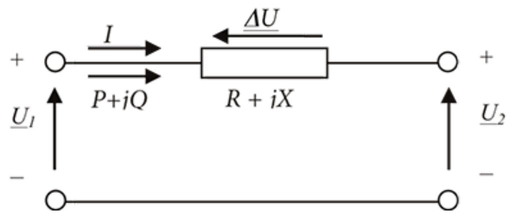


Figure 2.2: Generalised notation of the relation between power, voltages, and currents in the complex domain (adapted from [32])

Each injection or withdrawal of active and reactive power at a station influences cable currents and station voltages throughout the network through the network impedance. The level of influence depends on the magnitude of the change and the location of the stations and cables in the network.

An example is given using fig. 2.2, eq. (2.1), and eq. (2.2). If $\underline{U_1}$ is known, the active and reactive power that is consumed at the node with $U = \underline{U_2}$ is known, and that this power is fed through the branch with impedance $(R + jX)$, the voltage $\underline{U_2}$ can be determined.

$$\underline{I} = \frac{\underline{\underline{\Delta U}}}{\underline{Z}} = \frac{\underline{\Delta U}}{R + jX} = \frac{\underline{\underline{U_1}} - \underline{\underline{U_2}}}{R + jX} \tag{2.1}$$

$$\underline{U_2} = \underline{U_1} - \underline{\Delta U} = \underline{U_1} - \underline{Z} * \left(\frac{\underline{S}}{\underline{U_1}}\right)^* = (R + jX) * \left(\frac{P - jQ}{\underline{U_1}}\right)^* = \frac{(R * P + X * Q) + j(X * P - R * Q)}{\underline{U_1^*}} \tag{2.2}$$

However, depending on the type of the load or generator that is added to the node with $U = \underline{U_2}$, the currents that are injected or withdrawn could consequently also again be influenced by the station voltages. To approximate the actual state of the network under certain conditions as closely as possible, this operation requires an iterative method. The common method for such an analysis is according to Newton-Raphson, an iterative method that can be applied to calculate load flows iteratively until the results sufficiently converge.

$$\left[\begin{array}{c}\Delta P_1\\ \vdots\\ \Delta P_n\\ \hline \Delta Q_1\\ \vdots\\ \Delta Q_n\end{array}\right]=\left[\begin{array}{ccc|ccc}\frac{\partial P_1}{\partial \delta_1} & \cdots & \frac{\partial P_1}{\partial \delta_n} & \frac{\partial P_1}{\partial |U_1|} & \cdots & \frac{\partial P_1}{\partial |U_n|}\\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots\\ \frac{\partial P_n}{\partial \delta_1} & \cdots & \frac{\partial P_n}{\partial \delta_n} & \frac{\partial P_n}{\partial |U_1|} & \cdots & \frac{\partial P_n}{\partial |U_n|}\\ \hline \frac{\partial Q_1}{\partial \delta_1} & \cdots & \frac{\partial Q_1}{\partial \delta_n} & \frac{\partial Q_1}{\partial |U_1|} & \cdots & \frac{\partial Q_1}{\partial |U_n|}\\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots\\ \frac{\partial Q_n}{\partial \delta_1} & \cdots & \frac{\partial Q_n}{\partial \delta_n} & \frac{\partial Q_n}{\partial |U_1|} & \cdots & \frac{\partial Q_n}{\partial |U_n|}\end{array}\right]\left[\begin{array}{c}\Delta \delta_1\\ \vdots\\ \Delta \delta_n\\ \hline \Delta |U_1|\\ \vdots\\ \Delta |U_n|\end{array}\right] \tag{2.3}$$

The calculations involving a whole network are logically more complex than the calculation for these two nodes. Overall, the voltage changes at a certain node can be expressed as a function of the changes in loads at the other nodes in the network. This relation can be determined for the whole network, resulting in a matrix representing the relations (linearized for that specific state) between active and reactive power injection and the voltages and angles at certain nodes. Using this matrix in combination with the known data, the Newton-Raphson method can iteratively approach the data that is not known until a certain acceptable accuracy is reached.

2.3. Provision of electrical power

The provision of electrical power relates to the capacity of the grid. This is the amount of power provided over the distribution grid as limited by the equipment and cables. Capacity can be limited by the nominal ratings of the equipment. It can also be limited by topological constraints, such as the number of cables leaving a station or busbar connections. According to [34] and [35], capacity problems and voltage problems are the most common problems encountered in the distribution grid.

The asset's nominal rating is mostly influenced by its thermal capacity. Overloading this capacity increases the production of heat due to the internal resistance of the cables or equipment. This increases its temperature, which accelerates the aging of the equipment and may lead to damage and outages.

The current flowing through a branch or cable is a function of the active and reactive power flows. In general, the reactive power should be kept as low as possible, as the increased currents result in increased losses of the networks and lead to increased aging. In some cases, however, because the reactive power influences the node's voltage magnitude, a trade-off can be made between lower cable loading and meeting voltage constraints.

The power flows are overall a direct result of nodal mismatches between consumption and generation. Thus, the power withdrawn but not locally supplied and vice versa will need to be supplied at other nodes and transferred over the branches. This holds for both branches, cables, and transformers but may also include a certain capacity of the busbar represented by the node.

According to Articles 23 and 24 of the Electricity law [33], DSOs are required to provide access to the grid and transport energy for anyone who requests it. The capacity of the grid must therefore be sufficient to process the maximum instantaneous amount of power that is expected to be requested or supplied by its customers. An exemption for up to four years can be made if the DSO can show physical congestion and has applied and exhausted every option of congestion management [36]. Legislation on this aspect is currently the subject of discussion between ACM and grid operators [37].

Due to the changes in consumption and generation levels, the maximum instantaneous amount of power is likely to increase. Therefore, the impact of consumption and generation on the grid's capacity is evaluated in the following two subsections.

2.3.1. Changes in consumption

As a result of the energy transition, many changes are expected in the consumption of energy—for example, the Dutch resolution for gas-free living [4] drives the electrification of heating and cooking. Other aims towards reducing CO_2 and other greenhouse gas emissions are the electrification of mobility and possibly the integration of Carbon Capture and Storage (CCS), a process that captures CO_2 from air or from process-output and stores it, inhibiting it from entering the atmosphere.

Overall, energy consumption is expected to increase [18, 38, 39]. As the grid is more often than not underutilised, that alone should pose no problem. The problem lies in the simultaneity of consumption and the resulting power peaks exceeding the maximum instantaneous amount that can be provided. Aside from the power peaks, the overall daily pattern is expected to change as well. Trends that may influence this pattern include working from home, smart home management systems, increased efficiency, and more DC-oriented loads [28].

The simultaneity of consumption plays a significant role in the shortage of capacity [28]. For example, a typical 9-to-5 workday results in a large part of a neighborhood arriving home from work at around 18:00. After plugging in their EV, they will start cooking while just turning up the HP after a whole day of absence. Thus, the aggregated effect of the technologies over multiple households all starting simultaneously results in a large power peak.

Gupta et al. [38] model the levels of integration of PV, EV, and HP for a DSO's service area in Switzerland towards 2035 and 2050. The least-effort-scenarios for EV and HP deployment in 2035 show 15% of total passenger cars to be an EV and 11.2% of total residences conditioned by a HP. These scenarios already result in respectively 27% and 39% of the installed transformers to overload. From the scenario of Netbeheer Nederland's Investment plan 2022 (IP2022) described in Chapter 3, the scenario with the least EV and HP deployment (International Ambitions-scenario (IA)) prognoses 1.3 million EVs and 790,000 HPs. This corresponds with (coincidentally) 15% of 8.7 million cars registered in 2020 and 10% of total residences. It shows that the challenge ahead should definitely not be underestimated.

Previously, the deterministic aspect of power draw as a function of time played a large role in the household's overall daily profile, especially that of an aggregated group of households. Overall, the consumption of an aggregated group of households was fairly predictable, and trends were derivable from the yearly consumption. With large consumers such as HPs and EVs, the individual has a much larger influence on the overall behaviour [40]. The simultaneity- or coincidence-factor plays a significant role in the extra need for capacity [32]. Extra-large consumers, for instance, EV charging plazas or high-power chargers, may draw so much power that they require a connection at a higher voltage level. Integration on these levels could be constricted by the current topology of the assets.

In cases with large consumers, the effects of the different types of loads need to be evaluated under separate simultaneity factors and supplemented to the deterministic profile. Van Oirsouw [32] demonstrates that in some cases, the maximum loading of standard consumption is of almost negligible relative magnitude.

2.3.2. Changes in generation

Due to the objective of reducing greenhouse gas emissions, renewable energy generation is steadily replacing traditional generation. These intermittent generators are often connected to the distribution grid. As is the same for Electric Cooking (EC) and electric mobility, DRG barely has any mitigating aggregated effect and a high simultaneity factor. It is also often hard or undesirable to control [39], resulting in a decreased supply-side flexibility in respect to the conventional energy system [20].

In some situations, the increased levels of DRG exceed the maximum instantaneous amount of power that can be distributed [20]. DSOs are met with such large amounts of transportation requests that they experience problems with providing DRG plants with connections and enough capacity [36].

In small areas with residential-PV, the simultaneity factor is almost unity but decreasing with different orientations [28, 41, 42]. Other DRG types are also included for higher distribution levels (wind-on-land, large-scale solar). This can result in a larger influence of spatial differences but is unlikely to have a strong mitigating effect.

The power associated with the DRG on these voltage levels is much higher. Therefore, the integration of large generators not only puts a strain on the network but may also require dedicated connections and topological changes.

Aside from HP and EV, Gupta et al. [38] also models the integration of PV. In the least effort scenario, the integration of PV is modeled as following the current trend. The model projects 20% of the transformers to reverse overload by 2035. A large part of this is in rural areas, where the potential rooftop area is large. However, they omit the possibility to install PV directly on land and only consider the rooftop-surface area. This also results in all installations being assumed to be connected to the LV grid. Therefore, a direct comparison between their scenarios and that of IP2022 is unfortunately not possible.

2.3.3. Overview

The thermal capacity problems are highly influenced by the introduction of ETTs in every category. In addition, topological capacity is affected by the introduction of ETTs with large power ratings. As thermal capacity problems are essentially caused by nodal mismatches between generation and consumption, aligning these through flexibility is likely to have a strong mitigating effect. Therefore, flexibility is regarded as a likely solution to capacity problems.

	Causes								
	DRG		EV				HP	EC	Flex
	Residential PV/small DRG	Commercial/large DRG	Private small	Public small	Charging plazas	High power chargers	HP	EC	Flexibility as a solution
Effects									
Capacity									
Thermal	++	++	++	0+	0+	0+	++	+	(green)
Topological	0	++	0	0+	0+	0+	0	0	(orange)

Table 2.2: Overview of the relation between capacity problems and causes related to the energy transition

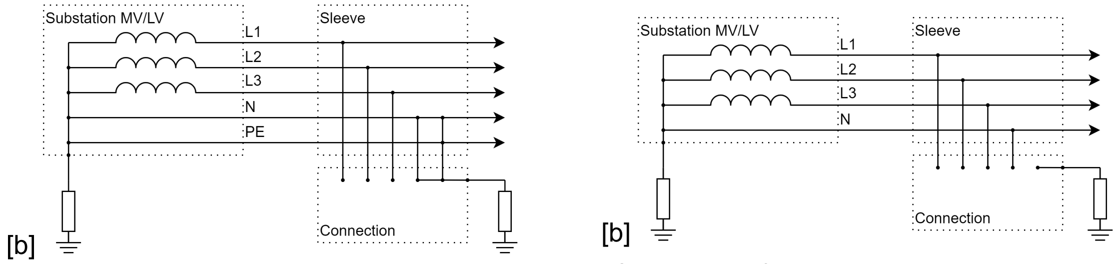
2.4. Safety

The safety aspect of the distribution system focuses on: Shock hazard protection, Reverse power flows, Unintended islanding, Fault levels and Cybersecurity.

2.4.1. Shock hazard protection

In the case of a line-to-ground fault, the current flowing through the return path can result in a substantial rise in ground potential. This eventually causes a shock hazard for every earthed enclosure.

In the Netherlands, the requirement for shock hazard protection is specified in Article 7.8 of the Netcode. Furthermore, the precise values are specified and further sharpened in Netbeheer Nederland's "Safety-definitions for LV-distribution grids", [44] derived from the Dutch norm for low voltage installations, NEN1010 [43].



(a) TN-C-S System (adapted from [32])

(b) TT System (adapted from [32])

System	$50\ V < U_0 \leq 120\ V$		$120\ V < U_0 \leq 230\ V$		$230\ V < U_0 \leq 400\ V$		$400\ V < U_0$	
[s]	AC	DC	AC	DC	AC	DC	AC	DC
TN	0.8	A_1	0.4	5	0.2	0.4	0.1	0.1
TT	0.3	A_1	0.2	0.4	0.07	0.2	0.04	0.1
U_0 is the nominal voltage from phase to ground. A_1 The need for switching off can be for reasons other than shock hazard.								

Table 2.3: Switching off-times for different nominal voltages [43]

The newly built electric infrastructure in the LV-grids is installed as a TN-C(-S-extra) system as shown in Figure fig. 2.3a [32, 45]. In these cases, the system provides a low impedance return path through the PEN/PE&N conductor(s). In the case of a line-to-ground fault, the low impedance return path reduces the magnitude of the potential rise of ground and increases the fault current resulting in quicker response.

In TN-C(-S-extra) systems, an additional shock hazard exists through the connection of the PE of the client to the PE of the substation. In the event of a line-to-ground fault in the MV grid, the currents can disperse through the PEN/PE&N conductor to the LV grid, where it can also cause substantial voltage rises.

In earlier built infrastructure, the TT system as shown in fig. 2.3b was often used. This system operates by providing a return path through ground in case of a line-to-ground fault. The impedance would be quite small due to the metal piping in the ground. With most metal piping being replaced by plastics, the ground impedance has risen. In many cases, the fault current is no longer sufficient to trip a breaker or fuse. The risen ground impedance also leads to an increased shock-hazard voltage. This is why the switching-off times in table 2.3 are shorter. In these systems, earth-fault detection is used [32]. This detection is, however, also increasingly applied in TN-C-S systems.

Residual current-based earth fault protections are expected to encounter increased problems with technologies of the energy transition due to the increase of DC components in the grid [46, 47], for instance, the DC components observed with the integration of PV inverters and other Power Electronic Interfaced Devices (PEID) (see also, section 2.5.4). These increased problems are mostly cases of false positives (nuisance tripping).

2.4.2. Reverse power flows

With the introduction of prosumers (combined consumers and producers), Distributed Generation (DG), and storage solutions as residential battery systems of Vehicle-to-Grid (V2G), the conventional assumption of a radial power flow in the distribution grid no longer holds. If local generation exceeds load, power can flow upstream to higher distribution levels. The assumption made when originally designing the power system may have led to decisions that cause the system to be potentially unreliable in the event of reverse power flows.

As shown in fig. 2.4, feeders in residential neighborhoods are protected at the source of the feeder, the distribution transformer. However, in the case of one or several large residential DG, the power flows in the feeder can be such as to overload a cable without the protection at the source of the grid connection ever intervening [28, 48].

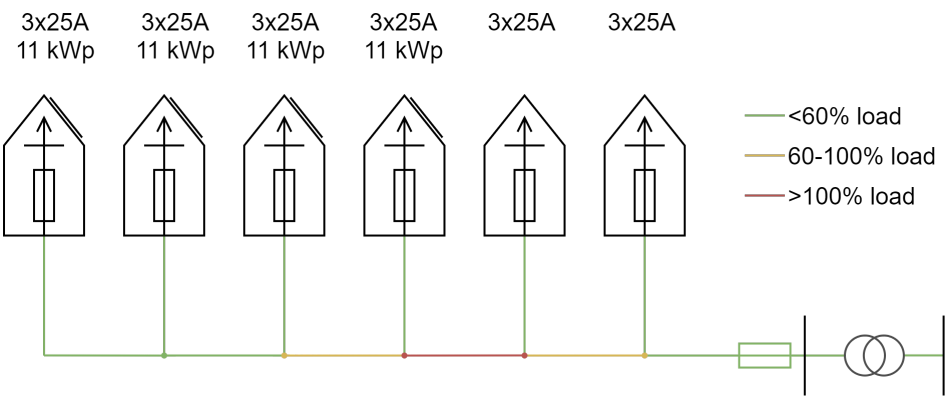


Figure 2.4: Exaggeration of reverse over-current failed to be detected

.

Reverse power flows are also identified to cause problems to the automatic tap changers of HV/MV transformers (HV) with current-based voltage control schemes [48–50]. This regulation is explicitly mentioned as a barrier towards maximum DRG integration.

2.4.3. Unintended islanding

Unintended islanding is when DG, distributed storage, or other PEID keep a portion of the grid energised when the connection to the mains or upstream grid has been cut off.

DRG is most commonly controlled as a PQ-generator with Maximum Power Point Tracking (MPPT), a control algorithm for power electronic devices aimed at maximizing power output. It will inject as much active power as the DG can deliver into the grid. For storage devices, this depends on the charging and discharging strategy. If power is injected when the grid is cut-off, the imbalance between the injected and the withdrawn power at that node can no longer be corrected through consumption at other nodes. This will often lead to over-voltages or over-frequencies [28, 49].

In the Netcode, the situations at which an inverter should switch off are specified in Article 3.8 ($P < 800\ W$) and Paragraph §3.4-3.6 depending on the voltage level and its nominal power.

Grid coupled DG must perform or use anti-islanding procedures or equipment to detect islanding and prevent dangerous situations. However, these procedures are tested in cases where the equipment or procedure is securing the only generation in that “island”-grid, not a grid where more generation is present.

Multiple detection schemes exist for signaling islanded operation. Simple implementations of anti-islanding equipment use voltage and frequency deviations in the case of a mismatch between generation and load. However, when the sum of the reactive and active power outputs match the sum of reactive and active power draw, the voltage and frequency stay within bounds resulting in a false negative detection.

2.4.4. Fault currents

DG with the ability to provide high short circuit currents should not cause the short circuit capacity of the distribution network to exceed its rating [9]. If the rated current is exceeded, the protective switchgear and overall equipment will no longer technically be able to handle the current, and the mechanical construction of the network may not be able to handle the excessive forces [49]. The Netcode specifies in Article 3.10 that a DG’s contribution to the grid’s short circuit capacity should be kept to a minimum. The DSO can assign measures to minimise the impact of the DG on the short circuit capacity [29].

Due to the increase of PEID-generation and possibly the introduction of microgrids, the grid is transforming from a mainly rotating machine-grid to a PEID-grid [45]. Unless the electronics are specifically designed for this, this change can result in lower provisions of short circuit power in the case of islanded operation. Where synchronous and asynchronous generators can contribute eight and six times their rated current, inverters normally contribute no more than one times their rated current [9]. This can result in lower fault currents which logically derived lead to a longer fault clearing time. HP, as they often use an asynchronous motor as a driver for the compressor, can also contribute to the fault currents.

For micro-grids, grids that can run independently from the upstream grid, the reliance on PEID-generation may call for new protection schemes. This could, for instance, be through the use of a flywheel connected to a synchronous generator as proposed by [49]. The chance of a problem caused by the increased PEID-generation for grid coupled glsLV-applications is not large. The grid transformer is expected to supply sufficient short circuit current, and PEID-generation does not contribute largely. For large connections, the contribution to short circuit current should be calculated and evaluated.

2.4.5. Cybersecurity

Nijhuis et al. [28] argue that integration of ICT does not affect the safety requirements of the distribution network. Based on its description of the integration of ICT, other sources explicitly disagree [12, 18, 51]. I agree with the latter.

Most sources agree that ICT is one of the main requirements of the energy transition [11, 12, 18, 21, 28]. It is essential to create more insight into power flows, energy usage, power quality, and fault mitigating measures. Besides insight, it can also provide controllability in grid configurations and potential flexibility. Across the whole definition, but especially on controllability, ICT can also become a risk.

Risks of cybersecurity can be identified along the well-known CIA-triad (Confidentiality, Integrity, Availability). The triad essentially translates to cybersecurity in the grid by guaranteeing that information is only available for the authorised (privacy-requirement), only commands given by those who are authorised (in the strictest sense) are executed, and access to remote assets is guaranteed. Along with the translation to the subject of this thesis, possible risks are the unauthorised remote control of distribution automation, manipulation of measurements, unavailability of distributed automation, and unavailability of distributed generation or other flexible resources. Cybersecurity, integration of grid reconfiguration, smart grid functionalities, and possibly demand response influence the distribution grid's safety.

2.4.6. Overview

Table 2.4 shows an overview of all safety-related problems that can arise as a result of causes related to the energy transition. Special cases which require specific conditions for this result to happen are written with parentheses. For example, EVs only contribute to reverse power flows or unintended islanding if used in a V2G-application, and their objective requires them to.

Of the effects, reverse power flows and unintended islanding are problems that essentially relate to the nodal mismatch between consumed and generated power. Reverse power flow problems that can be solved through flexibility will probably not relate to technical restraints following from conventional assumptions. Instead, they will more likely relate to limits set by the TSO, which focus on national balancing. The limits can essentially be translated as a capacity constraint and will be treated as such.

Unintended islanding can be solved through the application of flexibility by locally maintaining the balance between generation and consumption. This essentially means transferring from unintended islanding to microgrid operation, which would entail a completely different scope.

Besides reverse power flows and unintended islanding, none of the effects are likely to be solved through the use of flexibility as they do not relate to nodal mismatches of consumed and generated power. Flexibility does introduce another example of a problem that arises solely under a specific condition; that of cybersecurity. Here, using these technologies in combination with flexibility is likely to increase the risk, as flexibility is expected to require higher controllability. This problem does not apply to EC, as this is not a load that is typically used for this objective (non-deferrable load) [16, 17].

	Causes								
	DRG		EV				HP	EC	Flex
	Residential PV/small DRG	Commercial/large DRG	Private small	Public small	Charging plazas	High power chargers	HP	EC	Flexibility as a solution
Effects									
Safety									
Shock hazard protection	0+	0	0+	0+	0+	0+	0+	0+	
Reverse power flows	++	++	(0+)	(0+)	(0+)	(0+)	0	0	
Unintented islanding	+	+	(0+)	(0+)	(0+)	(0+)	0	0	
Fault currents	+/-	+/-	(+/-)	(+/-)	(+/-)	(+/-)	0+	0+	
Cybersecurity	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(0)	

Table 2.4: Overview of the relation between safety problems and causes related to the energy transition

2.5. Power quality

Power quality is defined to include all local properties related to the usability of the voltage to the customer. This usability is, for instance, mitigated in cases of a distorted voltage, voltages outside operational limits, or flickering. The authors of [28, 47, 50, 52] define the following concepts as part of power quality: Voltage dips and swells (fast and slow), Harmonics and distortion, Voltage imbalances/asymmetry, and DC components.

The Netcode specifies the operational limits of the power quality aspects in Paragraph §7.2 [29]. The aspects mentioned correspond to most of the aspects in the list above (excluding DC components), and the limits differ among different voltage levels. The limits set in the Netcode mostly correspond to the limits specified in the norm NEN-EN 50160 ”Voltage characteristics of electricity supplied by public electricity networks” [53]. The limits are commonly set based on measured 10-minute averages, of which a practical example is given in section 2.5.1.

2.5.1. Voltage dips and swells

Dips and swells in the voltage influence the steady-state voltage stability. Problems regarding the stability of the steady-state voltage levels are regarded as one of the most common problems in the distribution grid [49].

Using eq. (2.2), the ratio of the reactance over the resistance of the branches in the network can provide a general idea of how voltage dips and swells are influenced by active and reactive power flows. Table 2.5 shows that for MV and LV networks, the deviations in magnitude are predominately caused by active power flows. However, especially for MV grids, the influence of reactive power flows must certainly not be neglected.

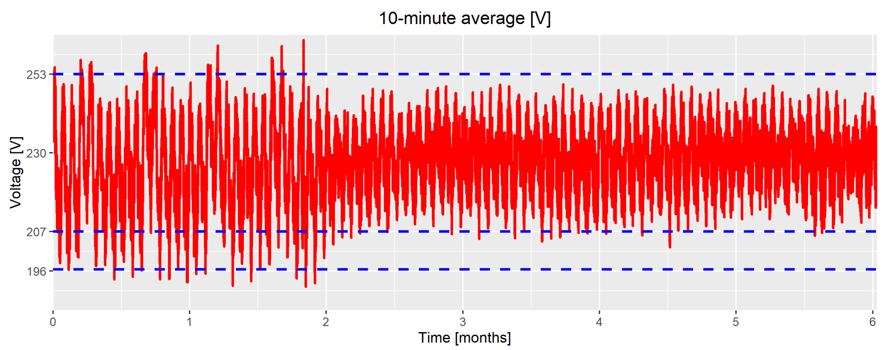
Voltage level	Type	R/x-ratio	Main influence on $\|U\|$	Main influence on δ
HV	Line	« 1	Q	P
MV	Cable	1-5	P&Q	P&Q
LV	Cable	» 1	P	Q

Table 2.5: An overview of the relation between voltage and active and reactive power in different types of networks (adapted from [32])

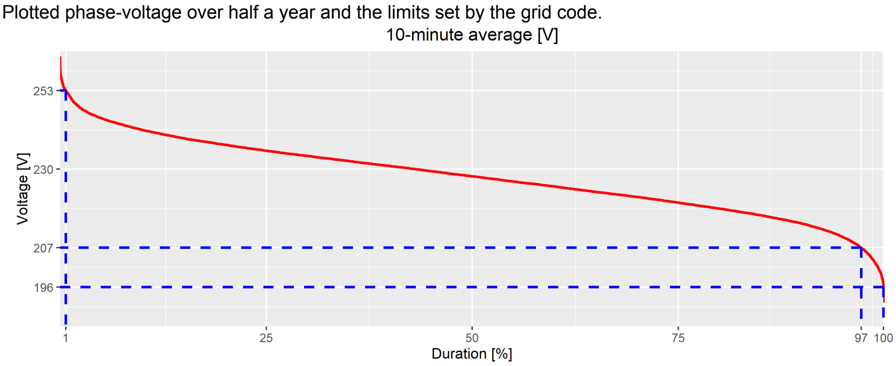
Using table 2.5 and section 2.2, the effects as noted in different sources can be supported. Nijhuis et al. [28] and Chindris et al. [52] for instance, note that dips and swells in the voltage are expected due to larger power flows and overall loading of the grid. They also highlight that voltage dips and swells are most common in rural areas with long power lines, which can be explained by the high resistivity.

The stability of the steady-state voltage can be influenced on both long as short timescales. Long timescales can, for instance, be the daily load profile or the profiles of DRG [50]. Long-term voltage dips and swells are to be more common due to the change in the grid to a bidirectional power flow and overall higher loading.

Several sources indicate the benefits of DG reactive power control for stabilizing voltages. At the moment, DG is still mostly applied at unity $\cos\varphi$. In cases where reactive power is controlled, it is usually at a fixed power factor [50]. Several studies have calculated that switching from zero reactive power to a fixed factor below unity or to variable reactive power can allow for 1.5 to 2 times as much PV integration at the costs of increased currents [9, 34, 41, 54].



(a) Plotted phase-voltage over half a year and the limits set by the grid code.



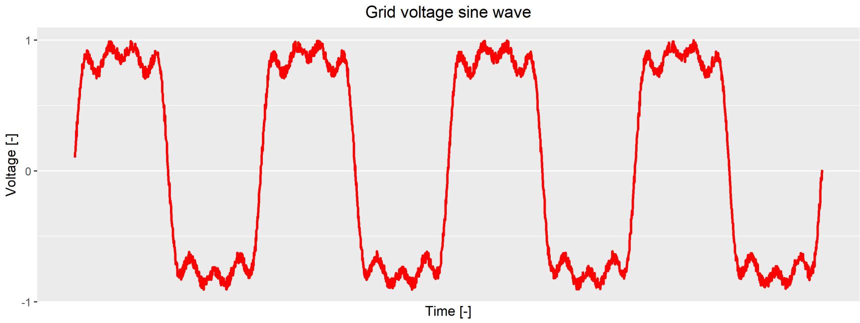
(b) The voltage duration curve of the above plot and the limits set by the grid code.

Figure 2.5: A voltage duration curve against the limits set by the grid code. The stability at this connection is insufficient, as several of the 10-minute averages are below 85% and above 10%

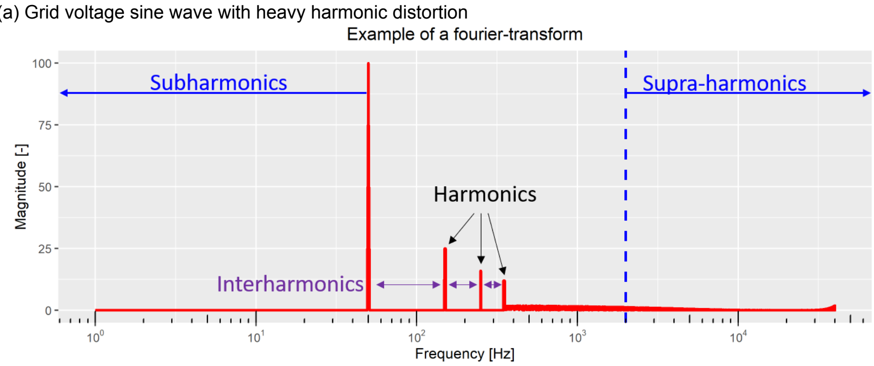
The occurrence of longer timescale variations must be limited both in time and in magnitude. This is demonstrated in fig. 2.5b for the example of a connection in the LV grid. The voltage magnitude for any connection in a LV grid should remain between ±10% of its nominal voltage for 95% of the measured 10-minute averages. It should also be between +10% and -15% for all measured 10-minute averages [29].

Shorter timescales variations, are also known as flicker, originate from switching operations (loads, generation, or network reconfiguration). These switching operations or short-term voltage variations can, depending on, among others, the strength of the grid and resonance characteristics, lead to inter-harmonics (see: section 2.5.2). Although the nuisance experienced due to flicker is subjective, the NEN50160 does set a limit based on a model that mimics the way humans react to flicker. From this model, the quantitative parameter P_{st} (short term) is determined. In addition, the P_{lt} (long term) can be determined by evaluating P_{st} over a period of two hours.

2.5.2. Harmonic distortion



(a) Grid voltage sine wave with heavy harmonic distortion



(b) Fourier-transform of the distorted waveform

Figure 2.6: A Fourier transformation of the distorted waveform including the descriptions of the different harmonics. The transformation indicates harmonic levels significantly higher than allowed.

Grid harmonics in general, quantified among others in the Total Harmonic Distortion (THD), are expected to increase in the future [50]. Harmonics are defined as positive integer multiples of the fundamental frequency. They result from non-linear loads where the current draw is not linearly proportional to the voltage. These can be periodic switching operations in power electronics, current draw in rectifiers, or cyclic variable loading in electric drives. Other frequency distortions related to harmonics are supra- and interharmonics. All terms related to harmonics are shown in fig. 2.6b

The definition of the frequency levels of supraharmonics differ among sources but mostly point towards frequencies in the range of 2 kHz to 150 kHz [47, 50, 55]. Supraharmonics are relatively new and directly linked to the integration of PEID. To be more specific, IGBT-interfaced devices (a specific type of transistor that is increasingly applied). These include, for instance, PV, EV-charging, and DC-chargers. The harmonics of IGBTs differ from those of earlier PE as thyristors because they are asynchronous towards the fundamental frequency, and therefore do not appear as integer multiples of said frequency.

Opinions differ on the influence of EV-chargers and other PEID on (supra)harmonics. [47] argues that due to the active PE interfaces, the actual emission of harmonics will remain low and that this is already demonstrated for EVs. [55] researched the propagation of supraharmonics from EV-charging into the grid. They found that the effects significantly differ for different EVs, grids, compositions, and combinations of multiple EVs. Significant outcomes are the heating of assets due to “the skin effect” and the interaction between numerous EVs.

Interharmonics are defined as frequency components that are not integer multiples of the fundamental frequency [56]. These can include all values, where a separation is made for frequencies with a multiple less than one. These are called subharmonics. Per that definition, subharmonics are a form of interharmonics.

Aside from the integration of PEID in the LV levels, [50] argues that the drivers behind increased harmonics also include the integration of FACTS controllers, High Voltage DC-links, and other large scale- and HV-PEID. The THD can quantify the level of harmonic distortion in the grid. This quantity compares the amplitude of harmonics to that of the fundamental frequency and expresses it as a percentage. This percentage is used to define certain limits for manufacturers of electronic equipment but also as a standard for system operators. The Netcode bases the operational limits of harmonics both on individual levels as on the THD. The individual harmonics relate mostly to the actual harmonics of the grid frequency, where individual interharmonics must remain below the lowest maximum value for an individual harmonic. Again, the limits are both based on magnitude and time. The values are evaluated over 10-minute averages and total time.

2.5.3. Voltage imbalances/asymmetry

Asymmetry occurs when one of the phases in a poly-phase system differs in magnitude compared to the other phases or where the phase angles between the phases differ [47]. The voltages in a three-phase system can be decomposed into three balanced components; the positive, negative, and zero sequence component [50]. The Netcode states the limits on the asymmetry as relative magnitude of the negative sequence component towards the positive sequence component. For example, for the LV grid, the negative sequence component must remain below 2% and 3% for 95% and 100% of the 10-minute measurements.

Voltage asymmetry is caused by asymmetrical loads or uneven distribution of single-phase loads among different phases [47, 57]. This concept is highly influenced by the integration of energy transition-related technologies as residential PV, EV-charging, and HP [47, 49, 50]. The latter two are almost always three-phase connected due to their high power applications. However, the first one is, to a large extent, single-phase connected.

The influence of residential PV on voltage asymmetry especially holds in neighborhoods where the households or apartments are single-phase connected. PV is installed to the full extent of the roof surface, and the inverter is connected to one phase only. The Netcode states that PEID with a nominal power that exceeds 5 kW must be three-phase connected and cannot be installed on a single phase. Relative to the maximum available power of a single-phase connection, this is already quite high. A three-phase connection is only requested when the installed capacity exceeds the connection; otherwise, it would increase expenses. Rönnberg et al. [47] however, argue that the chance of high imbalances due to PV is slim when the inverters are randomly distributed.

Although not common, in cases where HP and EV-chargers are single-phase connected, their influence on the imbalance is not always likely to cancel out as it would with PV. Especially with lower levels of integration, as the possible intermittent and varying simultaneity is not always likely to cancel out. Distribution among different phases for different households would therefore have a lesser mitigating effect.

2.5.4. DC Components

DC components in the grid can be seen as a special case of harmonics, the case where the integer multiple of the fundamental frequency is zero [56]. Effects of DC components in the system can include the saturation of network elements, increased corrosion due to electrochemical reactions, and the malfunctioning of protection devices [47]. The Netcode specifies no limits on this aspect.

Rönnberg et al. [47] mentions cases of DC components in the presence of PV inverters and some possible implications. The malfunctioning of protection devices (RCD) is further expanded on by [46], explaining that the reaction towards a fault condition is not doubted, yet false positive indications of faults are still possible and need to be investigated further. SRC [46] also highlights the influence on electrochemical corrosion.

2.5.5. Overview

Table 2.6 shows an overview of all power quality-related problems that can arise as a result of causes related to the energy transition. As voltage dips and swells are reliant on the active and reactive power flows in the network, which are the result of nodal mismatches of consumption and generation, these are likely to be solved through the application of flexibility. The other aspects are more likely to be solved through stricter regulation and protocol.

Flexibility might also provide a solution for asymmetry and problems related to reverse power flows. This is, however, unlikely due to more efficient alternatives. Voltage asymmetry, for instance, is a problem that arises explicitly in LV-grids, where redistribution of single-phase connections is significantly more likely than a flexibility market.

	Causes								
	DRG		EV				HP	EC	Flex
	Residential PV/small DRG	Commercial/large DRG	Private small	Public small	Charging plazas	High power chargers	HP	EC	Flexibility as a solution
Effects									
Power Quality									
Voltage dips and swells	++	++	++	0+	0+	0+	++	+	(green)
Harmonics and distortion	+	+	++	++	++	++	++	++	(orange)
Voltage asymmetry	++	0	++	0+	0	0	0	0+	(yellow)
DC components	+	+	+	+	+	+	0	+	(orange)

Table 2.6: Overview of the relation between safety problems and causes related to the energy transition

2.6. Summary

The literature research results in an overview of the problems expected in the future distribution grid related to the energy transition, including possible underlying causes. From these problems, several count as demonstrations of congestion, running into the operational limits of the power that can be drawn from or delivered to the distribution grid.

In Table 2.7, several colors indicate if flexibility is likely to play a mitigating effect. Although these problems are all relevant for the future distribution grid, only a few can be solved through either grid expansion or flexibility. Most of the results of this research question cannot and ask for regulation on system quality and electric compatibility. These are, for instance, the problems regarding the aspect of safety, harmonic distortion, and DC components. Examples of such regulations include the Requirements for Generators (RfG), Requirements for Generators (RfG) [58], and ACM its striving for improved shock hazard protection of LV distribution grids.

Overload of capacity and voltage swells and dips are problems where grid expansion or flexibility can play a mitigating or solving role. Therefore, these will be the only congestion and operational problems this thesis will consider for mitigating or avoiding through flexibility.

	Causes								
	DRG		EV				HP	EC	Flex
	Residential PV/small DRG	Commercial/large DRG	Private small	Public small	Charging plazas	High power chargers	HP	EC	Flexibility as a solution
Effects									
Capacity									
Thermal	++	++	++	0+	0+	0+	++	+	
Topological	0	++	0	0+	0+	0+	0	0	
Power Quality									
Voltage dips and swells	++	++	++	0+	0+	0+	++	++	
Harmonics and distortion	+	+	++	++	++	++	0	0+	
Voltage asymmetry	++	0	++	0+	0	0	0	0+	
DC components	+	+	+	+	+	+	0	+	
Safety									
Shock hazard protection	0+	0	0+	0+	0+	0+	0+	0+	
Reverse power flows	++	++	(0+)	(0+)	(0+)	(0+)	0	0	
Unintended Islanding	+	+	(0+)	(0+)	(0+)	(0+)	0	0	
Fault currents	+/-	+/-	(+/-)	(+/-)	(+/-)	(+/-)	0+	0+	
Cybersecurity	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(0)	

Negative effect Impossible Improbable Probable

Table 2.7: The table used for the representation of the results of this chapter

3 IP2022 scenario description

For a DSO, one of the difficult aspects of the energy transition is determining the direction the system is transitioning towards. As this direction is highly uncertain, the challenge to prepare the grid for this transition is large. To provide a common ground for DSOs to base their decisions on, Netbeheer Nederland has set up IP2022. This document contains three widely spread scenarios that describe the possible changes in the energy system. These scenarios can help DSOs to determine on a top-level what changes they can expect and can be used to assess and prepare their grids for the resulting operational impact.

This chapter aims to introduce the sources behind the three scenarios and highlight the key assumptions made that influence the fields of this research. Of significant importance are the levels of integration of ETTs, the distribution of large-scale DRG, and levels of electrification. This chapter starts with a description of the sources behind the scenarios. It then expands on several of the important levels and aspects.

3.1. Origin of the scenarios

Every even year, distribution- and transmission system operators have to submit an investment plan to the ACM and, for investments concerning the transmission system, the Minister of Economic Affairs and Climate Policy [33]. In this investment plan, the system operators describe their estimated future operations to keep the capacity of the grid sufficient. However, the assessment of this sufficiency is getting increasingly difficult. The energy transition heavily accelerates the developments in the grid, leading to a more dynamic and unpredictable need for capacity.

To assess the impact of the energy transition on the grid, system operators use several scenarios which represent certain directions to which the system can be transitioning. These scenarios represent the yearly developments of the energy system based on regulatory and political choices. By applying these scenarios to the grid, DSOs can evaluate when and where capacity shortages can be expected and under which conditions these bottlenecks arise.

Until recently, these scenarios were determined by the operators themselves. Since 2021, the scenarios are determined in cooperation. This allows the ACM to better compare the DSOs' performance [27].

The scenarios are simulated and quantified with the Energy Transition Model (ETM) of Quintel Intelligence. This model is built to improve the users' understanding of the challenges of the energy transition. First, it calculates and balances yearly demand and supply quantities for different sectors and forms of generation. The model then provides insight into the corresponding sizing of generation, emission of greenhouse gasses, and import/export of energy carriers such as hydrogen or Green Gasses, gaseous energy carriers mainly produced through digestion of organic biomass or organic byproducts. The scenarios are based on initiatives of the Ministry of Economic Affairs and Climate Policy: the Regional Energy Strategies (RES); a plan entailing information about the future energy system

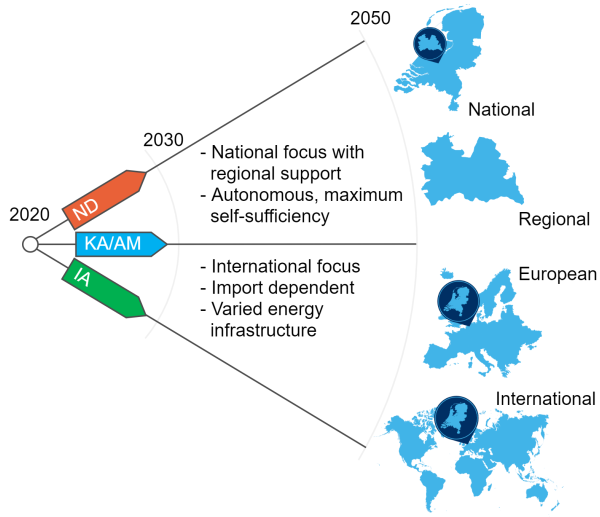


Figure 3.1: The direction of IP2022 to II3050

for a certain RES-region, and the Integral Infrastructure-outlook 2030-2050 (II3050); An outlook on the development of the energy system for 2030-2050. These initiatives originate from the CA2019 [4], the Dutch plan for adhering to the Paris Agreement.

The II3050 scenarios were meant to provide several outlooks on development between 2030 and 2050. For the years up to 2030, the CA2019 was assumed as a common starting point. For the years up to 2030, no official variation of scenarios existed. In IP2022, Netbeheer Nederland provides three scenarios that replace the outcome of CA2019 as a common starting point for the II3050 scenarios [27]. Each of the new scenarios steers the path towards 2030 in the direction of one of the II3050's scenarios; National Drive-scenario (ND) towards II3050's National, International Ambitions-scenario (IA) towards II3050's International-scenario, and Climate Agreement-scenario (KA)[1] towards a combination of Regional and European. [2]

The KA is set as the reference baseline scenario, as it is based on the CA2019 and, therefore, the best quantifiable common scenario. The scenarios ND and IA were introduced as a sensitivity analysis and to demonstrate and provide a wide range of possibilities.

Aside from the three nationwide scenarios, Stedin has created its own Management View-scenario (AM.2021). This scenario is almost the same as the KA scenario but redistributes several targets based on Stedin's research.

3.2. Scenario descriptions

This section describes the scenarios, along with the projected sizing of different forms of generation and consumption levels. First, the scenarios will be defined by their key aspects. The scenarios will then be compared by their projected composition of supply, generation, and storage. The details of AM.2021 will be addressed where they differ from KA. AM.2021 is not defined on a national level.

The KA-scenario is based on CA2019. The goal is set at a minimal greenhouse gas-emission reduction of 49% towards 1990 levels, where the Dutch government agreed to aim for a higher reduction.[3] One of the measures that should help in achieving this is the change in the Gas law ("de

[1] To distinguish between the scenario and the actual agreement, the scenario is abbreviated from the Dutch notation (KA) and the agreement at its English notation and with the year 2019 (CA2019).

[2] Ironically, the Climate Agreement-scenario (KA)-scenario (with a CO_2 reduction of 47%) is the only one that, according to the calculations in the ETM, will not achieve the CA2019 goal of 49%, as already indicated by several sources [46, 59, 60]. IA will exceed the goal slightly with 50% and National Drive-scenario (ND) even closes in on the new European Green Deal [61].

[3] In September 2020, the aiming seemed to have succeeded in the form of the European Green Deal [61] where the European

Gaswet") in 2018, resulting in the obligation for developers to build new buildings without a connection to the gas network (gas-free) [60]. From 2019 to 2021, developers have agreed to build 75% of new housing gas-free. After 2021, all newly built housing should be gas-free and use an alternative source of heating. In this scenario, housing still reliant on gas and gas use in other sectors will be provided by the local and renewable production of green gas.

The ND-scenario guides the development towards 2030 in the direction of the "National governance"-scenario of II3050. Energy independence on a national scale and a circular economy are key focus areas of this scenario. This is achieved by high levels of electrification in the built environment, mobility, agriculture, and industry, leading to an increase in efficiency and electricity consumption but an overall decrease in total energy consumption. The electric energy is primarily provided by DRG. This shows itself in low production of Green Gasses, high penetration of electric HP and overall Power-to-Heat (P2H); a process where electrical power is converted to heat for the storage of energy or addressing heat demand, an overall large battery storage, and high power flexible demand through Power-to-Gas (P2G); a process where electrical power is converted to/stored in a gaseous energy carrier.

The IA-scenario guides the development towards 2030 in the direction of the "International governance"-scenario of II3050. Strong cooperation between countries and continents allows for less energy independence, better allocation of resources, and more substantial reductions in greenhouse gasses. Energy carriers as hydrogen and green gas are essential in this scenario while electrification of, for instance, heating and mobility stays low. Due to the low penetration level of DRG, flexible demand through P2G and storage in batteries is less relevant. The abundance of energy carriers slows electrification and puts focus on hybrid alternatives.

Stedin its own AM.2021-scenario can be expressed as Stedin's view on its share in the national execution of the KA-scenario. It makes minor adaptions on the numbers to better fit the agreement to Stedin's service area.

Commission agreed to aim for a reduction of greenhouse gasses by 55%. However, the effects on relevant legislation and the impact on CA2019 will most likely become apparent after the summer of 2021. At the moment of writing this, the effect of the European Green Deal has not yet been quantified for the Netherlands. The national reduction of greenhouse-gas emissions before 2030 is also not (yet) redetermined by the national government [59].

3.2.1. Supply

All scenarios show increased levels of electrification in supply. ND has a relatively high cumulative installed generation power. This corresponds to its high levels of electrification and a high share of DRG in the mix. KA shows similar levels of electrification for Stedin's service area. However, still significantly less on a national scale. This is filled by higher levels of gas production and capacity. The high level of hydrogen production of the KA-scenario is a byproduct of the use of P2G as a flexibility measure. The production will mainly be used for export and industry and not for power generation.

In line with the current Dutch policy, coal-fired power plants will be phased out in all scenarios and will transition to biomass to a large extent in the years prior. Due to the long development time of nuclear power, the share is estimated to remain constant to that of the current Borssele-plant. Methane-fueled plants (predominately fueled by Green Gasses are expected to take on a prominent role as peak power production plants in all scenarios.

AM.2021 differs from KA in the share of PV. Stedin expects a higher share of generation by residential PV and a lower share by large-scale PV. This is motivated by the anticipated share of new houses to be built in Stedin's service area (~ 31% of new houses nationwide) and the regional strategies' vision on large-scale solar projects in the region.

As AM.2021 only specifies Stedin's service area, no specifications exist on the national scale.

		2020	2030			
Supply	**Unit**	**Ref.**	**KA**	**ND**	**IA**	**AM.2021**
Renewable Generation						
Onshore wind	MW	479	1,064	1,900	882	1,064
PV	MW	1,313	5,000	5,200	2,495	5,246
Large scale PV	MW	100	1,827	1,900	912	1,428
Utility	MW	433	1,827	1,900	912	1,827
Residential	MW	780	1,346	1,400	672	1,991
Biomass (national)	MW	561	600	2,000	600	-
Conventional generation (national)						
Nuclear	MW	485	485	485	485	-
Coal	MW	4,006	0	0	0	-
Methane	MW	18,984	13,622	11,897	12,641	-
CCGT (without CHP)	MW	9,170	6,520	5,967	5,967	-
Gasturbine	MW	280	0	0	0	-
Gas steam turbine (without CHP)	MW	800	800	800	0	-
Large CHP	MW	1,934	1,574	1,574	1,574	-
Small CHP (agriculture)	MW	2,479	2,107	1,735	2,479	-
Small (incl. CHP besides agriculture)	MW	3,321	2,621	2,621	2,621	-
Waste incineration plant	MW	759	782	782	782	-
Hydrogen (H2-fired power plant)	MW	0	0	1,400	1,400	-
Gas sources (national)						
Green gas	PJ	4,000	63,228	12,319	94,436	-
Hydrogen	PJ	176,400	268,400	209,276	294,400	-

Table 3.1: Levels of supply for the different scenarios based on IP2022 [27]

3.2.2. Demand

All scenarios assume an equal amount of residences in 2030. KA and ND both equip high shares of new housing with sustainable heat sources but differ in the amount of 'transformed' residences. ND shows a large number of transformed residences, mainly switching to full electric HP. IA also knows many transformations but mostly towards hybrid solutions (in line with a higher dependency on gas).

In line with the higher heating shares by heat grids, ND shows a large consumption of P2H in the industrial sector. CCS is less significant in ND. This is due to the already high focus on CO_2- and greenhouse gas reduction, and a circular economy. All scenarios show a shift towards electric mobility. Moreover, the levels of electric mobility correspond to those of overall electrification in the scenarios.

		2020	2030			
Demand	**Unit**	**Ref.**	**KA**	**ND**	**IA**	**AM.2021**
Residential sector						
Gas	(x1000)	1561.0	1,397.5	1,207.1	1,204.7	1,396.8
HP full electric	(x1000)	31.0	226.9	312.4	199.5	227.7
HP hybrid	(x1000)	13.5	105.4	70.9	276.1	105.5
Heat grid	(x1000)	142.2	182.8	322.1	232.3	182.7
Service sector						
Gas	%	86%	72%	62%	68%	72%
HP full electric	%	5%	15%	20%	18%	15%
Heat grid	%	5%	8%	14%	9%	8%
Biomass heat production	%	0	5%	5%	5%	5%
Hybrid HP	%	0	0%	0%	0%	0%
Boiler	%	0	0%	0%	0%	0%
Total reduction	%	-	51%	53%	47%	51%
Industral sector (national)						
Datacenters (nat)	GW	-	4.4	4.4	4.4	-
P2Heat (GW) (nat)	GW	-	0.5	4.8	0.8	-
CCS (MT)	MT	0	7.0	3.5	10.0	-
Industry (incl. H2 generation) (nat)	MT	0	7.0	3.5	7.0	-
Power generation (nat)	MT	0	-	-	3.0	-
Transport sector						
Personal vehicles						
EV (battery)	(x1000)	-	317.97	447.15	198.73	317.97
EV (fuel cell)	(x1000)	-	61.11	-	61.11	-
EV work-vehicle	(x1000)	0.62	51.24	76.90	23.46	51.24
Heavy transportation						
Electric city busses	(x1000)	-	1,231.0	1,297.0	1,077.0	1,231.0
Electric city trucks	(x1000)	-	3,643.1	6,921.3	1,730.3	3,643.1
Electric trucks	(x1000)	-	2,560.0	4,314.0	1,111.0	2,560.0
Compressed natural gas-trucks	(x1000)	-	1,154.7	1,154.7	1,154.7	1,154.7

Table 3.2: Levels of demand for the different scenarios based on IP2022 [27]

3.2.3. Storage and conversion (national)

Current/reference levels for 2020 are not well known and not defined in IP2022. Due to the high prices of electrical energy storage and the expectation that these will not drop anytime soon, it is expected that implementation of battery storage will first remain low before rising quickly near 2030. In all scenarios, it is assumed that both residential as commercial batteries will play a role.

ND is the scenario with the most prominent role for electrical storage. Both KA and ND show significant amounts of storage and P2G, corresponding with the need for flexibility due to high levels of intermittent renewable generation. The most prominent role for hydrogen in domestic use is logically set in the IA scenario. As seen in section 3.2.1, the excess generated hydrogen in the KA-scenario is exported.

It is assumed that 10% of the EVs will be connected to provide flexibility through storage at all times. The document has a discrepancy regarding the capacity per EV and the aggregated capacity considering the statement before. This report assumes only a portion (again 10%) of the connected capacity is regarded as controllable capacity. The charging-/discharging-rates (capacity divided by power) for small-scale and large-scale batteries differ: residential batteries are rated at 0.5C, EVs at 0.08C, and large scale systems at 0.25C.

The II2022 report highlights that the integration of residential batteries is highly uncertain. However, the integration of small-scale batteries, V2G-charging and -discharging, and large-scale storage near variable distributed generation may mitigate many of the challenges that are central in the scenarios.

		2020	2030			
Storage and conversion (national)	**Unit**	**Ref.**	**KA**	**ND**	**IA**	**AM.2021**
Batteries	GW		8.3	15.4	2.6	8.3
Residential storage	GW	-	2.5	5.0	1.3	2.5
Residential storage	GWh	-	5.00	10.00	2.50	5.00
V2G-storage	GW	-	0.8	1.1	0.5	0.8
V2G-storage	GWh	-	0.96	1.3	0.60	0.96
Large scale storage	GW	-	5.0	9.3	0.8	5.0
Large scale storage	GWh	-	20.00	38.0	3.20	20.00
P2Gas	GW	0	3.50	5.0	1.00	3.50
Hydrogen (National)	PJ	0	268.4	209.3	294.4	-
Residences (H2) (National)	PJ		-	-	2.0	-
Residences (H2) (Stedin)	PJ		-	-	0.3	-
Mobility (H2)	PJ	0	20.0	-	20.0	-
Industry (feedstock) (H2)	PJ	162.0	162.0	139.3	162.0	-
Industry (energy) (H2)	PJ	0	-	20.0	50.0	-
Generation (H2)	PJ	14.4	14.4	50.0	50.4	-
Export (H2)	PJ	0	72.0	-	10.0	-

Table 3.3: Levels of storage and hydrogen usage for the scenarios based on IP2022 [27]

4

Analyzing for root-causes

Chapter 2 resulted in an overview of the different operational problems that can arise as a result of the energy transition. The scenarios of Chapter 3 can help DSOs to determine on a top-level what changes the DSO can expect. However, it does not indicate how these changes translate into when and where the actual bottlenecks will arise. This requires a projection of the scenarios on the DSO's grid while considering, among others, its topology and social-geographical data.

In this chapter, the problems are further analysed by projecting the scenarios of Chapter 3 to actual grids in Stedin's service area using Stedin's grid analytic tools. The goal of this analysis is to get a better understanding of the root causes behind the problems identified in Chapter 2 to answer the following research question:

What are the root causes behind operational problems in the distribution grid and how can these be used to categorise the problems in the context of applying flexibility?

The first section consists of an analysis of Stedin's toolbox for analyzing the operational properties of its grid. First, this section describes the different tools, their benefits, and their shortcomings. Following, it proposes a combination of the tools to better assess the impact of the different scenarios for the energy transition on Stedin's grid. For this, a link between Stedin Energy Transition Impact Assessment Model (SETIAM) and grid analytic tools, Gaia and PowerFactory, is constructed.

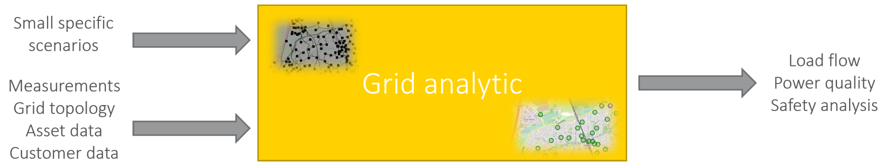
The second section describes the models that are created to perform the assessment. The results of this model are validated in the third section using static verification, face validation, and referencing to the actual grids. In the last section, the results of the LV and MV grid models are analysed and referenced to the results of Chapter 2.

4.1. SETIAM and grid analytic-tools

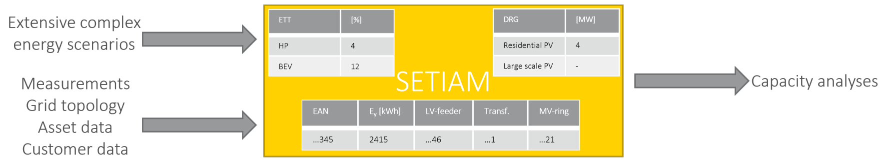
In this section, the different tools used in this project are introduced. They are provided with a background of their functionalities and shortcomings in determining the impact of the energy transition on the distribution grid. Finally, in the last subsection, the functionalities are combined to provide the model used in this analysis.

4.1.1. SETIAM

As the name suggests, Stedin Energy Transition Impact Assessment Model (SETIAM) was created to assess the impact of the energy transition on Stedin's distribution grid. For this, the model uses a probabilistic approach to combine information on the system users, social demographic data, grid topology, and grid assets with complex future scenarios as in Chapter 3 to perform capacity analyses (see: fig. 4.1b). The social demographic data ranges from the geographical classification of the location (e.g. level of urbanization, population density) to social aspects on a generalised neighborhood or city level (e.g. average level of income per household, percentage of households with driveways).



(a) Grid analytic tools



(b) SETIAM

Figure 4.1: Data flow and use of grid analytic-tools

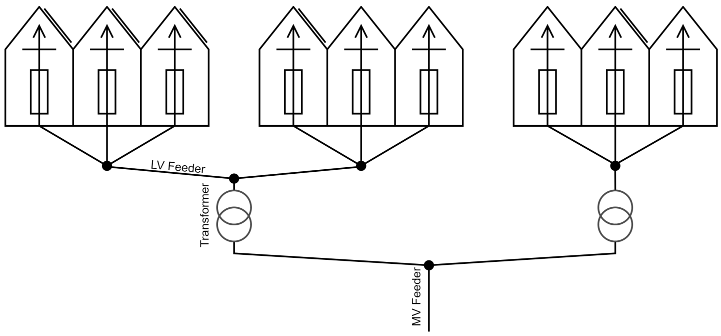


Figure 4.2: Example of SETIAM's radial power flow analysis

The scenarios provide a quantification of several key aspects of the energy transition. These include the projection of efficiency, growth factors, the demolishing and construction of new housing, and integration of key ETTs such as DRG, EV, and HP. SETIAM compiles a combined load and generation profile of all system users based on the modelled presence of ETTss, their annual consumption or historic profiles, and the efficiency and growth factors. These profiles are added for all system users that are connected 'behind' a grid asset, according to the radial topology as shown in fig. 4.2, to create the future loading profiles of upper-grid assets. SETIAM is solely equipped to model congestion in the form of thermal capacity regarding only active power levels. The other problems of the energy transition, as shown in the overview of table 2.7 are not taken into account.

4.1.2. Grid analytic-tools

Aside from SETIAM, the measurements, grid topology, asset data, and system user data are also used in grid analytic tools. In its common daily usage, the tools are mostly used to analyse (expansions of) current grids. These tools perform actual load flow calculations, providing much more information on the state of the grid. Firstly, this makes these tools more suitable for meshed grids, as are common in the Netherlands. It also provides the possibility of assessing changes in topology. Secondly, aside from the capacity of the grid, these tools can also determine aspects relating to the power quality and several of the found safety aspects.

The grid analytic tools use the same source of grid topology data as SETIAM, where the levels of loads and generation are based on the most recent available historic measurements. These measurements are applied as extreme values or measured load profiles, depending on the software used and the availability of information. For residential connections, for example, detailed profiles are usually not available due to privacy constraints. Here, minimum and maximum loads are constructed from the yearly consumption using Strand Axelsson-load flow analysis.

Stedin uses different types of software for different levels of its distribution grid, as seen in fig. 4.3. These tools contain, but are not limited to, the following functionalities:

- **Asset overloading**, capacity constraints of the assets in the form of current flows.
- **Nodal voltages**, the voltages at nodes (connections, junctions between cables) both absolute as relative to the feeding voltage (transformer).
- **Touch hazard voltage**, the danger of unsafe touch voltages in events of faults.
- **Short circuit current**, the currents in the event of a short circuit.
- **Voltage stability**, the effects on nodal voltages as a function of a load change (short term, flicker) and long term variations.
- **Voltage asymmetry**, both as a function of phase and magnitude.

4.1.3. Combination

SETIAM can be separated in a data acquisition, preparation and processing-part and an analysis-part. The latter part is one where significant benefits can be achieved through using the grid analytic tools instead of the radial addition. This idea is not new, Stedin has identified the shortcomings of using both tools separately and the possible benefits and insight of combining the tools. Initiator in this field is the department of “Netstrategie” (Grid Strategy), the department of Stedin that determines the guidelines of grid requirements, investment, and planning for the future. Out of the three tools, Grid Strategy has chosen PowerFactory because of its span over the MV and IV level.

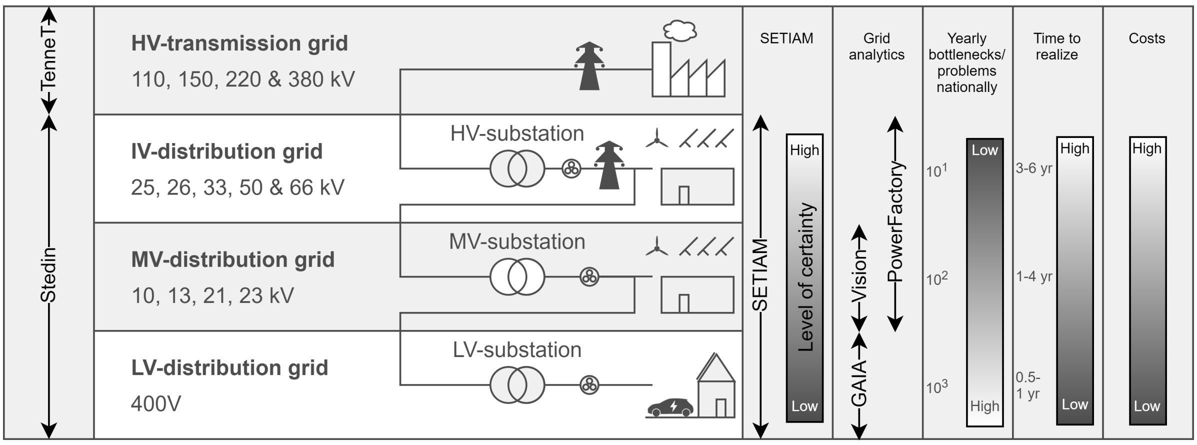


Figure 4.3: Different grid levels with different characteristics and modelling tools [26, 62]

At the moment, there is no integration of the prognoses of SETIAM into the grid analytic tool focusing on the LV-grid, Gaia. The reason for excluding this software from the analysis originates from the level of uncertainty of the data in SETIAM.

If a certain scenario is pursued, it means that the quantities of ETTs and CO_2 reduction set will have to be met on a national scale. Assuming that this has a high priority and all necessary actions are taken to meet this objective, these quantities have a high certainty of being met. The share that Stedin’s grid will need to facilitate depends on, for example, the share of the total national number of residents, locations for large scale renewable generation, and the presence, intensity, and location of certain industrial sectors. As these cannot be predicted with high accuracy for the future, the certainty of predictions starts to decrease. The quantities will then again need to be distributed over Stedin’s service area, again decreasing the certainty of the predictions.

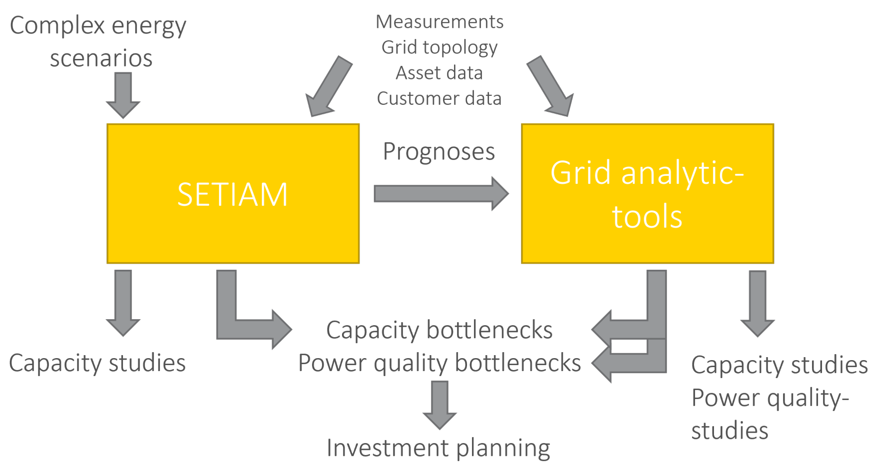


Figure 4.4: Combination of grid analytic and SETIAM

The decrease of certainty not only portrays itself in different geographical levels but also in the distribution levels of the grid. As seen in fig. 4.3, the certainty decreases with every grid-level because of the increased amount of made assumptions and decisions based on slight differences in probabilities. Due to the data-intensive approach and derived probabilities, the certainty on a city-wide level is arguable but definitely defensible. However, because of the generalization of households on a neighborhood level, the certainty of the exact distribution of technologies per connection is very low.

The location of changes in consumption or generation in a grid topology has a significant impact on load flow analysis. Because the certainty of the changes for specific locations in LV grids based on SETIAM are very low, the results of load flow analysis should not act as the basis of the investment. However, this does not serve as a problem because information on this level is not of great importance for DSOs. Because of the short lead times, low impact, and low costs of LV renovations and expansions, the need for predictability and proactive reinforcements is much lower. Instead, the yearly amount of bottlenecks and problems requires standardised solutions that can be quickly applied. However, as SETIAM considers social and geographical factors, its projection of the scenarios can help identify what phenomena and bottlenecks are to be expected in similar grids.

An example of this is the integration of PV. It is generally seen that there are higher levels of PV integration in areas with lower address density (rural areas). Because areas with lower address densities are likely to include longer distribution lengths, a consequence is that rural areas often experience more voltage stability problems (*see:* section 2.5.1). Following the literature, the integration of similar levels of PV on both rural and urban grids will likely demonstrate more severe problems in rural grids. However, SETIAM's distribution could increase the extent to which problems would be experienced in rural grids against urban grids due to the relatively higher levels of integration.

Because of the level of aggregation provided by the distribution transformers, SETIAM can already provide more certain calculations for the MV grids than in the LV grids. Because of this higher certainty, SETIAM is already being used as an indicator for reinforcements in MV-grids. This same certainty translates to modelling the MV grids using the combination of SETIAM and grid analytic tools. For IV and MV grids, fig. 4.3 shows fewer bottlenecks with higher predictability, costs and realization-time than for LV grids. Therefore these problems are more likely to receive individual attention.

4.1.4. Conclusion

The combination of SETIAM and the grid-analytic tools expands on SETIAM's current capacity analysis by also determining the minimum and maximum node-voltage levels, cable-segment overloading, reactive power levels, and voltage asymmetry. As indicated by the department of Grid Strategy, this can provide an additional indicator for investment planning. For LV grids, the functionality is limited by the uncertainty of the distribution. Therefore, this functionality does not allow for actual use in investment planning. However, its result can help identify what phenomena and bottlenecks are to be expected in similar grids. This observation regarding the uncertainty of distribution holds for LV grids, but the effect of decreased certainty with lower voltage levels should be noted in general.

By combining the insight SETIAM provides in the projection of the scenarios on Stedin's service area with the grid analytic tools their extensive functionalities, the insight into future problems for Stedin's service area can be increased.

4.2. Models

In the previous section, the shortcomings of the individual impact assessment tools are described and the benefits of combining the tools are highlighted. This section introduces and describes the combined application of SETIAM with two sets of software, Gaia for LV grids and PowerFactory for MV grids. For both tools, a script is developed integrating the data from SETIAM into load and generation profiles to assess the impact of the different scenarios on thermal capacity and voltage dips and swells. The following section describes the result of these models.

4.2.1. LV-grid modelling

The modelling of LV grids using the distribution provided by SETIAM can provide insight into the problems that are likely to arise for certain grid characteristics. One property on which this section focuses and I believe can work as an indicator is the Address Density (AD) in addresses/km^2 (denoted in Dutch as 'Omgevingsadressendichtheid' or 'OAD'). The goal of this model is, therefore, twofold:

- **Demonstrating increased problems due to the energy transition**, on the following aspects:
  - **Asset overloading**, capacity constraints of the assets in the form of current flows.
  - **Connection voltages**, the voltages at connections as relative per distribution 'level'.
- Proving the hypothesis that **the address density can act as an indicator to which problems can be expected due to the energy transition**.

For these goals, a script was set up that exports the distributions of SETIAM on the LV connection level and imports these properties in Gaia. The script is made to include the four main ETTs in the LV grid models, HP, EV, PV, and EC, and to correct the annual consumption of the connection for the efficiency and consumption trends of the scenario. The latter influences the power draw of the connection through Gaia's Strand Axelsson calculation.

The approach to look at relative voltage deviations instead of only absolute values (as is indicated by the Netcode) is derived from [63] and is also used by Stedin when designing new grids. This approach uses key figures for the share of the voltage drop or rise over different distribution 'levels'. These key figures are shown in fig. 4.5. The share of the voltage deviation towards its nominal voltage is evaluated for each of these 'levels'. This decomposition can be used to derive and categorise what actions can be taken to solve the problem.

Because of the need for a generalised approach, due to a large number of bottlenecks as described in section 4.1.3, multiple grids are selected in the model. A qualitative analysis follows the second goal to determine if a categorical approach based on other characteristics can be used to assess possible solutions for the encountered problems.

The data of SETIAM itself is provided with several assumptions in its 'disclaimer'. Some assumptions are expected to affect the validity of the model; these are mentioned in table 4.1. A significant difference is that where SETIAM uses hourly profiles over a whole year, Gaia is limited in the number of calculations that can be done. Because of this, Gaia only calculates two scenarios: 'Noon' (100% generation, 30% load) and 'Evening' (0% generation, 100% load).

The script includes several actions taken to limit the effect of some of the assumptions made by SETIAM and assumptions made to convert the data of SETIAM for use in this model. Table 4.2 describes the differences between the model in Gaia and that in SETIAM and their impact. A more extensive

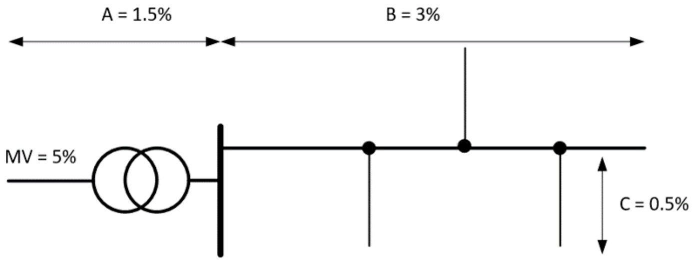


Figure 4.5: Relative voltage drop or rise per distribution level

Aspect	Assumption	Effect
Distribution of ETTs in general (3-7)	Currently known distribution of HPs, EVs and EC is unknown. Low certainty of exact integration on LV level. ETTs are distributed by a function that determines a probability per year, per connection. The highest probabilities are filled until the cumulative target is reached	+/−
HP	Heating power is based on historic gas usage.	−
EC (5)	EC is only installed if a connection switches from a gas-connection to a different source of heating.	−
EV (7)	Battery EVs and Plug-in Hybrid EVs are distributed according to a constant share. 58% of all EVs is a Plug-in Hybrid EV	0/−
Large DRG (9)	Large DRG is assigned based on RES, local subsidy requests and scenario data	+/−

Table 4.1: Assumptions made in SETIAM and their effect on the outcome of the model.

description can be found in appendix A, where the numbers mentioned under the 'Aspect'-column correspond with the numbering in the appendix.

Both in table 4.1 and in table 4.2, the effect columns indicate the level of expected increased problems. A zero indicates that this assumption or change is regarded to approach reality optimally. A positive or negative represents an assumption or change that was made due to the limitations of the software and indicates an expected increased (+) or decreased (-) level of modelled problems compared to reality.

4.2.2. MV-grid modelling

PowerFactory allows for the use of hourly profiles. This allows for the quantitative assessment of the yearly frequency and duration of overloading and thus points towards the amount of energy that would have to be additionally generated, used, shifted, or omitted. As mentioned in section 4.1.3, different factors lead to a less generalised approach for bottlenecks or problems as used in LV grids. Only one grid is included in this model which will be evaluated using a more qualitative approach.

- **Demonstrating increased problems due to the energy transition**, on the following aspects:
  - **Asset overloading**, capacity constraints of the assets in the form of current flows.
  - **Nodal voltages**, the absolute voltages at nodes (distribution transformers and customer connections)
- Proving the hypothesis that **the address density can act as an indicator to which problems can be expected due to the energy transition**.

Aspect	SETIAM	Effect	Gaia	Effect
PV (10)	Mismatch in currently installed PV in comparison to data in the Geographical Information System	+/-	Uses the Geographical Information System for currently installed PV	+/-
PV (11)	Peak value in combination with profile.	0	Maximum AC-output.	0
Gen. consumption (12)	Annual consumption in combination with profile.	-	Peak power draw from Strand-Axelsson	0
EC (13)	Implemented as a correction of the annual consumption.	-	Implemented as a nominal power draw based on observed key figures.	0
Hybrid HPs (14, 17)	Thermal power, electrical load profile based on annual gas usage and HPs's Coefficient of Performance (COP). Continuous share of heating.	+/-	Electric power, observed key-figures. Low contribution to peak load-scenario due to hybrid operation.	0
Full electric HP (16, 17)	Thermal power, electrical load profile based on annual gas usage and HP's COP.	+	Electric power, observed key-figures.	0
Private EVs (15)	Present/not present, probability distribution for “switched on” capacity per time-frame	-	Present, installed capacity, and “switched on” capacity based on simultaneity-factor and power of connection.	0
Public EVs (15)	Number of daily charging operations, probability distribution for “switched on” capacity per time-frame. Assigned to LV-feeder.	0	Present, installed capacity, and “switched on” capacity based on simultaneity-factor. Assigned to pseudo-random households.	0
New buildings (16)	Implemented according to connections on feeder	0	Not implemented.	-
Type of connection (18)	Irrelevant, no observation in this level.	0	Changed according to heat pump or PV-installation	0
Reactive power (19)	Irrelevant, no observation	0	$\cos\varphi$ is assigned according to common specifications.	+/-

Table 4.2: Assumptions made in SETIAM where counteracting measures in Gaia are taken.

SETIAM's aggregation of load profiles 'behind' the distribution transformers is assigned to the transformers in the network. Due to the prospected increase of DRG and high power EV-chargers (e.g. fast-chargers, public transportation depots, electric truck-chargers), many new connections are expected in the upcoming years, playing a large role in the overall loading of the MV-substation. It is therefore important to include these connections in the analysis. SETIAM bases the new connections on several sources as shown below.

- Granted subsidy-applications (PV, wind-turbines).
- Transport Indication (the step before a subsidy request) which show an arbitrary level of certainty (PV, wind turbines).
- Loads and generators specified by the area manager (general loads, general generators, PV,

wind turbines).

- Loads and generators included in RES, taken into account the scenario (general loads, general generators, PV, wind turbines).

- EV-chargers specified by Elaad, a partnership of Dutch DSOs for researching EV integration, taken into account the scenario (e.g. high power fast-chargers, public transportation-depots, electric truck-chargers).

Depending on the rated power of the technology, the new connection is either made by adding a new distribution-station (175 kVA-1.75 MVA) or by connecting to the MV-substation (1.75MVA-10 MVA[1]). The first three sources represent connections with a relatively high certainty that are included over all scenarios. The latter two depend on the quantities set in the scenarios and, therefore, differ among scenarios.

SETIAM's assumptions mentioned in table 4.1 also hold for the MV-domain. Aside from these, additional information was added to transfer SETIAM's data to PowerFactory. These changes are noted in table 4.3. A more extensive description can again be found in appendix A.

Aspect	SETIAM	Effect	PowerFactory	Effect
Topology (20,21)	Assuming a radial power-flow where technologies are assigned to feeders	+/-	Using the actual, possibly looped/meshed, topology where technologies are assigned to nodes	+/-
Information mismatch (20)	Information is actualised at a certain point in time	0	Information is actualised at a different point in time, requiring intermediate changes to be checked (both automatically and manually)	0
LV corrective action (23)	Several assumptions that seem improbable	+/-	Changes made in the LV model as counteracting measures to these assumptions are not transferred to the MV model	+/-
Reactive power (24)	Irrelevant, no observation		$\cos\varphi$ is assigned according to common specifications	+/-

Table 4.3: Assumptions made in SETIAM where the model in PowerFactory differs.

4.3. Correctness of the model

Evaluating if a model correctly represents a system is an important aspect of modelling, as it assures the modeller of the validity of the results derived from the model. This correctness consists of two aspects, Verification and Validation (V&V). The goal of the V&V is to evaluate the correctness of the modelled effect of different integration levels of energy transition technologies on distribution grids.

In this section, the concept of V&V is explained and applied to the models of this chapter. After highlighting several notions to explain why alternative V&V approaches are necessary, the concept is performed using 'Static testing' and 'Expert opinion'.

[1] 10 MVA is the upper level for a 10 kV grid as the MV grid in this model. This upper limit differs for different voltage levels.

4.3.1. Verification and Validation

V&V is an important step in the modelling process. Verification means evaluating if the model does as it is created and documented. The verification aspect evaluates if the model includes the assumptions and decisions that were noted and models the outcomes that were intended to be modelled. Validation means evaluating if the model's output under certain input conditions provides a reasonably accurate representation of the actual system.

Validation is generally best performed by comparing the model's outcome under certain input conditions to an actual system under the same input conditions. In these models, this would consist of two parts. The first is the validity of the grid models in PowerFactory and Gaia. This relates to the correct implementation of the technical properties of the DSO's assets in the modelling software and the validity of the modelling software. The grid models and the software can be validated using real-life measurements of current-flows and voltage distributions. The second part entails the correct implementation of the ETTs and its technical properties to assess their effect on the grid. This would again require real-system measurements, this time of one or several households of varying types and sizes, including varying levels of ETTs.

Unfortunately, measurements of these kinds were not available for both the LV grid as for a large part of the MV grid. Measurements of the LV-grids were unavailable due to privacy restrictions. Measurements of MV grids are not yet readily available, as Stedin is currently still integrating these meters on a large scale. Several case studies and pilots have been performed where measurements of ETTs have been collected to gain key figures on the impact of these technologies on Stedin's grid. However, as the values used in the models are, among others, based on these sources, validating them along these would be meaningless.

As mentioned under section 2.3, the individual behaviour has a large impact in the case of large consumers and generations. This is also the case with the energy transition technologies; their collective influence is relatively high compared to the current general loading of the grid. Also, because of the weather dependency of DRG and HP, it would be very improbable (or impossible) that any measured profiles would exactly match with the model. The validation is therefore proposed to focus on performance indicators instead of profiles. Examples of such values are:

- Minimum and maximum node voltage deviations in respect to the transformer
- Branch (transformer or feeder) loading-levels

It should be noted that it was not the intention to test these real system applications on the outcomes of the scenarios. Exact validation of the scenarios based on actual integration is not possible because of a combination of factors. As the scenarios are defined as the equivalent of "corner flags of the playing field" of the energy transition [27], they themselves do not depict absolute paths that need to be followed. It would be of no use to validate existing grids to any of them as the result would be meaningless. Secondly, even if a certain scenario would be followed on a national scale, the uncertainty of the distribution of technologies at the LV level will render the validation useless for this specific purpose.

Because of the lack of real system measurements and the other reasons shown above, these models are validated using alternative approaches.

4.3.2. Alternative validation methods

To still evaluate the correctness of the results of the model with sufficient accuracy, I've looked at several aspects with which the results of this model could otherwise be verified and validated. For this, the thesis of El Mir [64] provided a comprehensive overview of several possible methods. As a result, the following methods were identified as possible verification methods and possible validation alternatives to real-life validation:

Static testing is a verification method used to verify if the functionalities of a model sufficiently capture the aspects of the conceptual model. It is performed by analyzing the data flow of the model and evaluating the in- and outputs of sub-functions, separately and/or as a whole. In a way, it can be a sub-application of ”Face validity” (next method) that focuses on verification.

Face validity, otherwise known as ”Expert opinion”. The model itself cannot be validated using real-life data from the application it is modelling if this data is not available. Validation through Face validity includes one or several experts examining the model and its outcomes based on their knowledge and expertise of the modelled subject. The levels to which the validation is performed can range from solely reviewing the outcomes for a certain input (solely validation) to the complete flow of data in the model on a programming level (validation and verification). This depends on the extent of the application. Other validation techniques that can provide additional insight for performing Face validity are ’Graphical displays’: graphically representing outcomes; and ’Static testing’: verification of (individual) model functions.

Sensitivity analysis acts to validate the relations between input and outputs of the model. It relates the changes in inputs to the changes in outputs and compares them to real-life application relations. Thus, sensitivity analysis can provide insight into the validity of a model in combination with an expert opinion or real-life data.

Comparison to other models is a validation technique that determines the validity of another model (reference model) to be sufficient to represent a real-system case. The model to be validated is then validated to the ’real system’, which is represented by the reference model. This technique, to a certain degree, ’assumes’ validity of the reference model. This assumption can be based on promises by the supplier of the model or a performed validation based on data that is or was only available to the supplier of the reference model. However, the validation of the new model stands or falls with the validity of the reference model. If the new model replaces the reference model or if the reference model acts as a benchmark in this field of modelling, the comparison is also called a ”benchmark test”.

Extreme input validation means running the model with impossible or improbable input parameters to determine the robustness of the model. The model’s output under these input parameters should still correspond to a likely outcome if the input conditions were real. This type of validation is essential in highly complex models with multiple reactive elements. Complexity is defined as the extent to which sub-functions interact, making the outcome of the whole different from the ’sum’ of its individual parts (holism versus reductionism). The level of complexity in this model is not as such that it is fit for this type of validation.

4.3.3. Final verification

For verification of the model, ’Static testing’ in combination with ’Expert opinion’ is used. The model will be separated into functions and steps, which colleagues with corresponding fields of expertise will evaluate.

LV-grid

- The assumptions regarding the transformation of the data of SETIAM in loads or generation in the LV-model are evaluated by a member of the Grid Strategy department responsible for the strategy of new LV-grids.
- The functions that transform the data of SETIAM in loads or generation in the LV-model are evaluated by an engineer of SETIAM.
- The integration of the LV-model in Gaia is evaluated by an engineer of the Grid Analytic-team.

MV-grid

- The functions that map the data of SETIAM in loads or generation in the MV-model are evaluated by an engineer of SETIAM.
- The integration of the MV-model in PowerFactory is evaluated by the area manager of the MV-grid.

4.3.4. Final validation

Due to the unavailability of real-life data for the LV-grid, the model is validated by a combination of ”Face validation” using graphical displays and ”comparison to other models”. Colleagues with corresponding fields of expertise will perform the face validation. ’Comparison to other models’ refers to the fact that the models describing the physical grids are built in reputable software, of which their ability to represent reality properly is supported and trusted by senior engineers and specialists. Furthermore, this and other software from this range have been used as benchmarks for new applications and are therefore regarded as sufficiently accurate to perform these calculations.

The outcomes of the **LV-grid** model under provided input conditions are validated by a member of the Grid Strategy department responsible for the strategy on renovating existing LV grids.

The outcomes of the **MV-grid** model under provided input conditions are validated by the area manager of that MV grid.

4.4. Results from modelling

4.4.1. LV-grid modelling

The twenty LV-grids in the MV-grid of Houten that were chosen are shown in fig. 4.6. The grids are chosen based on the availability of a Gaia-model and a varied distribution of AD, from 36 to 2347 addresses/km^2. The four different scenarios of Chapter 3 will act as excess measurement while also providing a certain indication of sensitivity.

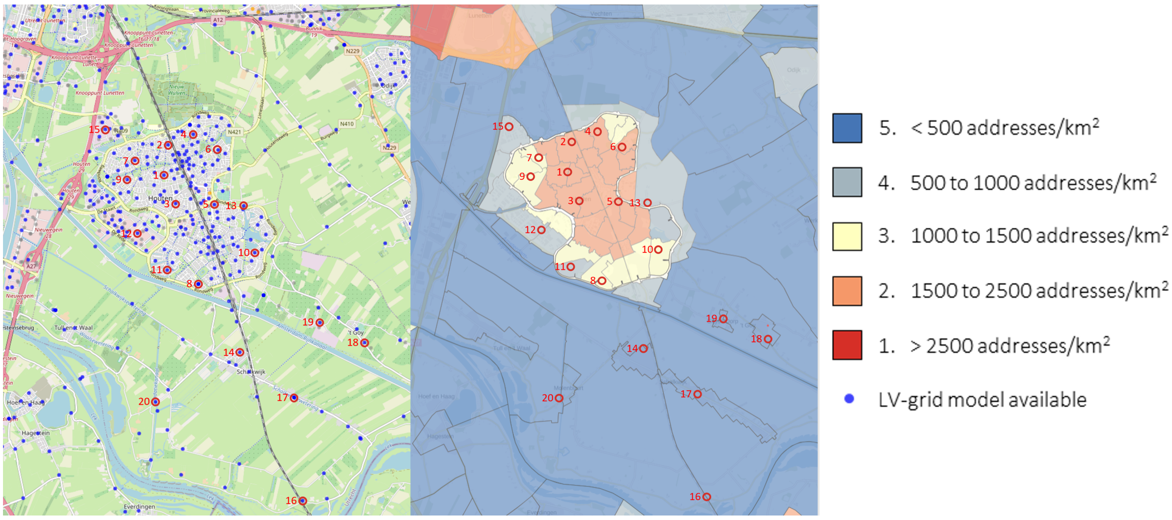


Figure 4.6: Overview of MV-grid of Houten and the twenty LV-grids used in the analysis.

Table 4.4 indicates the increased encountered problems due to the energy transition. Overall, the problems demonstrate themselves among all assets, either in voltage or capacity problems. Due to a relatively low loading in the base scenario, cable loading is relatively safe even though the increase in loading is relatively high for both ’Evening’ as ’Noon’. However, both scenarios show that voltage problems over the cables are significant. Transformer loading was already quite high, especially in the evening, resulting in quite a lot transformer-related problems. The share that reactive power plays in these problems is also clearly visible. Where generation operates at unity power factor, consumption (overall, but especially generic consumption and heat pumps) operates at a slight inductive factor. This increases the encountered voltage deviations for consumption. This is especially prominent on Level A, the transformer, in comparison to Level B, the cables. This is because the transformer has a relatively low R/X-ratio in comparison to the cables used. Only a few connections are in violation due to the voltage drop over the connection cable.

		Noon			
Voltage	**-**	**AM.2021**	**IA**	**KA**	**ND**
- Transformers in violation (A)	8%	8%	2%	3%	3%
- Nodes in violation (grid) (B)	20%	18%	6%	14%	15%
- Nodes in violation (connection) (C)	1%	1%	1%	1%	1%
Capacity					
- Cable loading increase	89%	130%	42%	97%	87%
- Cables overloaded	3%	2%	1%	2%	2%
- Transformer loading increase	90%	127%	44%	93%	97%
- Transformers overloaded	11%	11%	2%	10%	10%
		Evening			
Voltage	**-**	**AM.2021**	**IA**	**KA**	**ND**
- Transformers in violation (A)	32%	27%	27%	29%	32%
- Nodes in violation (grid) (B)	24%	17%	14%	17%	22%
- Nodes in violation (connection) (C)	2%	1%	0%	1%	1%
Capacity					
- Cable loading increase	51%	53%	37%	48%	64%
- Cables overloaded	2%	2%	2%	2%	2%
- Transformer loading increase	27%	27%	21%	26%	34%
- Transformers overloaded	17%	14%	13%	13%	17%

Table 4.4: Overall results of the LV-modelling, divided into capacity and voltage problems relative to the design policy.

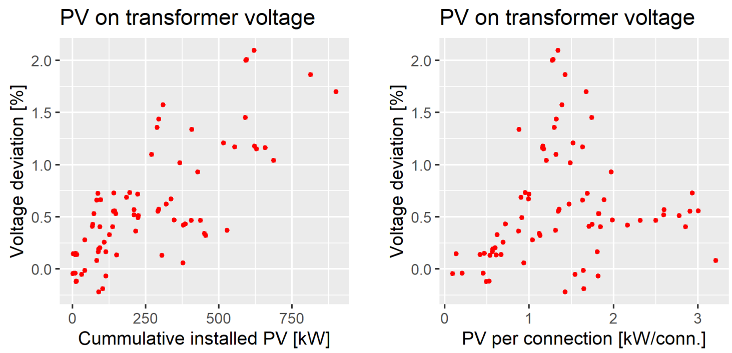
In this analysis, one of the LV-grids is excluded. This entire grid is located in a neighborhood specified by Stedin to transfer to full electric HP SETIAM, with according changes to the grid. This specific grid was already on the verge of overloading, and after this transition, the simulation represented an extreme outlier. As outliers can significantly influence the outcome of a correlation analysis, this specific case was excluded.

		Noon			
	Voltage	**AM.2021**	**IA**	**KA**	**ND**
A	- Transformers voltage deviation	0.30	0.24	0.26	0.30
B	- Nodes voltage deviation (Grid)	0.15	0.03	0.11	0.11
C	- Nodes voltage deviation (connection)	0.11	0.03	0.08	0.08
	Capacity				
D	- Maximum loading of cables (abs.)	0.30	0.15	0.26	0.24
E	- Transformer loading increase (rel.)	-0.43	-0.33	-0.40	-0.41
		Evening			
	Voltage	**AM.2021**	**IA**	**KA**	**ND**
A	- Transformers voltage deviation	-0.05	-0.08	-0.10	-0.08
B	- Nodes voltage deviation (grid)	0.03	0.02	0.00	0.00
C	- Nodes voltage deviation (connection)	0.11	0.08	0.10	0.08
	Capacity				
D	- Maximum loading of cables (abs.)	0.09	0.14	0.13	0.15
E	- Transformer loading increase (rel.)	0.08	0.11	0.12	0.11

Table 4.5: Correlation between the encountered problems and the AD

The levels of correlation between the AD and the encountered problems are shown in table 4.5. A red marking indicates a low statistical significance (p-value > 0.05). Especially for the 'Evening'-scenario, the correlation between encountered problems and the address-density as well as its statistical significance are very low.

The overall correlations observed for the noon scenario are significantly higher. Overall, this table indicates that with increased AD or increased urbanity, the power flows of transformers are negatively



(a) Cumulative per grid

(b) Average installation per connection

Figure 4.7: Correlation between PV and grid transformer voltage deviation. Cumulative per grid vs average installation per connection. Cumulative shows a positive correlation of 0.76, average of 0.16.

influenced (decrease and/or become negative) and node- and transformer voltages deviate positively. Both indicate higher loading due to distributed generation, indicating an increased level of problems in urban instead of rural areas. This is unexpected but can be explained and does not necessarily contradict with earlier found information.

A qualitative approach showed that the installed PV power per household has a negative correlation with AD where cumulative installed power per grid has a positive correlation. As can also be seen in table 4.6, the correlation between, for instance, voltage deviations in the category B and C of the nodes and ETTs, in general, is quite low. When higher levels of aggregation are achieved (e.g., transformer), increased effects start to show. These high cumulative levels were only rarely reached in rural areas.

Large PV installations connected at the LV grid (up to 175 kVA) were scarcely present in this analysis. The overall integration of large generators in the LV grid by SETIAM can be called conservative. Installations over 10 kWp are scarce. Of over two million connections, only a thousand have installations above 20 kWp, decreasing to fifty above 30 kWp. Installations on top of barns or on former agricultural land, as are prominent in Dutch rural areas, often exceed 175 kVA, requiring a connection to the MV grid.

Another approach to explain this finding is the share of the voltage deviations from the MV grid. Analysis of the rural grids in this model shows that the types of main LV feeders in these areas are often no different from those used in urban areas, only significantly less loaded. These feeders were also not significantly longer than those in urban areas. If this is, however, evaluated for the MV grids, the rural areas have significantly higher shares of small intersections and longer cables.

Several high correlations between ETTs and the encountered problems, shown in the table 4.6, stand out. Especially the relations indicated between PV and the 'Evening'-scenario and the those between HP and EV and the 'Noon'-scenario. These correlations are analysed using the installed power of the ETTs, which is highly cross-correlated among ETTs. This can be explained by the relation between a large rooftop area (larger PV), a larger house to heat (larger HP), and room for a driveway (private EV). Even though PV is not switched on in this scenario (generation is at 0%), the installed power is still assigned to the connection.

Overall, the goal of this model is partially achieved. In all scenarios and grids, overall loading and voltage deviations increased for the future, even though overall loading through general consumption decreases. For the loading through consumption, the overall correlation between the AD and encountered problems was low and statistically insignificant. However, for the noon scenario, a significant correlation was found, indicating that urban areas are likely to encounter increased problems due to DG in the LV grid compared to rural areas.

		Noon		
	Voltage	**PV**	**HP**	**EV**
A	- Transformers voltage deviation	0.76	0.30	0.26
B	- Nodes voltage deviation (grid)	0.12	-0.01	0.01
C	- Nodes voltage deviation (connection)	0.15	-0.16	-0.07
	Capacity			
D	- Maximum loading of cables (abs.)	0.62	0.41	0.33
E	- Transformer loading increase (rel.)	-0.71	-0.49	-0.31
		Evening		
	Voltage	**PV**	**HP**	**EV**
A	- Transformers voltage deviation	-0.42	-0.85	-0.38
B	- Nodes voltage deviation (grid)	-0.02	0.02	-0.14
C	- Nodes voltage deviation (connection)	-0.11	0.01	-0.51
	Capacity			
D	- Maximum loading of cables (abs.)	0.53	0.43	0.65
E	- Transformer loading increase (rel.)	0.45	0.74	0.45

Table 4.6: Correlation between ETT and encountered problems, divided into capacity and voltage problems relative to the design policy.

4.4.2. MV-grid modelling

The MV model is applied to the MV-grid of Houten for the four scenarios of Chapter 3. This is the same MV-grid as the one that includes the twenty LV-grid of the previous model. The overall layout of the grid, presented in fig. 4.8, shows the high geographic diversity. Corresponding findings in section 2.5.1, low address density shows longer intermediate distances and a lower station density.

The grid will be evaluated through a quasi-static load flow analysis along with similar performance indicators as the LV-grids.

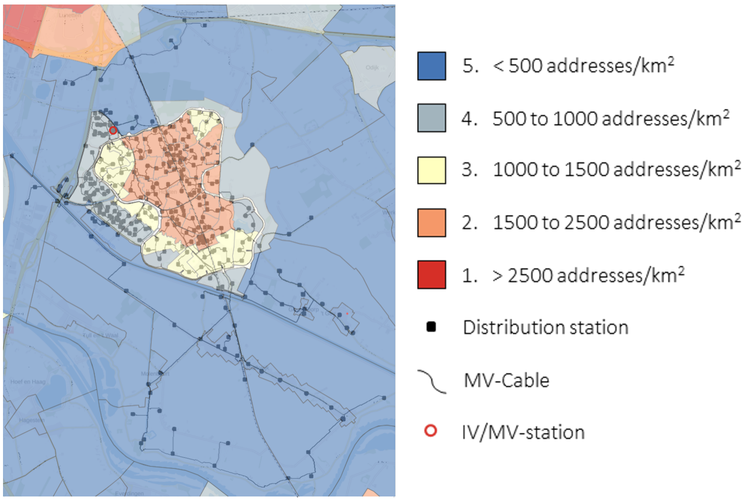


Figure 4.8: Map of the MV-grid of Houten with address density

The IV/MV transformer is fitted with an automatic tap-changer to regulate the voltage of the MV bus. Stedin's MV design policy defines the allowed share of deviations in this regulation to be 1% of the nominal voltage. Furthermore, the equivalent of connection cables does not exist in this topology and is therefore not taken into account. Therefore, only the voltage drop over the network is used, where the limit considers the 1% drop over the transformer.

Figure 4.5 indicates the allowed voltage deviation of the MV grid voltage according to the LV design manual to be equal to $\pm 5\%$. The Netcode specifies the same allowed voltage deviations for MVconnections as LV connections: $\pm 10\%$ for 95% of all 10 minute-averages and -15% and + 10% for all 10 minute-averages [29]. A distinction could be made between supplying distribution transformers or client stations. In this evaluation, no distinction is made between connections and distribution-transformers and both are evaluated on a deviation of $\pm5\%$.

In a quasi-dynamic load flow calculation, a cable is marked as overloaded at a loading of either 50% or 60%, depending on the cable type. These numbers originate from the MV design policy and relate the redundancy as described in section 2.1. The amount of overloaded cables is quite high and, with an average of 66 cables per scenario, signals quite high costs and labor. Even though this model uses quasi-dynamic profiles instead of two static cases, table 4.7 shows the results in a similar overview as used in the LV model. The individual minimum (negative) and maximum deviations and loading of the assets are used, which are not necessarily experienced simultaneously. Cable loading is not evaluated on the direction and, therefore, the same in both overviews.

The majority of voltage violations are experienced due to increased consumption. On the other hand, the capacity problems are mostly related to increased generation and demonstrate themselves at higher levels of aggregation (i.e. the loading of feeders from IV/MV station or that of the IV/MV transformer). For example, the IV/MV transformer becomes overloaded for generation in almost all scenarios. However, a significant share of this overloading is from large connections directly connected to the IV/MV station, resulting in relatively less impact on voltage distribution or network loading.

The amount of distribution transformers overloading directly connects to the results from the LV model. The maximum loading is compared to the maximum transformer loading of the base year in general. These are also quite significant. Even more so than for the LV model. This might depend on integrating public charger-plazas and new housing, which are neglected in the LV model.

		Consumption			
Voltage	**2020**	**AM.2021**	**IA**	**KA**	**ND**
- Stations in violation	7%	21%	22%	23%	25%
Capacity					
- Dist. Transformer loading incr.	-	110%	93%	114%	128%
- Dist. Transformer overloaded	2%	21%	21%	23%	25%
- Transformer loading	68%	99%	112%	101%	117%
		Generation			
Voltage	**2020**	**AM.2021**	**IA**	**KA**	**ND**
- Stations in violation	14%	21%	22%	21%	23%
Capacity					
- Dist. transformer loading incr.	-	-2%	-33%	-23%	-23%
- Dist. transformer overloaded	1%	15%	1%	8%	8%
- Maximum transformer loading	-24%	-150%	-61%	-129%	-130%
		Common			
Capacity	**2020**	**AM.2021**	**IA**	**KA**	**ND**
- Cable loading incr.	-	72%	65%	68%	81%
- Cables overloaded	4%	15%	14%	15%	17%

Table 4.7: Overall results of the MV-modelling for generation.

The middle graph of fig. 4.9, showing the relation between voltage problems and AD, highly resembles that of the resistance of the cables with the AD. This also holds for the cable loading but to a lesser extent. The capacity of the cable is limited by the dissipation of power through the resistivity of the cable, which is closely related to the cross-section. A lower cross-section, in turn, means a smaller distance between the phases reducing the reactance. Therefore, cables with a high resistance also have a higher R/X-ratio, resulting in increased voltage problems through active power flow.

By applying the outcome of section 2.2, the low reactance of the cable shows a relatively small influence of reactive power in compensating voltage dips and swells and thus a low potential for reactive power compensation. Also, the capacity problems often accompanying voltage problems do not allow local regulation of additional reactive power as the cables are already overloaded.

The increased problems in both capacity and voltage can thus be explained by the smaller cross-section of cables in rural areas. This can be seen in fig. 4.10. As rural areas demonstrate the largest voltage magnitude dips and swells, the common conception that address density is negatively correlated with voltage dips and swells is mostly dependant on the share in the MV grid.

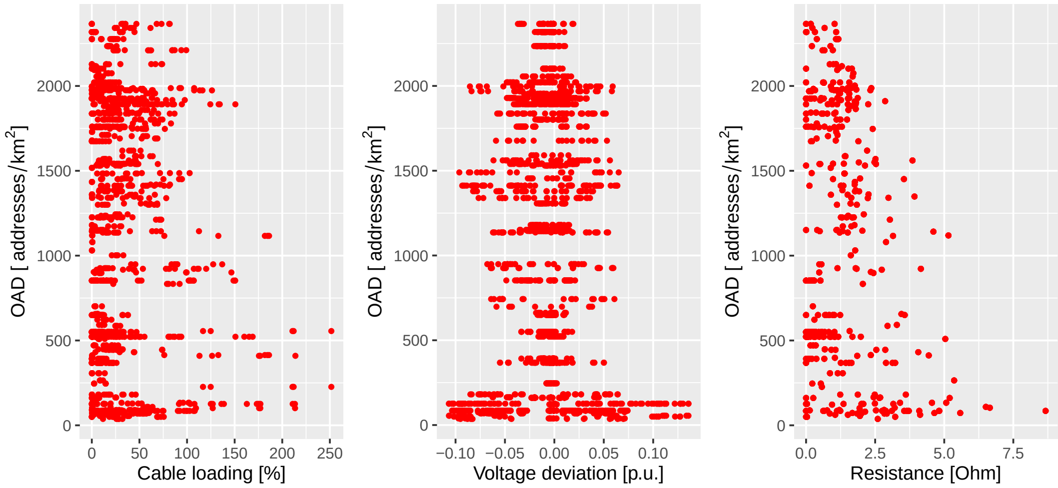


Figure 4.9: The increased resistance reactance corresponds with increased problems for very low address densities.

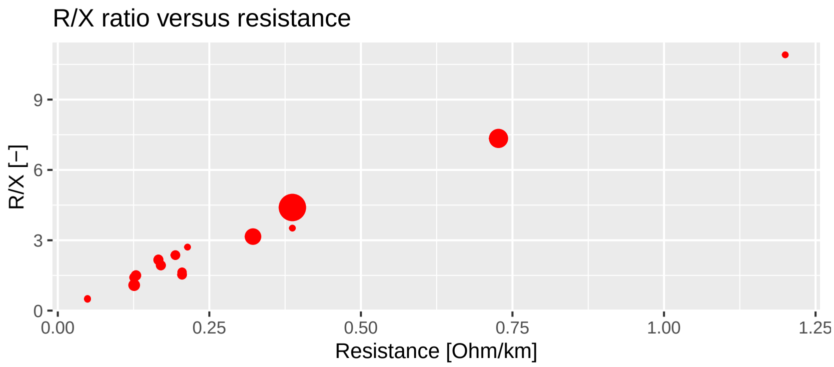


Figure 4.10: Resistance/reactance-ratio. Cables with low cross-sections have a higher resistance and lower reactance. Due to the lower cross-section and overall smaller distance between the phases, cables with a high resistance also have a higher R/X-ratio. Cables commonly have a R/X-ratio of somewhere between 1-5 (*See:* table 2.5), but higher ratios are also present.

An interesting aspect of the simulation is the significant decrease in problems that are encountered for areas with an address density varying from 300-900 addresses/km^2. This is especially clear in fig. 4.11 and fig. 4.9's voltage graph. These address densities generally correspond to large rural villages or small towns, but for this specific case are mainly represented by Houten's industrial areas (light industry, retail, offices). Over the whole range of the address density, this specific area is averagely represented. In the number of experienced problems, it, however, barely shows any.

Due to PowerFactory modelling with a yearly power profile, bottlenecks can also be quantified on a temporal aspect. By combining the several scenarios, these values create several ranges quantifying the overloading. These ranges include the level of overloading, the duration, and the frequency. What also becomes apparent from the temporal aspect is that problems for several assets often occur simultaneously due to the topology.

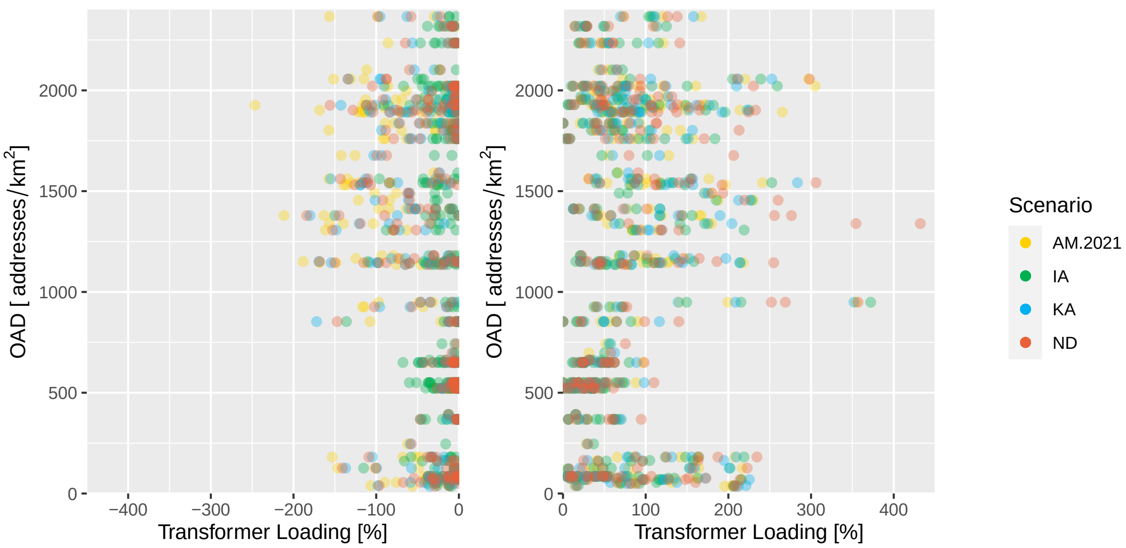


Figure 4.11: Transformer overloading in both consumption and generation showing a significant gap between 300 and 900 addresses/km². The effect of Stedin's assumption on residential/small scale LV PV (*see* Chapter 3) again also becomes clear, showing the highest negative loading in the AM.2021- and the lowest in the IA-scenario.

5

Feasibility of flexibility

The fitness of a solution towards a specific problem or bottleneck encountered in the grid depends both on the solution as the problem. In some sense, problems can generally be not fit to be solved by solutions other than reinforcement, independent of the other solution. This chapter expands on this premise by providing the means to quantify the ability of a problem to be solved through flexible resources. The research question formulated for this part is:

How can the feasibility of solving or delaying specific operational problems through flexibility be determined?

In this- and the following two chapters, the structure of OTE's 'Reinforce unless' is followed. This chapter starts with providing a legal background that enables the application of flexibility. This is followed by an analysis of the current process for analyzing problems for their fitness in being solved by flexibility, based on OTE's framework's Quick Scan. It concludes with proposing several additions and changes to this Quick Scan. Chapter 6 and Chapter 7 follow up on the second and third aspects of the framework, the sufficiency analysis based on the flexible resources, and the cost-benefit analysis.

5.1. Legal background

The framework assessed the applicability of flexibility in the context of legislation. However, when writing the framework, the writers of the regulatory framework could not conclude if the current legal framework allowed flexibility as an alternative to grid reinforcement. Therefore, one of the assumptions made in the framework was that legislation would be adapted to fit the requests of DSOs.

Kuiken and Más [6] evaluated the legal framework for integrating flexibility in Dutch distribution grids on a national and European level in the same year, 2019. In that year, the application of flexibility was not as strongly incorporated in the law as it is now.

Currently, European Legislation has defined the use of flexibility more explicitly with the introduction of the Clean Energy Package CEP. The EU Directive 2019/944 has replaced the repealed EU Directive 2009/72 [65, 66], which is commonly referred to by Kuiken and Más. Article 32 of the EU 2019/944 specifies the use of flexibility by system operators *"where such services cost-effectively alleviate the need to upgrade or replace electricity capacity and support the efficient and secure operation of the distribution system"* [66].

Kuiken and Más describes that the use of flexibility, both in the EU 2009/72 as in the study commonly referred to as Demand Side Management, was both encouraged as it was complicated. At that time, the EU 2009/72 already encouraged flexibility over investments in capacity (art. 3.10), although the definition of capacity seems more pointed towards generation capacity than grid capacity.

The article describes several restrictions towards the integration of flexibility. The main limitation is indicated to be the influence on the free market. Kuiken and Más discusses that applying flexibility influences the market of supply and demand, where the unbundling requirements inhibit the DSO in doing so (2009/72, art. 26; Elektriciteitswet, art. 10b). However, Kuiken and Más determine that with the task of purchasing energy for compensating grid losses, the DSO performs a similar act of influence on the market. Finally, Kuiken and Más also discuss that the application of flexibility could lead to the degradation of market freedoms. They argue, however, that this would not be the case. By accepting a certain agreement, the use of your potential in other markets is decreased. The application of flexibility leading to degradation of the market freedoms is no more true than that ancillary services towards a TSO would do so.

Another specific point of attention in the article is the Tariff structure, as mentioned in the introduction. The "Tarievencode Elektriciteit" (Tariff-code Electricity) [67] specifies that both consist of a fixed tariff, for, among others, maintaining the connection and administrative costs; and the variable tariff, for, among others, covering grid losses and operational costs. The variable transport tariff of a consumer differs for connections and different voltage levels. For connections below MV, the variable tariff consists of a tariff based on the capacity assigned to the category of connections this connection belongs to ($kW_{capacity}$). These categories are, in general, quite wide, and the cost assignment is skewed. The third category, for instance, includes the largest amount of general households. This category ranges from 4 kW up to and including 17.3 kW and is monetised for the former. The following category ranges from 17.3 to 24 kW (includes only one typical connection) and is monetised at 20 kW.

Research by Netbeheer Nederland [68] suggests that due to the increase in high-power technologies as EVs, HPs, and PV, the maximum consumption of households in the first category will shift from the lower bound to the upper bound. This increases the loading of the grid without providing DSOs the proper means to bear the costs. The current tariff structure for <MV is a barrier towards the efficient financing of the energy transition and the cost-cause principle; however, it is not likely a barrier towards the integration of flexibility. The contracted capacity of a connection represents both the contracted level as the capacity limited by the fuses and, in some cases, the capacity of the connection itself. A different tariff structure cannot impact these technical restraints.

For connections at or above MV, the variable tariff consists of a contracted capacity in $kW_{contract}$ and a maximum consumption kW_{max} for each month. Aside from the higher costs associated with consuming more than usual to provide flexibility, the costs can also rise from consuming more than contracted.

In general, it seems logical that the kW_{max} should always be below $kW_{contract}$, and that exceeding this level should result in a corrective measure. However, if at any point in a year, kW_{max} exceeds $kW_{contract}$, the $kW_{contract}$ is readjusted to the kW_{max} for the whole upcoming year. This clearly obstructs the flexibility that could be provided by a consumer even more; switching to a higher $kW_{contract}$ automatically obliges the consumer to bear the costs for a whole year [67, 69]. Thus, contrary to the <MV connections, a different tariff structure can impact the flexibility provision of MV-IV connections.

DRG is exempted from transport tariffs, as they only apply to consumers (Tariff-code art. 3.4.1). This discourages producers from maintaining grid-efficient behavior. Netbeheer Nederland [68] therefore argues that a specific feed-in transportation tariff can result in more efficient grid usage, such as introducing storage to decrease peaks. Van Gerwen et al. [70] state that other tariff structures are currently under investigation; however, at this moment not yet allowed.

5.2. 'Reinforce unless': Quick scan

This section will introduce 'Reinforce unless' its Quick Scan. The Quick Scan consists of a few short check-questions that can determine if a problem or bottleneck fits an application of flexibility as an alternative to investment. This section starts with distinguishing the two different applications of flexibility.

- The first is an application in the case of 'Reinforce unless', where the bottleneck is identified sufficiently in advance to realise possible grid reinforcement. In this case, utilizing flexibility is seen as a (temporary) alternative to reinforcement. Flexibility as an alternative can be applied as long as it remains economically beneficial.
- The second application of flexibility is in case of an unexpected increase in the need for transport capacity where a reinforcement cannot be realised in time. In this case, flexibility is used as a

bridging measure to maintain system users' market freedoms. This application is better known as congestion management.

OTE specifies that although they seem similar, significant differences exist. Congestion management is focused on the short-term application of flexibility to avoid overloading where flexibility in the 'Reinforce unless'-context essentially 'provides' excess capacity as reinforcement would.

Congestion Management
Congestion management can again be subdivided into two stages. The first stage starts when a shortage of capacity is indicated by the transport-prognosis of the realised connections while considering an appropriate margin for natural growth of capacity use. At this point, the DSO will publicly announce a notice of congestion and start its research on the application of congestion management. During this process, new transportation applications are no longer granted (for applications that would increase congestion).

The process consists of several aspects. First, the grid operators must determine if it is technically and operationally feasible to use flexibility, if the expected duration of congestion is between 1 and 4 years, and if sufficient flexibility is available. During this stage, the DSO will try to avoid overloading of capacity through the use of flexibility to be able to continue granting transportation applications. The flexibility is contracted on a voluntary basis. Based on the outcome, the DSO can either allow new connections through the use of flexibility or fully declare congestion based on the notice. The period of congestion ends when the realization of reinforcement has taken place.

The second stage does not have to be reached but starts when the DSO determines that the appropriate margin for the natural growth of capacity use was insufficient to account for the actual natural growth. In this case, overloading of the capacity is imminent. The DSO will then again try to realise sufficient capacity through flexibility. This time, the DSO uses the full possibilities provided by Article 9.7 of the Netcode, which allows it to oblige system users above a certain connection power to provide a bid [29].

Due to the energy transition, congestion and congestion management are topics that are rapidly increasing in relevance. ACM determined that, so far, the application of congestion management has been limited. Overall, the DSOs find that the current regulatory structure obstructs them in effectively performing congestion management. In 2020, the DSOs, under the collective of Netbeheer Nederland, have handed in a proposal to the ACM to actualize the current congestion management code, as simplified and described above. After a few iterations, the ACM has recently released a concept version of the new congestion management code [37] that allows for increased application of congestion management.

The focus is mainly on applying flexibility as an alternative to reinforcement; however, the aspects in this chapter are commonly applicable to both applications. Therefore, this thesis will also refer to changes due to this legislation where possible.

5.2.1. Current Quick scan

The framework proposes to start with a Quick Scan to determine if flexibility could provide a valid alternative to reinforcement. It provides an example of several technical property-oriented check-questions to determine if a bottleneck is fit for further analysis. If the answers to any of these questions are negative, the outcome of following the framework is indicated to likely also be negative. At that point, flexibility can be already be dropped from the alternatives study.

The report emphasises that the check-questions and the presented key figures need to be developed based on experiences in actual applications. These numbers are, therefore, merely subjective indications.

1. Is the occurrence of a shortage in capacity less or equal than **five** times a week?

2. Is the overall duration of overloading of the asset less than **1500** hours a year? (comparable to a **4** hour overload each day)

3. Is there reason to assume **sufficient** flexible power in the requested direction available in the prospective grid?

Aside from the above selection questions, the framework also specifies the following two questions. A positive answer to any of the questions below may lead to deviating from the decision as caused by the questions above, as they specify a project-specific, more beneficial business case.

4. Are there possibilities to replace or add flexibility options where the grid operator can play a facilitating role?

5. Are there currently any reinforcements planned where flexibility could be a preliminary option to congestion-management?

The first two rules specify the duration and frequency of overloading. The yearly amount of energy that would have to be additionally locally generated, used, shifted, or omitted will rise with both frequency and duration.

The third rule specifies the availability of sufficient flexible resources in the grid. This consists of a two-step approach, first determining if flexible capacity is present by a Request for Information followed by a more concrete Request for Proposal.

The key figures of **Rule 1 and 2** in the quick scan are merely subjective indications. These numbers are set quite wide such that flexibility is not preliminarily ruled out as an option, and the bottleneck is regarded as another opportunity to gain experience on the subject. Along with this experience, these key figures can later be refined. In the original framework, no Quick Scan condition is set on the maximum intensity of the bottleneck or problem, for instance, maximum overloading of an asset. As the 'Reinforce unless'-framework was a collective effort of different stakeholders of the energy system, Stedin was both aware of as involved in creating this framework. In the early adoption of this framework, the responsible parties used the same key figures as indicated by the framework. However, aside from the frequency and duration of the bottleneck, Stedin also added a maximum intensity of overloading.

Flexible resources are addressed based on transport prognoses or observed trends in deviations from the transport prognoses. Therefore, the application of flexibility resembles that of the application of a redispatch-action of a TSO, where parties supplying this service can be addressed to adjust their transport to alleviate an expected bottleneck. As is also the case with a redispatch-action, the magnitude of the adjusted power evaluated over the imbalance settlement period (equal to the shifted or curtailed energy) will influence the price of the flexible operation.

As the decision of whether flexibility is a feasible alternative depends highly on the costs of such redispatch operations, evaluating solely and individually the frequency and duration of the bottleneck is not likely to provide a reliable indication. Instead, the required, flexible services to alleviate the bottleneck, i.e., the product of the three different components, is more likely to provide a realistic indication. This is also more in line with procedures currently used, as GOPACS. The yearly costs of flexible energy can then be approximated using the average price of such a redispatch-action and the average required level of flexible power, the duration, and the frequency of the event.

Rule 3 of the Quick Scan specifies that sufficient flexible resources should be available. The availability of resources not only specifies the existence of flexible resources but also relates to its ability to act as a sufficient alternative for reinforcement. This, in turn, also depends on the technical capabilities of the available flexible power, the location of the available flexible power in the network, and the sensitivity of the problem towards the provided flexible power at that location.

Section 5.3 proposes a way to quantify the required flexibility as a function of its location in the network. Following up, this information is cross-referenced with the installed flexible capacity of the network in **section 5.4**. Combined, this answers both the overall technical feasibility and the financial feasibility of solving a bottleneck.

The fourth rule can provide information on possible initiatives that have come up from local investors or energy initiatives. For example, this can apply to Power-to-x solutions, where electric power is converted to a different form of energy (heat, gas), local storage solutions, or CHP, a generating unit providing both heat and electric power resulting in a high overall efficiency. This essentially extends the third rule to a future-oriented approach. It can, however, also influence the decision on the initiative in the event of the involvement of the DSO and/or the services that can be delivered in favor of the DSO aiding their business case.

Maintaining room for exceptions based on possible innovations occurring within the premise of the network could prove to be beneficial and actually receives more room for implementation in the CEP. Therefore, **Rule 4** is maintained.

The fifth rule applies to a specific case where a shortage of capacity is expected before an already planned reinforcement takes place due to, for instance, the depreciation of the asset. The framework argues that, in this case, flexibility can provide an additional business case. However, it is unclear how this could be the case, as no further elaboration on the subject is given.

ACM regards investments in assets that proved unfit to remain in operation over their regulatory lifetime (the depreciation period for an asset-type specified by ACM) as disinvestments. Before 2014, these disinvestments were taken out of the overall regulated Standardised Asset Value (Gestandaardiseerde Activa Waarde (GAW), in Dutch) of the DSO over which the DSO is provided a return on its investments [71]. Since then, the ACM changed its opinion on this subject and allows DSOs to retain the asset value as part of the pool. Under the condition before 2014, it could prove beneficial to use flexibility to extend the unit's lifetime: the investment would not have to be advanced (likely return over the difference in present value), and the DSO can fully depreciate the asset (return over Standardised Asset Value).

Another explanation is that the framework refers to a related process where the simultaneous execution could play a cost-reducing role. An example could be replacing cables simultaneous to another process that requires excavation, e.g., piping or road work. Depending on the different processes, this can severely decrease the eventual reinforcement's overall costs, allowing higher costs for flexibility in the meanwhile. Stedin already applies the approach of collaborating with different disciplines performing similar operations. The addition of flexibility to this approach to decrease the urgency of reinforcement to align with other processes can be beneficial.

Rule 5 seemed to be based on legislation that was no longer active; I found no arguments to retain this rule.

5.2.2. Assumptions

The framework is created with the additional aim of providing certain robustness towards changes in the energy system. It addresses several aspects of assumptions that influence whether this framework can effectively solve a specific bottleneck or operational problem. The most important policy and regulation considerations and -assumptions applied in the framework towards the aspects in this chapter are the following:

1. There can be no degradation in any of the three market-freedoms. I.e., system users must maintain freedom of capacity, freedom of transaction, and freedom of dispatch.

2. DSOs should pay attention to the possible interaction between bottlenecks in grids related to those of other grid operators. Solving this bottleneck or problem should not lead to creating or intensifying a bottleneck in the grid of another operator. Problems should, in general, be solved for the overall lowest possible social costs.

3. The integration of flexibility to solve a bottleneck or operational problem should not lead to another bottleneck or operational problem arising.

4. To operate in a non-discriminatory manner, only the technical characteristics (i.e., the characteristics of the exchange of active or reactive power over time) should play a role in comparing different resources). The operation must remain neutral towards the origin of the flexibility.

Assumptions 1, 2, and 3 relate to the procedure of solving a bottleneck through the application of flexibility. As indicated above, flexible resources are addressed based on transport prognoses or observed trends in deviations from the transport prognoses. The following action, however, leads to an imbalance in the national electricity market. A market party that agreed to deliver or consume will no longer (fully) comply with its agreement. The DSO can address another market party to solve this imbalance, following a similar procedure as redispatching by the TSO. However, as Assumption

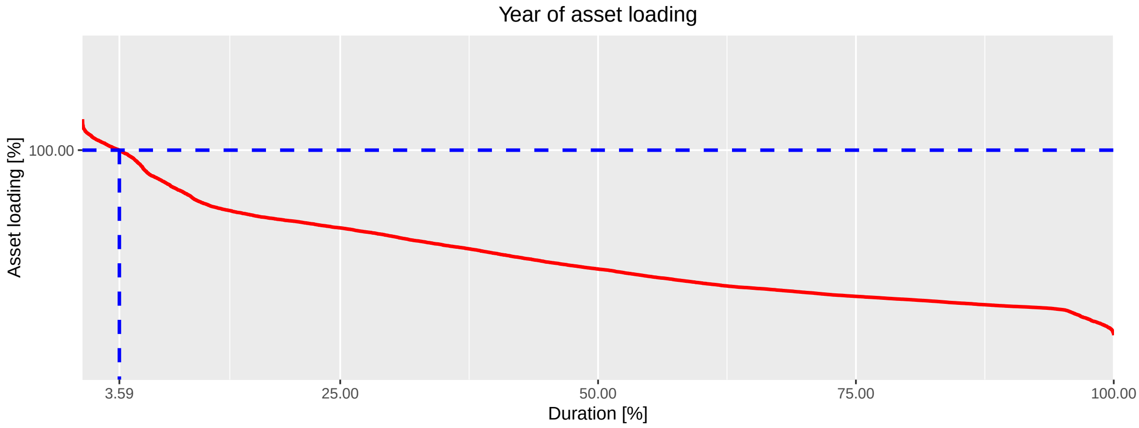


Figure 5.1: Load duration profile of a transformer showing a short overloading.

1 guarantees the three market freedoms, market parties in the congested area could still enter the redispatch market and solve this imbalance. The same holds for a redispatch operation being targeted in another congested area. In a way, this means that the three assumptions given above can be said to contradict each other.

The above assumptions are regarded in the way that holds for redispatching on a transmission level. System users may deviate from their prognoses, requiring DSOs to maintain a probable margin in their capacity provision. However, similar to dispatching on a transmission level, spatial and topological constraints can be set in participation in redispatching. This also includes redispatching on other grids. GOPACS is a good example of this, as it references the offered redispatch bids with available transport capacity in the respective grid.

Assumption 4 regarding maintaining a neutral view on the origin of the technology is generally valid as DSOs should not discriminate in their operation. However, new legislation could indicate cases where this assumption is slightly outdated. For example, the EU its CEP prohibits system operators from the market-based re-dispatching of renewable production beyond 5% of their yearly energy production [2] in favor of a higher overall economic efficiency. This can visually be represented as in fig. 5.1, for instance, for the case of a transformer.

Using an integration of the area between the y-axis, the blue, and the red line, the energy required to be curtailed can be calculated. However, curtailment is not an option if this already exceeds 5% of the yearly production of available renewable generation. In this case, the energy could be stored, or a solution in demand response can be sought.

For an application in the form of congestion management, the current Dutch legislation is even stricter. Currently, Netcode Article 9.9 excludes ”connected parties with power-generating units that only use one or more non-controllable energy sources” [29], focusing on weather dependant DRG. This legislation is likely to be changed to correspond to European legislation as described above.

Overall, maintaining neutrality towards solutions can decrease the overall effectiveness of the Quick Scan. The availability of a certain type of flexibility could better be combined with the general applicability towards the specific bottleneck to ensure that flexibility is not overestimated when considering additional legislation constraints. Possible legislation constraints will therefore be addressed in reference to the flexible sources they apply to in section 6.1.

5.2.3. Summary

The Quick Scan provided by OTE is given as a first step, created to provide DSOs with a general direction as to what this scan should include. Along with this definition, I propose several aspects which can be relatively quickly identified and can aid in a more directed indication of feasibility. Table 5.1 summarizes the proposed changes to the assumptions and rules regarded in the framework of ’Reinforce unless’.

	Rules	
1, 2.	Evaluation based on frequency, duration, and presence.	Evaluation based on additionally locally generated, used, shifted, or omitted energy using section 5.3.
3.	Reason to assume sufficient flexible power.	Quantifying necessary and sufficient flexible impact through section 5.3 and section 5.4.
4.	Review future initiatives for potential in deferring investments	Review future initiatives for potential in deferring investments
5.	Deferring investment based on upcoming investment	-
	Assumptions	
1, 2, 3.	Solving bottlenecks without degradation of market freedoms, while regarding interaction with other grids, and regarding interaction with other bottlenecks.	Geographical/topological restriction of participation in redispatch and maintaining probable margin to respect the market freedoms.
4.	Non-discriminatory selection of flexible resources	Non-discriminatory selection of flexible resources considering regulation

Table 5.1: An overview of the proposed changes of relevant rules and assumptions in 'Reinforce unless' its Quick Scan.

5.3. Quantification of active and reactive power-levels

From the overview of problems provided in Chapter 2, capacity-problems and voltage dips and swells were identified as the problems that are most likely to be solved through the use of flexibility. Section 2.2 also introduced a representation of the grid that was used to provide a background to several of the problems in the overview and to describe the concept of load flow calculations shortly.

Section 2.2 specifies the concept of a matrix representing the relation between changes in power flows and changes in nodal voltages and branch currents, which is used to iteratively approach the unknown values in power flow calculations using the Newton-Raphson method. This subsection will further dive into this concept and its relation to the use of flexibility based on the thesis of Yus Santana [72].

5.3.1. Sensitivity

Yus Santana made a model using Matpower to actively assess the impact of different sources of flexibility on a network. The model uses three different forms of flexibility under different constraints to keep the nodal voltage levels in the allowable range.

For this objective, she started from the general idea of the matrix as indicated in Chapter 2. This matrix indicates that the voltage V_i of a node i that is not the slack-node can be seen as a function of the reactive and active power injections and withdrawals at other nodes in the network, as summarised in eq. (5.1). Following this definition, the differential function of the voltage at that node can be expressed as eq. (5.2). Finally, as this derivation becomes complex, the partial derivatives are approximated by eq. (5.3).

$$U_i = f(P_1, P_2, \cdots, P_n,\ Q_1, Q_2, \cdots, Q_n) \tag{5.1}$$

$$dU_i = \sum_{j=1}^{n} \frac{\partial U_i}{\partial P_j} dP_j + \frac{\partial U_i}{\partial Q_j} dQ_j \tag{5.2}$$

$$\frac{\partial U_i}{\partial P_j} \approx \frac{\Delta U_i}{\Delta P_j} \quad , \quad \frac{\partial U_i}{\partial Q_j} \approx \frac{\Delta U_i}{\Delta Q_j} \tag{5.3}$$

Yus Santana calculated the values of $\frac{\Delta V_i}{\Delta Q_j}$, and $\frac{\Delta V_i}{\Delta Q_j}$ through applying a small ΔP and ΔQ and several nodes in the network and documenting the response. The results can be represented in the matrix, where each value represents the overall influence, described as the overall sensitivity, of the load (column) on the node (row).

The same operation can be performed for the branch loading. Through this operation, the branch loading L_k of branch k can be obtained from a reactive or active power change in the load at node j. Here also the approximation is assumed to suffice:

$$\frac{\partial L_k}{\partial P_j} \approx \frac{\Delta L_k}{\Delta P_j} \quad , \quad \frac{\partial L_k}{\partial Q_j} \approx \frac{\Delta L_k}{\Delta Q_j} \tag{5.4}$$

The sensitivities were mapped and scaled according to the influence a certain load has on the overall variations of the node or branch. The thesis determined these values as insightful in ranking the loads on their influence on reliable network operation.

Aside from the approach used by Yus Santana, the same result can be obtained by using the Jacobian matrix used in the power flow equations itself (eq. (5.5)). However, the approach used by Yus Santana combined with a more indicative quantity of the actual change in exchange can provide a better indication of the final steady-state.

$$\left[\begin{array}{c} \Delta P_1 \\ \vdots \\ \Delta P_n \\ \hline \Delta Q_1 \\ \vdots \\ \Delta Q_n \end{array}\right] = \left[\begin{array}{ccc|ccc} \frac{\partial P_1}{\partial \delta_1} & \cdots & \frac{\partial P_1}{\partial \delta_n} & \frac{\partial P_1}{\partial |U_1|} & \cdots & \frac{\partial P_1}{\partial |U_n|} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial P_n}{\partial \delta_1} & \cdots & \frac{\partial P_n}{\partial \delta_n} & \frac{\partial P_n}{\partial |U_1|} & \cdots & \frac{\partial P_n}{\partial |U_n|} \\ \hline \frac{\partial Q_1}{\partial \delta_1} & \cdots & \frac{\partial Q_1}{\partial \delta_n} & \frac{\partial Q_1}{\partial |U_1|} & \cdots & \frac{\partial Q_1}{\partial |U_n|} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial Q_n}{\partial \delta_1} & \cdots & \frac{\partial Q_n}{\partial \delta_n} & \frac{\partial Q_n}{\partial |U_1|} & \cdots & \frac{\partial Q_n}{\partial |U_n|} \end{array}\right] \left[\begin{array}{c} \Delta \delta_1 \\ \vdots \\ \Delta \delta_n \\ \hline \Delta |U_1| \\ \vdots \\ \Delta |U_n| \end{array}\right] \tag{5.5}$$

The Jacobian Matrix represents the relation between changes in exchanges of power and changes in node voltages. The change in cable loading can be obtained by combining this matrix and the impedance or admittance-matrix, where $\underline{\Delta U_1}$ and $\underline{\Delta U_2}$ denote the nodes on either side of the branch.

$$\Delta L_k = \Delta \frac{|\underline{I_k}|}{I_{max}} = \frac{1}{I_{max}} \frac{\underline{\underline{\Delta U_1}} - \underline{\underline{\Delta U_2}}}{\underline{Z}} = \frac{1}{I_{max}} \frac{\underline{\underline{\Delta U_1}} - \underline{\underline{\Delta U_2}}}{R + jX} = \frac{1}{I_{max}} (\Delta \underline{U_1} - \Delta \underline{U_2}) * Y_k \tag{5.6}$$

5.3.2. Reverse application

Aside from providing insight into the overall influence of loads on certain indicators in the grid for that specific state, the approach can also be used in reverse. As these values can be calculated for all the nodes in the system where power can be injected or withdrawn, these sensitivity indicators can provide insight into where flexibility is best applied to solve capacity overloading and voltage problems. This approach can even be applied even further:

If I am interested in reaching a certain voltage deviation at node i or a certain cable loading decrease in branch k in respect to the current situation, what active or reactive power should I inject or withdraw at node j to obtain this?

By addressing the current situation as $t = 0$ and a through-flexibility-improved situation as $t = 1$, the branch loading and voltage deviations can be described as in eq. (5.7), where ΔV_0 and ΔL_0 represent the unallowable deviations beyond the maximum levels of the nodal voltage and the cable loading, respectively.

$$V_{i0} = V_{nom} \pm \Delta V_{max} \pm \Delta V_{i0}$$
$$L_{k0} = \pm 100\% \pm \Delta L_{k0} \tag{5.7}$$

The amount of flexible reactive or active power that needs to be injected or withdrawn at node j to solve the problems at node i or branch k can be approximated using eq. (5.8).

$$P_{j1} = \Delta V_{i0} / \frac{\Delta V_i}{\Delta P_j} \quad , \quad Q_{j1} = \Delta V_{i0} / \frac{\Delta V_i}{\Delta Q_j}$$
$$P_{j1} = \Delta L_{k0} / \frac{\Delta L_k}{\Delta P_j} \quad , \quad Q_{j1} = \Delta L_{k0} / \frac{\Delta L_k}{\Delta Q_j} \tag{5.8}$$

The sensitivities in the matrix are linearized approximations of the actual derivative of the nodal voltage and branch loading for this specific state. Suppose an approximation of the active or reactive power that is to be injected or withdrawn at a specific node is actually modeled as such. In that case, the actual influence on the problem is likely to be different than that what was calculated. However, the same applies to the actual load flow calculations. This approach is, in fact, the same. The approximation should converge quickly after a few iterations. Due to the linearization of that specific state, the convergence over multiple iterations may lead to very different results, as indicated by the first calculation. This can either be beneficial or detrimental and may eventually lead to favoring flexibility at different connections. Li et al. [73] show that to a large extent, these values are representative. However, the actual accuracy is checked using an accuracy index. The calculations are reiterated until sufficient accuracy has been achieved.

The matrix that expresses the sensitivity of the experienced problem towards active and reactive power changes at the nodes in the network can thus aid with the implementation in several ways. It can firstly act as an indicator of where flexibility has the largest potential in mitigating this problem. This indicator can aid in comparing different resources based on the sensitivity assigned to their respective points of common coupling but, through their actual physical representation, also act as a measure of effect versus cost.

5.4. Required flexibility

The previous section shows that both voltage as capacity problems can be expressed as a nodal mismatch of apparent power. The required flexibility to mitigate such a problem thus depends not only on the magnitude of the bottleneck but also varies among the different nodes. Whether a node can impact a bottleneck depends on the presence of flexible resources but also the flexible resources' abilities under its current state of operation.

The current state of operation limits the range of instantaneous and temporal technical capabilities of the asset. For example, if the bottleneck is simulated to occur when the asset's capacity in the mitigating direction is already fully utilised, the asset will not be able to mitigate the risk associated with the bottleneck on an actual occurrence. Also, temporal abilities can be included, such as the SoC of storage capacity or the maximum duration or deferral of a certain process.

Li et al. [73] mathematically defines the abilities of what it calls 'controllable resources' in active distribution networks. These controllable resources include, but are not limited to, flexible resources. They define several operating regions of controllable resources. The first is the Flexibility Provision, consisting of the total technical instantaneous capabilities of a flexible resource. This is followed by the Flexibility Availability, which further constrains the abilities of the resource through security constraints as maximum station voltages and maximum loading of lines.

A visual example is given in fig. 5.2. It describes the constraints of DRG. This power electronics interfaced DRG's active and reactive power limits are first limited by the technical capabilities of the inverter. This is mostly due to the maximum current or apparent power. The second constraint is the active power level of the main driver, in this case, the potential from solar irradiation or wind. The intersection of these regions creates the Flexibility Provision. Furthermore, the abilities are constrained by the size of the connection, also due to the current or apparent power, the voltages of the station, and the current-carrying capabilities of the lines. The resulting region of flexible operation consists of the intersection of the constraints (the Flexibility Availability). As DRG mostly acts as an MPPT at unity power factor, flexible operation in the case presented in fig. 5.2 allows decreasing the level of generating and adjusting reactive power levels towards the constraints of the apparent power levels. In this case, the required change by decreasing the reactive power level can enable additional generation further down the string.

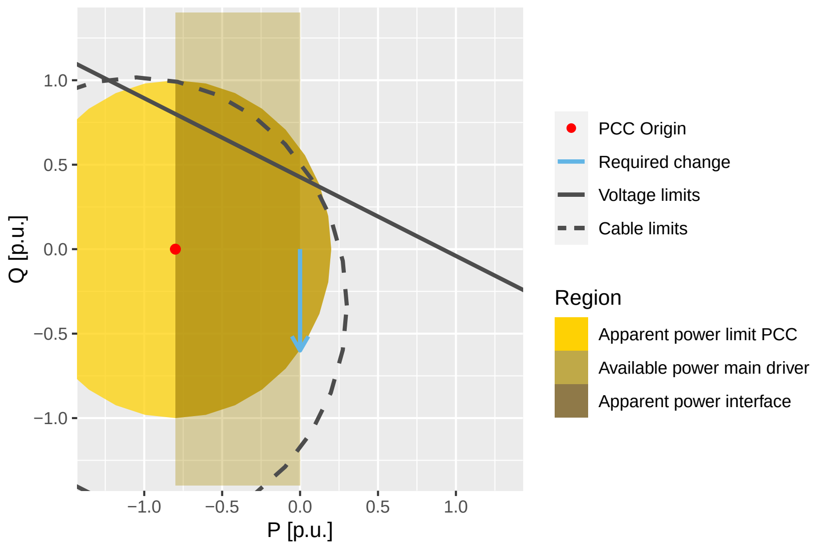


Figure 5.2: Example of constraints on a PEID DRG

If all controllable resources are combined, an operating region in the form of state spaces can be defined that includes all operating possibilities of the included resources. Two are mainly relevant, the Region of Secure Operation (RSO) and the Region of Diverse Operation (RDO). In general, the RSO represents the possible states of the flexible resources in the network while still maintaining security constraints. Along with this definition, the RSO equals the operating region of states that fulfill the objective of this thesis.

The RDO represents a subset of the RSO, which includes additional operational requirements. For example, reduced line loading limits, reducing line losses, reducing voltage deviations, or integrating DG penetration. The introduction of an additional objective is outside the scope of this thesis. I expect the RSO to limit the flexible operation in such a way that additional objectives will have little room to make a sufficient impact. The inverse is, however, possible. System users are rarely aware of the influence their equipment has on line loading and voltage distributions. Their view of the RSO is generally only limited by the grid connection. Because of this, the other way around is, of course, possible. This would mean that the resource is already fulfilling a primary objective inside the RSO of the system user, but inside that RDO still has room also to provide flexibility (*see:* "Peakshaving" in appendix C).

The effect of potential solutions can be determined using the sensitivity matrix. The overall impact of flexible power on a certain problem can be defined as the sensitivity of that problem in respect to the instantaneous abilities of the asset. The sensitivities combined with the Flexibility Availability can be used to determine an optimal power exchange which maximizes its impact on the bottleneck. Rewriting eq. (5.8) and regarding the change of apparent power injection at node j equal to that power exchange, the asset's impact on the problems at node i or line k can be quantified through eq. (5.9).

$$\Delta V_i = P_j * \frac{\Delta V_i}{\Delta P_j} \quad , \quad \Delta V_{i0} = Q_j * \frac{\Delta V_i}{\Delta Q_j}$$
$$\Delta L_k = P_j * \frac{\Delta L_k}{\Delta P_j} \quad , \quad \Delta L_k = Q_j * \frac{\Delta L_k}{\Delta Q_j} \tag{5.9}$$

Outside of affecting this specific station and problem positively, the solution might also negatively affect the stability of other N stations or M cables. Therefore, their implementation should be constrained by the RSO as defined by the other limiting factors in the grid (other node voltages or line loading). By evaluating the combined potential impact of flexible resources on the bottleneck per case, the sufficient availability of flexible resources (technical feasibility) and the costs (financial feasibility) can be estimated. Using the available grid analytic tools, this solution can be found relatively quickly. Therefore, using the right approach and data, such a procedure can still be regarded as 'a quick scan'.

Of course, these tests are merely case evaluations. If the flexible capacity is already fully utilised, the capacity can be insufficient to alleviate the bottleneck. However, the use of characteristic profiles indicates under which situations such a bottleneck occurs. The current operational states of the flexible assets also relate to these situations. Multiple evaluations of these assets should therefore provide a representative view of the instantaneous abilities of the assets in these situations.

It is, of course, also possible that several of the assets might be unavailable during the period of overloading. Unavailability would also significantly decrease the certainty and reliability of supply. Such unavailability can be quantified using several probabilities. To guarantee sufficient certainty of supply, section 6.2 determines the combined minimum levels of impact and availability as a function of multiple probabilities.

Combining section 5.3 and section 5.4 and evaluating these properties over the different occurrences of bottlenecks, the Rules 1, 2, and 3 of the framework's quick scan can be evaluated. This results in a yearly amount of required energy exchange and the required available flexible power. Overall, this chapter showed that the three important aspects that link a specific problem to a possible solution are magnitude, time, and location. These aspects are used in the following chapter to address the fitness of certain solutions to a general bottleneck.

6

Possible solutions through flexibility

This chapter presents several flexible resources that can serve as solutions to the identified problems of the previous chapter. These solutions will be described on their fitness as flexible resources. The research question formulated for this part is:

What solutions in the form of flexibility can be applied to solve or delay operational problems?

This chapter will start with analyzing the current guideline for assessing possible solutions, based on 'Reinforce unless'. The assessment is the second step in the evaluation of the framework, which can be summarised in two aspects: compliance with regulation and legislation; and sufficient security of supply.

The potential solutions for mitigating the operational problems are listed and described on their overall potential and constraints. This chapter is concluded by an overview of the potential solutions along with a general assessment and their influence on the operational problems of Chapter 2.

6.1. Compliance with regulation and legislation

In section 5.1, the relevant legislation for the application of flexibility, as (indirectly) specified by the Elektriciteitswet and the Netcode, is described. Additionally, the flexible resources may be restricted by specific legislation, for instance, the RfG for distributed generation.

6.1.1. Greenhouse gas emissions

Overall, the incentives related to greenhouse gas emissions are assumed to be incorporated in the price of the flexible power provision. However, if additional valuing of greenhouse gas emissions is required, it can easily be monetised using the value of a tonne of CO_2-equivalent as determined by the company. Stedin, for instance, as included in the Risk matrix, currently assigns a value of €50/tonne of CO_2-equivalent.

For flexibility through some form of redispatch, the difference between emissions of the two generating technologies should be used. For effects including a shift of consumption, the initial shifting should not change emissions. However, a rebound effect might, where the additional "payback"-energy consumption [19] can be monetised using the average emission of CO_2-equivalent/MWh and the value of a tonne of CO_2-equivalent.

6.1.2. Reactive power provision

The introduction of the RfG enabled DSOs to specify reactive power capabilities of new DRG [58]. For the Netherlands, this legislation is further implemented and specified in the Netcode [29].

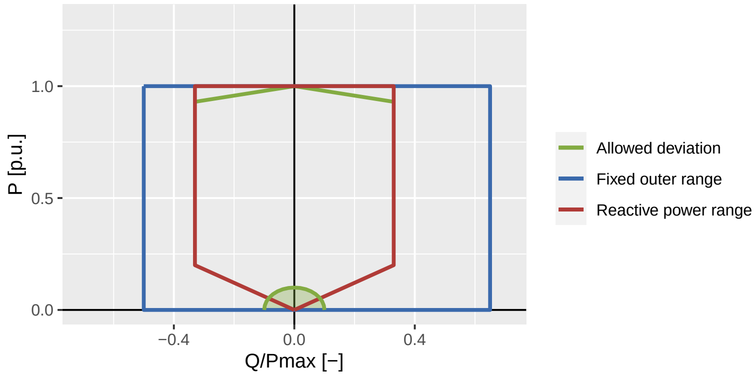


Figure 6.1: PQ-Operating region for a Type B or Type C generator as specified by the Netcode [29]

The Netcode [29] constrains the share of reactive power a system user may exchange with the grid by specifying limits for the $\cos\varphi$ or displacement power factor (dPF). These constraints effectively additionally limit the provision of reactive as a function of its active power level. Without any additional contractual agreements, these limits are set on 0.85 inductive and 1 (Art. 2.27). For system users with generators, it is assigned based on the generation type as defined by the RfG [58]. Type A generators, generators with a nominal power varying from 800W to 1 MW, are specified to maintain a dPF between 0.9 inductive and 0.9 capacitive for LV grids (Art. 3.4), and 0.98 inductive and 0.98 capacitive for MV-HV grids below 110 kV (Art. 3.15).

The other generating types connected to the distribution grid, Type B & Type C generators, should also comply with Art 3.15. Although somewhat contradicting, also to a given operating region in the P-Q domain, specified in fig. 6.1. This operating region contains operating points with dPF varying from around 0.52 capacitive to 0.52 inductive.

Existing producers are exempt from these specifications and must comply with Art. 14.3 and 14.4. According to Art. 2.27, DSOs can specify additional contractual agreements on the reactive power levels and dPF. It is assumed that if reactive power provision aids in solving or mitigating a specific bottleneck, DSOs will specify additional contractual agreements to enable these services. An exception is made for LV-grids, where the dPF constraints are maintained.

The optimal ratio between active and reactive power depends on the apparent power through an asset for capacity bottlenecks or the R/X-ratio for a voltage bottleneck. In both cases, the optimal direction of mitigating action by a flexible resource will likely consist of a relatively small share of reactive power compared to active power. The set limits are therefore realistic in comparison with demand.

6.2. ’Reinforce unless’: Sufficiency criteria

The framework specifies that for the application of flexibility is to be accepted as a valid alternative, it should be proven that the flexibility does not lead to a degradation in the security of supply. This is what the framework calls its sufficiency criteria. This is not an evaluation that compares solutions among each other but compares it to a general minimal benchmark. The solution is deemed sufficient if the overall results indicate an outcome equal to or above the benchmark on all categories.

6.2.1. Sufficient security of supply

To assess the security of supply-sufficiency of a certain solution, the risk acceptance of the DSO is used. The risk acceptance of the DSO equals the risk that the DSO is willing to accept without the need for mitigating measures. A risk is a combined factor of probability times impact. The probability is set as the yearly occurrence where the impact is defined based on several of Stedin’s company values.

The categories for which the impact on company values are quantified are ’Safety’, ’Quality of service’, ’Financial’, ’Law and Regulation’, ’Clients and image’, and ’Sustainability’. The probability is set as the yearly occurrence of the risk varying from lower than once in 10,000 years to more than 1000 times a year. In the matrix included in this report as fig. 6.2, only the categories of 'Quality of service' and 'Financial' are shown. Overall, the levels of the company values are equalised along a monetised value.

The matrix is primarily applied on a portfolio level; it indicates the risk of a certain problem that exists over the whole grid of Stedin, e.g., the risk of cybersecurity or the prolonged use after the maximum lifetime of a certain asset type. Until recently, Stedin's policy was to not accept any risks on the levels of sufficient capacity. However, the strain of the energy transition forced Stedin to also apply a 'risk mitigation'-based evaluation of its bottlenecks. These are not evaluated on the benchmark for minimal cost-efficiency but are furthermore evaluated in the same manner.

Stedin generally accepts, and will not take actions to mitigate, risks that are quantified with a level of "Laag" (L), Dutch for "Low". Its risk appetite, the risk above which the DSO will immediately intervene and take mitigating action, for its electrical power system is quantified with the level "Zeer Hoog" (ZH), translating to "Very High". Risks quantified between L and ZH (M, H, ZH) are mitigated, but only if deemed economically feasible.

The risk associated with a certain bottleneck or operational problem is in general equal to the frequency of occurrence (probability) multiplied by the impact of this bottleneck on company values. The estimated frequency, or probability, can be easily assessed through quasi-static load flow or contingency analysis. The problems of overloading and voltage dips and swells relate to several company values but are overall difficult to express.

Voltage dips and swells may lead to violation of *Law and Regulation*, of which several levels of severity can be specified but the actual severity to be expected remains subjective. Overloading may be measured in the deterioration of the asset and possibly the resulting failures. These can be quantified in the higher probability of *downtime of customer connections* and loss of income due to *increase of the DSO's CAIDI* (both categorized under 'Quality of Service'). However, as indicated in section 2.1, the redundancy in normal operation means assets are mostly operated at half their capacity, severely reducing the risk of deterioration[1].

One of the most accurate and feasible ways of quantifying the impact is directly through the theoretical, probable *downtime of customer connections* and *loss of income due to the increase of the DSO's CAIDI*. These can be determined through the probability and impact of a fault in the network. DSOs have extensive data on the failure frequency of certain assets and asset types. The probability of a fault in a part of the grid can be calculated based on this data. By combining this data with a probability of overloading, the probability of actually overloading a normally redundant asset can be calculated. The energy that is excessively drawn or supplied above the asset's capacity (both as a function of thermal capacity and voltage constraints) can then be used to calculate a share of connections or energy that will need to be curtailed to fulfill the constraints. The impact can then be assessed by evaluating either the *'not delivered'-energy* through the curtailed energy, or the *downtime of customer connections* and *increase of the DSO's CAIDI* through the average duration of switching operations, diagnosis, and repair. Which impact is used depends on which is highest, a function of the number and size of the system users in this grid.

A second, feasible way to quantify the risk of an outage is by regarding the *energy* that is excessively drawn or supplied above the non-redundant constraints of the grid *as not delivered*. The advantage of this approach is that it can be identified rather quickly. Even though the risk matrix values the costs of this energy quite high, in comparison to an actual outage, the overall impact and resulting risk are probably relatively low. The increase in downtime and CAIDI are likely to entail a much higher impact. The higher frequency potentially compensates this; this would, however, differ per case. Aside from the drawbacks, this approach does have multiple significant benefits. Firstly, it is commonly applicable for both voltage as thermal capacity constraints, in excessive consumption as generation. Second, the relation between the application of flexibility and risk mitigation is much easier to assess. Also, the value of curtailed connections or energy due to the failure frequency analysis may often be as abstract as it uses the 'not delivered '-energy based on redundant operation. DSOs often lack the controllability

[1] As already described in section 2.1, it may seem counter-intuitive to apply flexibility to resolve a bottleneck that only occurs in fault conditions. However, to ensure unconditional redundant operation, just as is the case with reinforcement, DSOs are likely to apply flexibility even if a condition would only arise when the redundancy is addressed.

Impact	Quality of service Non-delivered energy	Financial Financial damage	Nearly impossible <0.0001 times per year	Very improbable 0.0001 - 0.001 times per year	Improbable 0.001 - 0.01 times per year	Possible 0.01 - 0.1 times per year	Probable 0.1 - 1 times per year	Yearly 1 - 10 times per year	Monthly 10 - 100 times per year	Daily 100 - 1000 times per year	Permanent >1000 times per year
Very big	1GVAh – 10GVAh	10M€ – 100M€	L	M	H	ZH	EH	EH	EH	EH	EH
Big	100MVAh – 1GVAh	1M€ – 10M€	V	L	M	H	ZH	EH	EH	EH	EH
Medium	10MVAh – 100MVAh	100k€ – 1M€	V	V	L	M	H	ZH	EH	EH	EH
Small	1MVAh – 10MVAh	10k€ – 100k€	V	V	V	L	M	H	ZH	EH	EH
Very small	100KVAh – 1MVAh	1k€ – 10k€	V	V	V	V	L	M	H	ZH	EH

Figure 6.2: Risk-matrix of DSO Stedin with two examples of measures of impact. These values are subject to frequent change.

to curtail but a part of the grid and, more importantly, lack the insight to determine the actual impact of such an operation.

Therefore, the approach using *'not delivered'-energy* is chosen to assess the impact of bottlenecks. However, it is noted that solely using the 'not delivered'-energy probably underestimates the actual risk and asks for specific attention when comparing solutions.

6.2.2. Risk of applying flexibility

Similar to the risk of a bottleneck, the risk associated with the application of flexibility is defined as: *the probability that the available and applied flexible power is insufficient to resolve the encountered problem multiplied by the impact of this problem on the company values.*
The latter is generally equal to the impact of an overload before flexibility or reinforcement is applied. The probability that available and applied flexibility is insufficient depends on:

- the ability of the asset to assist;
- the temporal availability of the assets;
- the probabilities of the risks associated with the request for flexibility;
- and the current state of operation.

As mentioned in section 4.1.1, Stedin prognoses bottlenecks of the future according to SETIAM, which uses (characteristic) profiles along with growth and efficiency factors. Aside from the scenarios not providing a single truth, the exact time, duration, and magnitude of an encountered problem can not be predicted. However, the assessment using these profiles provides a general idea of the conditions under which such bottlenecks arise.

In practice, the profiles are also heavily influenced by large connections and should be seen as a center-line along with probable margins. When designing grids, the rule of thumb is that engineers consider a certain margin at least equal to the loss of the largest generator and the largest consumer when determining the minimum and maximum loading. This rule should also be applied when determining the minimally required flexible impact. Aside from a flexible resource deviating from the requested profile, a large consumer or generator, depending on the direction of the encountered bottleneck, that deviates from its prognoses can also trigger overloading. Therefore, I argue *that the probability of a flexible resource deviating from its prognoses is equal to that of a general consumer or generator doing so.*

An equal risk for general system users and flexible resources deviating from their prognoses does not mean that the risk should not be taken into account, but that the margins should be kept such that safe operation is always guaranteed as it would be in a situation without flexibility. Therefore, the risks equal for flexible resources and large consumers or generators are described but assumed to be considered in normal grid operation. These risks are included in *the ability of the asset to assist:* P_a. An example is the inability to respond due to being cut off from the grid due to a fault.

The temporal availability of an asset: P_b, is defined as the general availability of an asset to assist over time. It can be defined as the average time an asset is available as a percentage of the total time. The time the unit is unavailable can be due to maintenance, repair, or its main process simply not being executed/available. An example of this is the percentage of time an EV is connected to the charger. This factor can be adjusted if the temporal availability is almost certain to match with the encountered bottleneck. Potentially, the generation and load profiles of the resources can be consulted for this.

The risks associated with requesting flexibility: P_c, includes the communication infrastructure required for addressing the flexibility and also the availability of sufficient data. If a bottleneck is not recognised, it can't be acted upon. A project by Dutch DSO Liander [42] where residential flexibility is used to decrease congestion showed quite disappointing results. The report determined this to be due to several causes, among which five relate to the availability. ICT infrastructure is explicitly mentioned, both for insight in current power flows as for controllability of flexibility.

The current state of operation reflects the range of instantaneous and temporal technical capabilities of the asset concerning its current operational state and its impact on the bottleneck, as determined in section 5.4. This factor does not influence the overall availability of the asset but does influence the extent to which the flexibility may be applied. The generation and load profiles of the resources can again be consulted for this.

6.2.3. Summary

The overall probability that the available and applied flexible power is insufficient to resolve the encountered problem is a function of the combined availability $\{P_a, P_b, P_c\}$ and the potential impact of the assets on the problem, evaluated per time frame.

The combined availability of a single asset is given by eq. (6.1).

$$P_A = P_a * P_b * P_c \tag{6.1}$$

Evaluating the impact and availability of all available flexibility resources results in a solution-space representing the unavailability as a function of the required, flexible impact. This solution space can be tested along the maximum allowable unavailability following from the risk evaluation. The upper limit of the risk indicated as ”L” in the matrix, and thus the maximum risk allowed, is set at €3,000 per year. This can also be derived using the double logarithmic scale of the risk matrix. The maximum allowed risk is corrected for the expected frequency and duration of the bottleneck to represent the maximum risk of a single bottleneck.

Equation (6.2) creates a list F of tuples with the probability p_m of having the available impact L_m. This list is based on the m possible binary combinations B of the n evaluated assets. This list is sorted based on L and can be created for multiple different operating points or occurrences of the bottleneck to determine the minimum combined evaluation of availability and impact.

$$\begin{aligned} m &= 2^n \\ B &= [[B_1, B_2, \dots, B_n]_1, [B_1, B_2, \dots, B_n]_2, \dots, [B_1, B_2, \dots, B_n]_m] \\ F[m] = (p_m,\ \Delta L_m) &= \left(\prod_{i=1}^{n} |(1 - B[m][i]) - p_i|,\ \sum_{i=1}^{n} B[m][i] * L_i \right) \end{aligned} \tag{6.2}$$

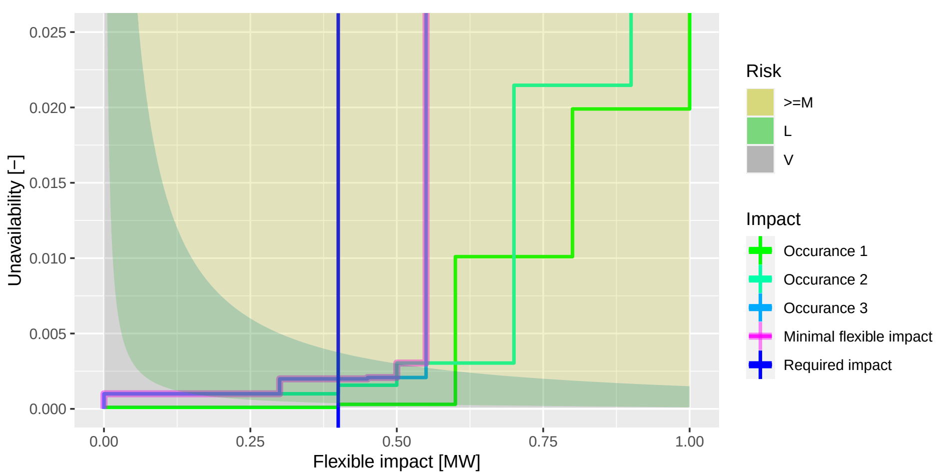


Figure 6.3: Evaluating the availability of flexible resources towards the provision of flexible impact for three occurrences of overloading. In this example, the flexible power is capable of delivering enough impact to mitigate the risk sufficiently.

An example of such an evaluation is given in fig. 6.3 for the case mentioned earlier, where three characteristic times of overloading are evaluated. The impact of three flexible resources is evaluated on all three occasions. As the product of the y- and the x-axis represent a certain risk after the mitigation, this risk can be evaluated using the limits of the risks represented by the shaded areas. ”Minimal, flexible impact” shows the worst-case scenario of the combined three resources. In this example, the three resources together can sufficiently guarantee enough flexible power to mitigate the risk.

Using this evaluation, the available flexible power can be evaluated on sufficient impact and availability, determining the overall sufficiency of the flexibility.

6.3. Flexible resources

The previous sections described requirements on regulatory, environmental, temporal, and technical aspects. These sections showed that the ability of flexibility to be deployed as an alternative to investment depends on numerous factors.

This section describes the aspects on which the flexible resources are judged and doing so, describes the flexible resources on these aspects. The aspects are listed in table 6.1, and consist of the *instantaneous* and *temporal* abilities and constraints (where active power is shown in generator convention), the *voltage levels* it’s able to influence, *availability* constraints, and the *potential* in 2030 (shown as ”Stedin’s service’s area potential/national potential”).

The introduction of this thesis defined flexibility as *”The ability to shift or adjust levels of generation or consumption based on a variety of incentives”* [1]. Thus, certain incentives lead to system users using the ability to shift or adjust the levels of consumption or generation. This shows that certain resources can do this without compromising the fulfillment of their own ’goals’.

The actual goals originate mostly from consumption. Examples are a heated house, sufficient energy content in the battery of your EV to get from one place to another, etc. The ability to shift generation and consumption while still fulfilling these goals is best explained using the concept of Multi Energy System (MES). This section will therefore start with the description of this concept.

6.3.1. Multi-Energy Systems

MES is a concept in which energy demand and supply are described through multiple energy vectors (different forms of energy flows, e.g., heat, electricity) provided through the optimal interaction of multiple energy systems (e.g., the electricity grid and gaseous energy carriers). Thus, the energy system is considered using a holistic approach, where the provision of energy for specific end-use can be provided through multiple systems, overall increasing the robustness and flexibility of the provision [74, 75].

The concept of MES consists of interactions between multiple energy sectors. For example, in the past, heat was primarily provided using boilers powered by the gas sector. However, with the electrification of heating and the introduction of heat pumps, the electricity sector interacts with the gas- and heating sector. Figure 6.4 shows a significant number of possibilities regarding energy system integration. Facilitating these interactions should lead to more (cost-)efficient use of resources and networks, overall higher robustness of the system, and, consequently, reduced capital expenditure of network reinforcement [75].

Chicco et al. [74] visualize a MES as a system of nodes that are connected through branches, similar to the representation of the distribution grid given in section 2.2. The difference is that these nodes are no longer solely locations for generation or consumption to be connected. Instead, these are ”multi-energy nodes”, representing different MES components, or combinations thereof, able to convert or store energy of different forms. The branches are no longer solely cables but represent the coupling of these nodes by the different networks (e.g., electricity grid, gas grid, District Heating (DH) system).

The input and output, the storage, and conversion can be represented in flow vectors, state vectors, and conversion efficiency matrices [74]. Along these representations, constraints can be defined for the steady-state and temporal capabilities of the components and storage (nodes) and the networks (branches). These can include but are not limited to rated power, storage capacities, and energy flow constraints.

	Levels of influence	Instantaneous abilities	Availability constraints	Temporal constraints	Installed potential	Primary Objective
Supply side flex						
DG:						
- Peakshave						
- Emergency power						
CHP						
- CE-CHP						
- Turbines						
DRG						
- Small						
- Large						
- Cable pooling						
- Drop N-1						
Demand side flex						
Res. Demand Response						
- Appliances						
- EVs						
- HVAC (HP)						
Industrial demand response:						
- Load shedding						
- Load shifting						
Demand/supply flex						
Storage						
- Gen. Battery storage						
- V2G						
System integration						
- P2G						
- Fuel cells						

Table 6.1: An overview assessing the capabilities of flexible resources.

When referring to flexibility as an alternative for grid reinforcement, the constraints provided by the electricity grid are, of course, of special consideration. By expressing the constraints of different forms of energy into their translation to the electrical domain, the electrical flexibility can be expressed in up- and downwards variations for each of the other domains. This results in a feasible operating region in which electrical flexibility in the form of active power can be provided. In the context of fig. 5.2, this constraint is addressed as the ”Main driver”-limit.

Furthermore, as described by fig. 5.2, *the instantaneous abilities* of the flexible MES-node are constrained by the apparent power limit of the point of common coupling and that of the interface. Appendix C shows the substantiation of the RSO of the assets in table 6.1 and its shaping of the ’Instantaneous abilities’-column.

Using a combination of different MES resources, the flexible operating region can be increased. An example of MES is given by fig. 6.5, where active power flexibility is required due to a surplus of DRG. The optimal operating point can be determined along a heating constraint of 1 p.u.

The operating point can be deconstructed in the P2G and HP vectors or on the three vectors of P2G, HP, and boiler. The optimal construction depends on additional optimization strategies (reducing CO_2-emissions, increasing economic efficiency, etc.).

The optimal deconstruction due to an optimization strategy influences the marginal costs of devi-

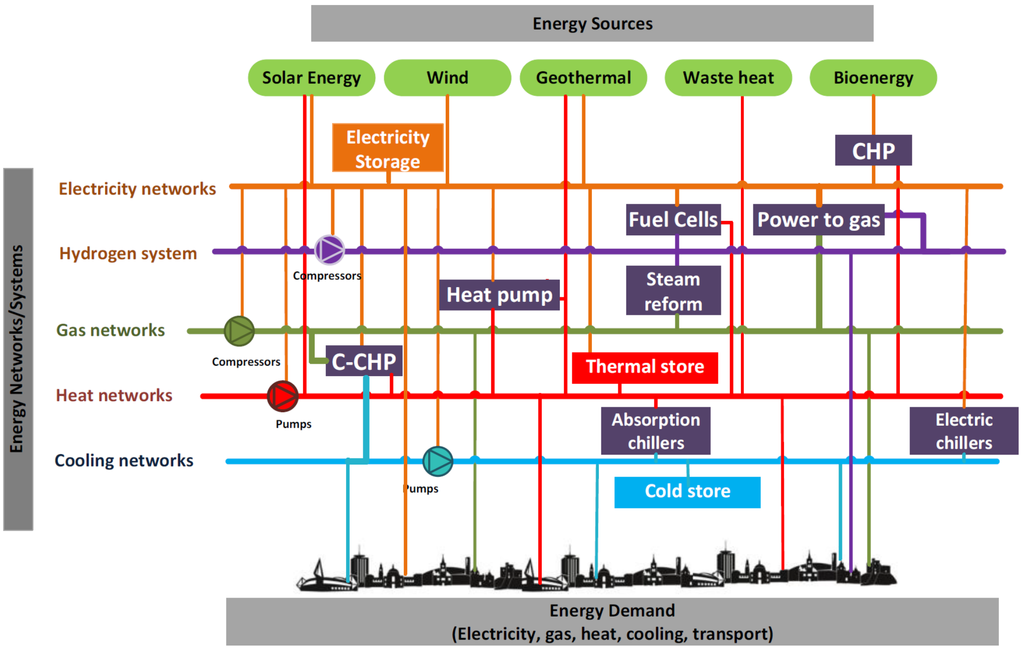


Figure 6.4: Different energy sectors interacting through specific MES-assets (adapted from [75])

ating from its exchange with the electricity grid and is, therefore, an important aspect. This aspect is covered in table 6.1 under the column *'Primary Objective'*.

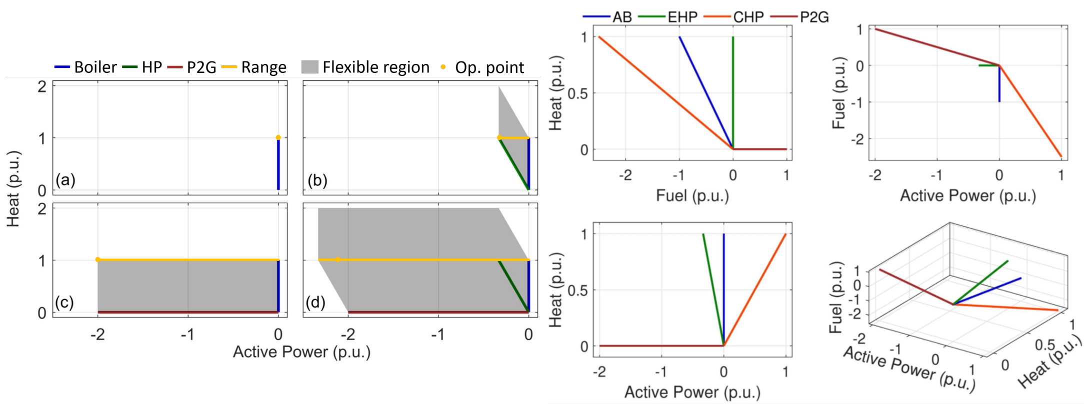


Figure 6.5: The flexible operating region as a function of vector-representations of MES-assets, and constrained by a heat demand of 1 p.u., increases as more assets are integrated. This is visually represented by the Minkowski-sum of the vectors. As the alternative, in this case, was set to be curtailment, converting the surplus using P2G is deemed more efficient (adapted from [74]).

Aside from its Primary Objective, the resources may already fulfill an additional secondary objective that uses its flexibility. These are other markets in which the system users can benefit from offering their services, for example, ancillary services for the TSO. Even if resources are effectively 'unlocked' by the DSO and currently not active in flexibility markets, the system users operating these resources are likely to maximize their profits and pursue other options [76]. However, providing services in other markets is likely to *constrain the availability*.

Other constraints of the *availability* of an asset can include maintenance of conventional distributed generation as diesel generators or CHP, the weather-related production of DRG, and the share of EV being connected and available for V2G or allowing reduced charging power. For the latter, for example, Netbeheer Nederland assumes a continuously available connected capacity of 10% of electric vehicles with 60 kWh capacity and 5 kW charging. In Stedin's grid, this results in 0.1-0.22 GW of charging power to be available in 2030 [27]. Furthermore, availability may vary seasonally, e.g., due to the interaction with weather and temperature or the seasonal application of peakshaving plants.

The concept of MES can be drawn wider to include all sources of flexibility. Each grid-connected generator or consumer (generator or load, as described in section 2.1) can be seen as a MES node that interacts with the electricity system. It can convert electricity to another form, or use it directly, to obtain a certain goal. Whether this node can be used as a flexible resource depends on the conversion process and the underlying driver.

The solutions in the form of flexibility are commonly categorised in supply-side flexibility, demand-side flexibility, and demand-supply flexibility. The remainder of this subsection describes how these categories fit in the description of MES. The following subsections further describe the remaining characteristics of flexible resources as discussed in the introduction of this section, and shown in table 6.1, supported by the concept of MES.

Demand-side flexibility as a MES node

Demand-side flexibility relates to all actions that consumers can take to reduce a mismatch of generation and consumption. It can relieve both a shortage as a surplus of energy by respectively decreasing or increasing consumption. Demand-side flexibility can be represented as a node that converts electric energy to another domain, where the demand for the converted form has a certain flexibility.

For instance, if the example of heating is considered, the end goal is a comfortable temperature. The electrical energy is converted to heat, which translates to an increase in temperature as a function of thermal inertia. Within the predefined range of temperature, the conversion process of heating and thus electricity consumption is flexible. HPs, for instance, also often use a form of heat storage. The acceptable range in temperature of this storage also provides flexibility.

TKI Urban Energy researched the application of flexibility in the built environment in the Netherlands and considered the application of HPs as flexible resources promising [70]. Other Heating, ventilation, and air conditioning (HVAC) equipment, as, for instance, air conditioning, is deemed less suitable. This is due to the impact on the user, lower controllability, and, commonly, the lack of an additional storage element besides the thermal inertia of the property.

Another possibility using this example is converting the energy from a different supply. The example of a hybrid HP can fulfill the demand for a comfortable temperature by addressing a different supply vector, the gas network [77].

A more abstract example is the demand shifting of a production process. The end goal here is produced goods being available at a predetermined time. However, the process might also allow more goods to be produced; the remainder can then be temporarily stored. Because of overproduction at an earlier time, production can be decreased later. Similar to thermal inertia, this possibility resembles that of electrical energy storage, just in a different form. This is beneficial, as electricity is typically expensive to store [11].

A second possibility is specified as load-shedding. In this case, the production process is shed, and the demand in the other domain remains unfulfilled. This results in a significant effect on the consumer its operation. Therefore, it can only be a proper alternative for a process without strict production requirements and with meager benefits, thus low marginal costs for the application of flexibility [70, 78].

Another possibility using this example is the spatial shifting of a process. This can again be demonstrated as the coupling of nodes through branches. For example, if at a certain node, the production cannot be realized due to a constraint in the supply of electricity, a node at a different location might be able to fulfill the supply of this product through an interconnecting branch (transport of goods). An example of this is a data center, which operation may be shifted to another data center [79]. In this case, the communication network can be seen as a connecting branch.

The possible range of states of conversion in which the node can operate while still fulfilling the demand defined in the other domain represents the flexible operating range of the node. All examples fulfill the demand for the converted form of electrical energy through different means, be it storage, a different energy vector, or interaction with another node. The operating state which is eventually maintained again depends on optimization, for instance, maximizing economic benefits (i.e., cheapest combination).

Supply-side flexibility as a MES node

Supply-side flexibility relates to all actions that generators can take to reduce a mismatch of generation and consumption. It can relieve both a shortage as a surplus of energy through respectively increasing or decreasing generation. Supply-side flexibility can be represented as a node that converts energy from a certain domain (e.g., fuel in conventional generation, wind or solar in the case of renewable generation) to the electrical domain.

Considering generators as MES nodes can be more abstract. In the event of generators, there is not necessarily an obvious driver in another domain that drives the node to convert to electrical energy. Here, the driving force is the objective optimization. For DRG, the energy in the other domain is free. To maximize profits, the energy is commonly converted to electric energy to the fullest extent, where conversion is only decreased in the event of negative prices. The flexibility this resource may provide, therefore, commonly originates from decreasing its conversion. However, doing so means profits are no longer maximized, and the system user may wish to be compensated.

In several provinces in China, curtailment of large renewable generation to retain a stable grid was already applied as early as 2012 [80]. Essentially, curtailment can be seen as a sign of an insufficient flexible system [74]. It can also be seen as a logical consequence of higher shares of intermittent renewable energy sources with low capacity factors.

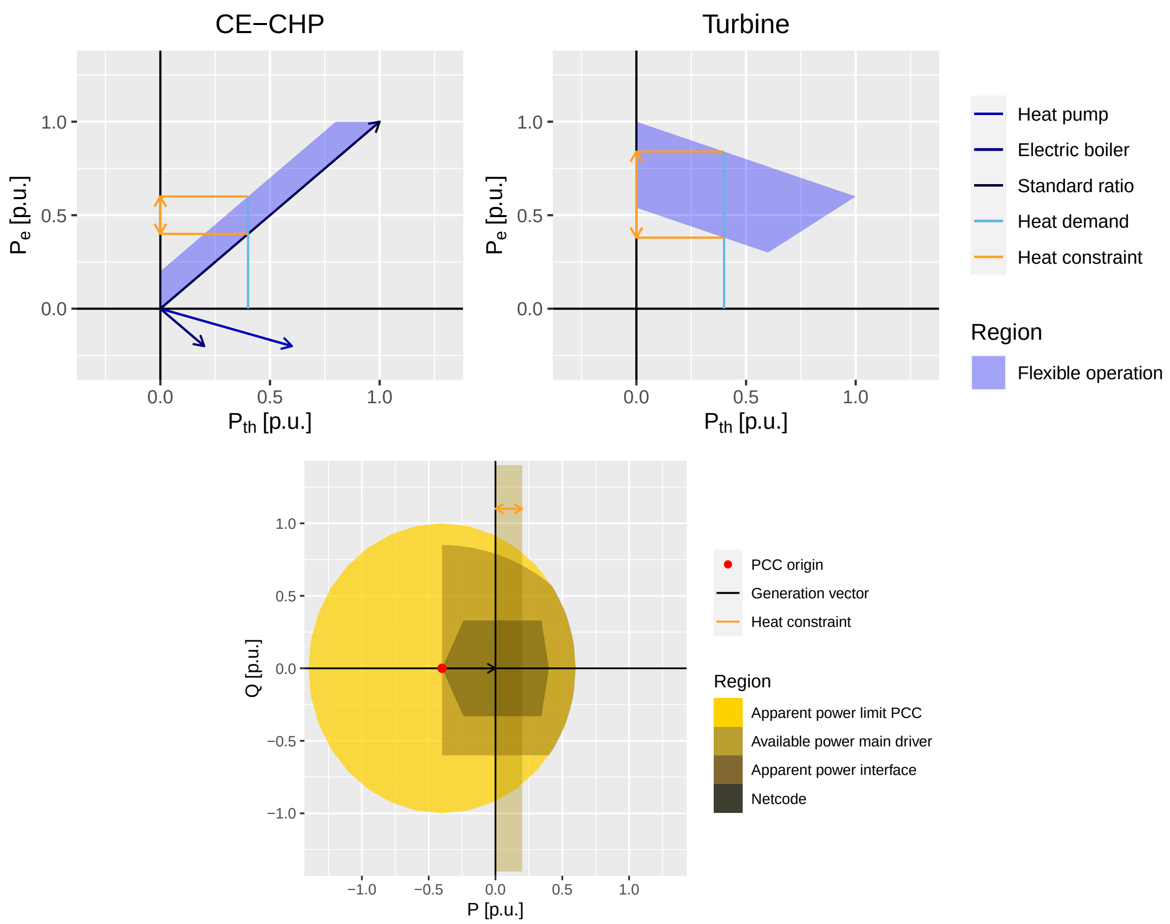


Figure 6.6: Relation between thermal and electric power output (inspired by [80] and [81]) and its projection on reactive and active power capabilities of a CHP.

An example of another generator, a CHP, is shown by fig. 6.4. This generator, however, does have a certain 'driver' in another domain; that of heat requirement. Figure 6.5 and fig. 6.6 show along the 'Standard ratio'-vector that for every unit of heat, one unit of electric power is produced. The heat demand constrains the production of electrical energy. However, as shown in fig. 6.6, the vector describing the relation between electrical and thermal power possibly allows for some variation by dissipating additional heat.

If the losses in heat are properly compensated, the system user may be willing to generate more electrical power at the loss of dissipating the excess heat. In the other direction, an additional heat demand may again be fulfilled using another vector, or the goal of maintaining temperature may allow some margin in operation.

A third example of the supply-side flexibility considered in this section is that of conventional diesel generators. Diesel generators are predominately used in cases where there is a high shortage of power for a relatively low duration of time. Examples of this are events, during grid maintenance, peakshaving, or as emergency power. The first two of these are often mobile applications, as the requirement of their service can be planned quite well. However, the latter is often stationary, as it cannot be predicted when its service is required.

The interesting aspect of using emergency power plants as a flexible resource is that the plant does not have a primary objective with a stable grid. This means that the installations are nearly always available for providing flexibility. The optimization, therefore, commonly results in no production. To incentivize system users to submit their generators as flexible resources, the marginal costs of generating energy through the generator instead of withdrawing from the grid need to be fully compensated.

The European Union and the Dutch government exempts stationary generators for emergency applications with less than 500 running hours per year from its emission standards. This, however, does not hold in the case of peakshaving or grid-feeding operation other than required for testing [82] (Activiteitenbesluit, Art. 3.7.b [83]). Therefore, maintaining documentation of running hours, additional operational costs as maintenance and fuel, and upgrading equipment to fulfill emission requirements can negatively influence the business case of implementing emergency power for flexibility applications.

Demand-supply flexibility as a MES node

Demand-supply flexibility includes all aspects that can be seen as both demand and supply-side flexibility. Boßmann and Eser [84] describe it as *".. the spatial or temporal decoupling of supply and demand by extending electricity grids or energy storage capacities"*. Along this definition, it encompasses the fields of storage, interconnections, and grid-side flexibility (for example, re-configuring of grids through distributed automation). From these three, storage is the option that applies to the distribution grid and complies with the earlier definition.

Consumption and generation can be locally matched using storage without temporal shifts in the actual consumption and generation. Flexibility in the form of storage is therefore also known as temporal decoupling and peak shifting. This is because the peaks in electricity usage are handled by the storage system and shifted towards an off-peak period. As there are many similarities with demand shifting, the distinction is made that the energy is returned as electrical output.

Here also, storage as a MES node lacks a driving force in demand and is driven by optimization. This is no longer solely steady-state optimization (i.e., balancing energy flows) but also optimization over a time frame. The strategies maintained for this optimization determine its operating points and determine the required compensation to deviate from these operating points.

Energy storage systems can be categorised by the timescale in which they operate. Papaefthymiou et al. [85] compare several storage solutions on their timescale, maturity, and decentral operation (see fig. 6.7). This timescale can range from short-term operations as balancing, to mid-term operations as (spot) energy trading, to long-term operations as mitigating the effect of seasonal variability.

Storage as an alternative for reinforcement is best categorised as decentral mid-term storage. The Netherlands is deemed geographically less fit for applications of pumped hydro [86]. Besides, options as Compressed Air Energy Storage (CAES) and pumped hydro are generally not considered 'decentral' storage. Therefore, according to fig. 6.7 [85], the main solution for energy storage as an alternative for reinforcement is battery energy storage.

As indicated in section 3.2.3, storage plays an important role in the scenarios of Netbeheer Nederland. The total instantaneous ability of battery storage is assessed to be between 2.6 and 15.6 GW. The battery storage solutions implemented in the scenarios consist of large-scale battery storage, residential battery storage, and V2G solutions.

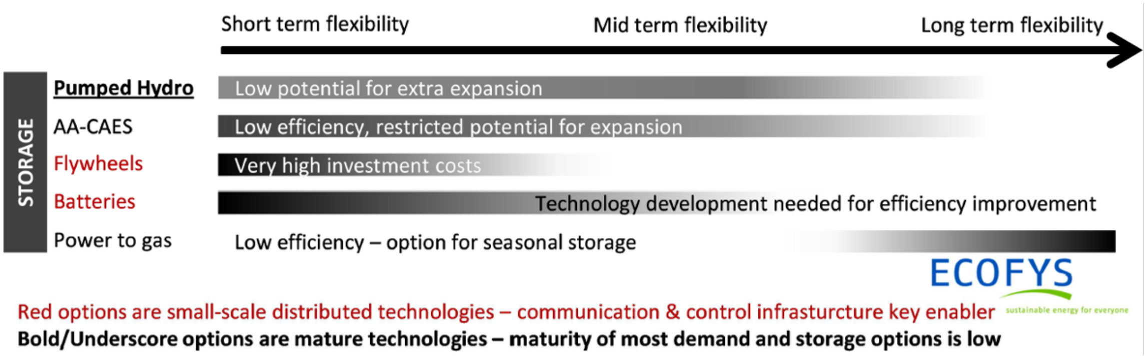


Figure 6.7: Comparing storage solutions on timescale, maturity, and decentral operation (adapted from [85])

6.3.2. Levels of influence

The distribution levels in which the flexible resources can mitigate a bottleneck depend on their location and their (aggregated) size in respect to the bottleneck. The different grid levels have different characteristics and include different types of flexible resources. The combination of these three allows for different possibilities to influence bottlenecks.

Figure 4.3 shows that Stedin's grid contains/the distribution grid can be divided into three distribution levels: LV, MV, and IV. Overall, The flexible resources described in table 6.1 can influence their own connection level and upper grid levels. The resources can therefore be subdivided into the lowest grid levels they can impact. Overall, the discussion on this topic is best highlighted with the example of the LV grid. This subsection will end with a summary to draw the conclusions to a wider scope.

LV grids

Resources located in LV grids are commonly described as residential flexibility. Residential flexibility includes residential demand response, which includes all actions which change or shift the usual household consumption pattern based on an incentive or command. This makes residential demand response a trade-off between the consumer's comfort and flexibility in the power system. Residential demand response can be categorised based on the impact demand response has on daily life. Gottwalt et al. [17] groups appliances in three categories: non-deferrable loads, fully automatic controllable devices, and semi-automatic controllable devices.

The first category includes TVs, electric cooking, and lighting, appliances of which the user most likely will not adapt its usage. The second category involves some form of customer interaction but consists of appliances that are highly deferrable. These include what Van Groot-Battavé [16] describes as 'wet appliances'; dishwashers, washing machines, and dryers, but also includes EV-chargers. The last category includes devices with low impact on user comfort. These are mostly devices that perform actions with a large, often thermal, inertia, like heating, ventilation, and air conditioning HVAC.

Based on these categories, table 6.1 defines the following residential demand response categories; household appliances, EV-chargers, and HVAC. Aside from residential demand response, residential flexibility also includes small-scale DRG and residential storage.

The LV grid is characterized by highly dispersed loads and generators with overall low predictability. No load prognoses have to be submitted for LV system users. Instead, grid planning and BRP use characteristic profiles. These profiles are typically quite accurate for high aggregations, where disturbances are relatively small. However, at lower aggregations, such as single LV grids, such profiles are not sufficient to accurately predict when and where bottlenecks will arise. Applying flexibility in LV

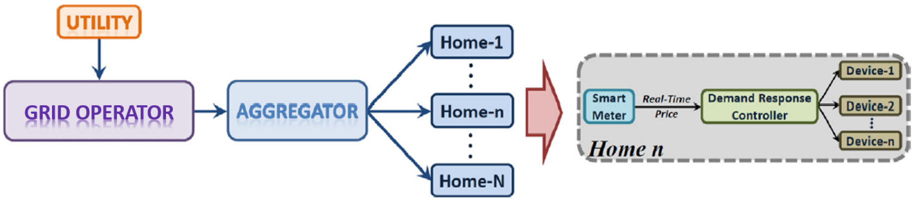


Figure 6.8: Functionality of an aggregator in demand response (adapted from [21])

grids, therefore, requires real-time intervention. This is generally also troublesome, as insight in the assets of the LV distribution grid is currently insufficient.

Because of the relatively low magnitude of power of residential equipment in respect to the required power for alleviating common bottlenecks, many participants would be needed to make any significant impact. As it is inefficient for multiple potential service users (TSO, DSO, and BRP) to deal with that many participants individually, an intermediate entity is often required: an aggregator.

The aggregator enforces the required action from households and performs the individual reconciliation after the service [21]. The aggregator only recently acquired a legal position with the introduction of the CEP. Along this new legislation, aggregators should enjoy the same status as other participants in service markets for TSOs or DSOs [66].

The application of residential flexibility based on a dispatchable principle, as assumed in this thesis, has severe technical challenges. Trading the available flexibility first requires reliably assessing or forecasting the available potential of flexibility. This requires extensive knowledge of the states of the appliances, their changes over time, and the system users' need for these appliances. E.g., reducing consumption at a certain time slot is only possible if there is consumption taking place by a controllable device at that time, and vice versa. Furthermore, mitigation of the real-time-pinpointed bottlenecks requires a fast, centralized, coordinated response that controls the flexible resources remotely. This, of course, puts the resources at a cybersecurity risk.

DSO Liander [42] showed that when applying residential flexibility, a significant risk exists in the uncertainty of uncontrollable load and the overall availability of controllable load. In this study, the aggregator was responsible for both the uncontrollable and the household's controllable loads. Forecasting errors in the uncontrollable load increase in lower aggregations. Especially for LV grids, with around 100-200 households per transformer, Liander has shown this error to be significant.

Previous pilots and projects have focused mostly on reducing peak loading on a national scale. However, this strategy will probably prove less or insufficient for LV- or even MV-grids unless it is specifically coordinated for this (for instance, in the form of local energy communities); participants can be highly dispersed, participation in earlier projects seem quite limited [21], and the forecasting error increases significantly with lower participation [42]. These results show that residential demand response using a dispatchable principle is more fit for application on higher voltage levels.

Autonomous control

Central coordination of dispatchable, residential flexibility is shown to be difficult. A solution to the uncertainty of residential loads may lie in autonomous control. Several studies highlight the benefits of using decentral autonomous control in mitigating capacity and voltage problems. Examples of such forms of control are voltage-based active power control ($P(V)$), voltage-based reactive power control ($Q(V)$, or $\cos\varphi(V)$), active power-based reactive power regulation ($\cos\varphi(P)$), non-unity constant $\cos\varphi$, and decentrally coordinated charging with voltage constraints. Such autonomous control mechanisms reduce the need for centralised control and insight and its accompanying cybersecurity risks.

Examples of autonomous control for consumption are given in [87–89]. [88] and [89] show reactive power control with a capacitive $\cos\varphi$ and coordinated charging with voltage constraints (in this case with bidirectional charging, V2G), respectively. Leemput et al. [87] compares uncoordinated EV charging against charging with a voltage droop characteristic.

Autonomous control for mitigating generation bottlenecks is also applied. Several sources highlight the social benefits of controlling solar PV in LV grids, mostly related to higher penetration and overall

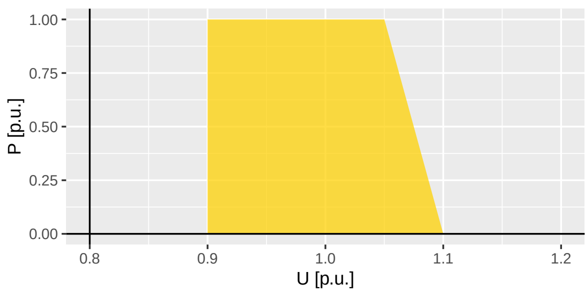


Figure 6.9: Curtailment as a function of measured voltage (adapted from [34, 90, 91])

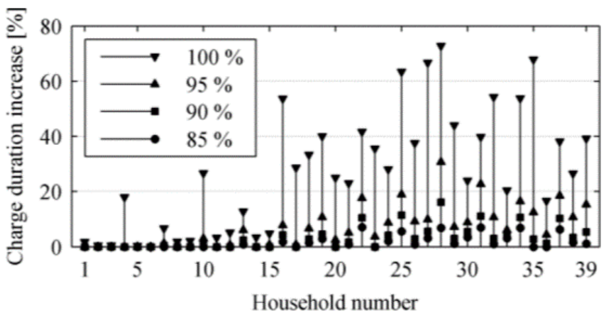


Figure 6.10: Unfair droop regulation disadvantages for households further up the feeder (from [87]).

energy yield [34, 63, 90, 91]. An example voltage-based autonomous active power control has been shown to cut the net present value of needed investments in half [34] by linearly decreasing power output when terminal voltage rises (see: fig. 6.9) [34]. Besides active power curtailment, [34] and [63] also name regulation of reactive power based on a voltage droop function and regulation of $\cos\varphi$ based on power output (mandatory in Germany).

Overall, the applications of autonomous control resulted in lesser voltage deviations and sometimes, with voltage-based active power regulation, no violations. These strategies are modeled to be effective in both consumption and generation. However, such methods also show significant drawbacks that need to be overcome.

Critics state that large implementation of independent autonomously controlled devices may give rise to new instability problems [34]. They believe that such a system is only possible if the control parameters have been thoroughly researched and if their implementation is mandated. Also, the system users have a right to use their contracted capacity. Therefore, curtailment or limiting capacity through these autonomous strategies without proper grounds is not likely to be accepted by system users. This would, for example, require the DSOs to reimburse prosumers for their curtailed generation. Especially the latter is indicated as a severe barrier towards the use of this resource [70].

Voltage-based strategies ($P(V)$, $Q(V)$, $\cos\varphi(V)$) will disadvantage system users with higher voltage sensitivity towards the fed power ($\Delta V/\Delta P$) (e.g., further from the transformer). This holds for both generation and consumption. $\Delta V/\Delta P$-specific parameters could improve this. However, applying such parameters is labor-intensive and, for generation, leads to overall lower production [90, 91]. An example is provided in fig. 6.10; the higher the household number, the larger the distance to the transformer, and the higher the charge duration increase due to limited power levels.

Furthermore, strategies that do not curtail/limit active power but control the share of reactive power (const. $\cos\varphi$, $\cos\varphi(P)$) show fairer results. However, their effectiveness differs between grid topologies and asset types based on the R/X-ratio of the grid. Overall, the effects are limited, and the desired result is less certain/not guaranteed.

6.3.3. Integration of new solutions

As described, energy storage is a main pillar in all scenarios. According to the scenarios by Netbeheer Nederland, residential storage and LV connected V2G storage make up a significant amount of the total capacity. At the moment, the amount of general decentrally installed batteries is still low. Aside from the balancing and frequency response market, the business case for battery storage is quite poor.

The operation of storage systems for energy arbitrage and increasing self-consumption does not have a positive business case, due to, among others, the current 'Salderingsregeling', current taxing system, and overall relatively small differences in energy prices [2][69]. Due to the price of batteries and the aforementioned disadvantages, the installed capacity is expected to remain low in the near future to rise shortly before 2030 [27].

Because of the relatively poor business case for batteries, which now mostly consists of the balancing and frequency response market, the question arises of what the best location for integrating battery storage is. Logically, the application of flexible resources for balancing and frequency response shows a very high simultaneity factor. In a scenario with large-scale integration of decentrally installed batteries, such a simultaneity can result in large power peaks in the distribution grid [77]. This, of course, is not limited to batteries alone.

Netbeheer Nederland [77] assumed centralised locations for energy storage in its model for "The grid of the future" (i.e., near DRG plants or HV stations). This overall minimised the stresses on the distribution network in its model. However, they indicate that incentives towards decentralizing storage, as a business case from congestion management, may severely influence the eventual flexibility provision.

Highly decentralised storage might alleviate bottlenecks by reacting to local incentives (i.e., reduce congestion, DSO). This is beneficial for the DSOs. On the other hand, flexibility might be locked in in the event of a request for system flexibility. Due to the relatively high instantaneous abilities, its flexibility is then likely limited by the constrained access to upper grid levels. However, if grids are eventually reinforced, local flexibility is no longer necessary, and a portion of the revenue stream disappears. Stecca et al. [76] indicate that unclear revenue streams due to, among others, as described above, are the main barrier towards integration.

The overall technical abilities, constraints, and possible secondary objectives of V2G are similar to those of residential batteries. However, the discussion on its integration differs. Where a discussion can be started about the benefits of residential batteries compared to larger, upper grid, utility-scale storage, it is already clear where EVs will be connected. Whether it is beneficial to utilize the capacity of their batteries as flexible resources and to what level this flexibility should be facilitated is similar to the overall integration of flexibility in LV grids.

The remaining resources of table 6.1 are most commonly connected at the MV and IV levels. These large-scale flexible resources contain industry-specific loads and processes of sufficient size (or can be aggregated to sufficient size) to provide flexibility, large distributed conventional or renewable generators, and utility-scale storage and conversion.

Dispatchable demand response is likely to be insufficient to resolve LV bottlenecks. At higher aggregations, i.e., higher voltage levels, the defects of the strategies may be sufficiently mitigated for residential demand response to actively participate in the flexibility market. For LV bottlenecks themselves, autonomous control methods may mitigate the impact of the large-scale integration of ETTs. However, using such strategies will effectively keep the access of residential flexibility to upper grid levels limited, leaving large shares of residential flexibility 'locked'.

For the integration of new assets as storage, distributed renewable generation, P2G assets, and P2H assets, DSOs need to determine where these assets are best connected. Even though DSOs do not have any control to determine where these new assets will be located, their relation does influence the business case of these assets and possibly also influences future investments. It is in the best interest of both parties to determine the most efficient point of connection.

Overall, DSOs need to determine if the deferring of relatively low LV (and possibly also MV) invest-

[2]For more information on the barriers formed by the "Salderingsregeling" and the current taxing system, *see:* [69])

ments outweighs the lack of flexibility in upper grid levels and the system balancing pool. Currently, where DSOs lack capital, labour force, and room in spatial planning, the answer will most likely be affirmative.

6.3.4. Temporal constraints

Temporal constraints can relate to three main aspects: capacity constraints, shifting and rebound effects, and seasonal variability. Capacity constraints deal with the limited energy content or provision limits the duration a certain impact can be made. They include the fuel for conventional generation and the capacity of storage options. The capacity constraints apply to the storage vectors of the MES description.

Shifting and rebound effects are not constraints but temporal effects originating from constraints set to the storage vector.

Shifting effects occur when a capacity constraint is set at a certain point in time. To fulfill this constraint, a certain average level of conversion needs to take place. By maintaining a higher level of conversion now, a lower level must be maintained later. An example is the charging of electric vehicles. The primary objective is to guarantee sufficient energy content (SoC) for the user to reach its destination. By decreasing the power levels at the start of charging, the charger may need to significantly increase its power draw near the closing of the given time frame to still reach sufficient SoC.

However, shifting effects are not solely reserved for actual storage capacity. They can also apply to loosed constraints provided by, for instance, thermal inertia. Turning on a P2H unit prematurely will raise the temperature closer to the upper constraint, causing the 'option' to turn the P2H unit on later to become unavailable, shorter in duration, or lower in power. The flexibility of the energy exchange depends on the thermal inertia of the heated property and the arbitrary levels of the desired comfort defined by the residents. According to Hillberg et al. [7], thermally well-isolated houses (an overall common requirement for electric HP) can defer the heating through HP up to three hours [70].

Other examples of shifting effects are industrial energy-intensive processes with a low capacity factor in which intermediate or raw products can be temporarily stored [92]. Paulus and Borggrefe name several examples of such processes, as aluminum electrolysis, paper pulp production, and electric arc furnaces. In such processes, the energy is not stored in a generic form but as the energy content of an end-product. Thus, a process with these characteristics can be shifted over time with a relatively low influence on the overall process.

Rebound effects are similar to shifting effects and deal with the degradation of energy content. In some cases, maintaining a higher content in the storage vector may result in a larger degradation. An example is the case of heating and cooling. If heat is 'stored' at a higher temperature, the increased temperature difference may result in more energetic losses (degradation of the heat content/absence). These losses might need to be compensated later, resulting in additional electrical consumption. Zhang et al. [19] call this the "payback" of the operational procedure.

Seasonal variability occurs when demand or consumption is related to seasonal changes as temperature or weather. Examples of resources that show seasonal variability are P2H resources, CHP, and DRG. As bottlenecks themselves are also likely to show seasonal variations, the variability of flexible resources can either be beneficial or detrimental. Bottlenecks originating from higher consumption are typically more severe in winter due to overall higher consumption, where bottlenecks originating from generation are typically higher in summer due to the relation with solar production. See fig. 6.11.

For CHP, for example, the seasonal varieties are beneficial as heat and electricity requirements have similar seasonal variability. On the contrary, P2H shows detrimental seasonal variation as the heating requirement is lower when DRG production is higher.

A specific benefit of MES is the ability to cope with the integration of DRG through converting the excess energy to forms of other vectors which are cheaper or easier to store. Examples of this have already been given, for instance, heat storage in the form of thermal inertia for HP. However, as mentioned, this shows a significant seasonal mismatch. In addition, fig. 6.7 indicated that P2G could be an option for seasonal storage. In this case, the at-that-point relatively cheap summer electricity can be stored in the form of gaseous energy carriers to be used in times of scarcity in the winter.

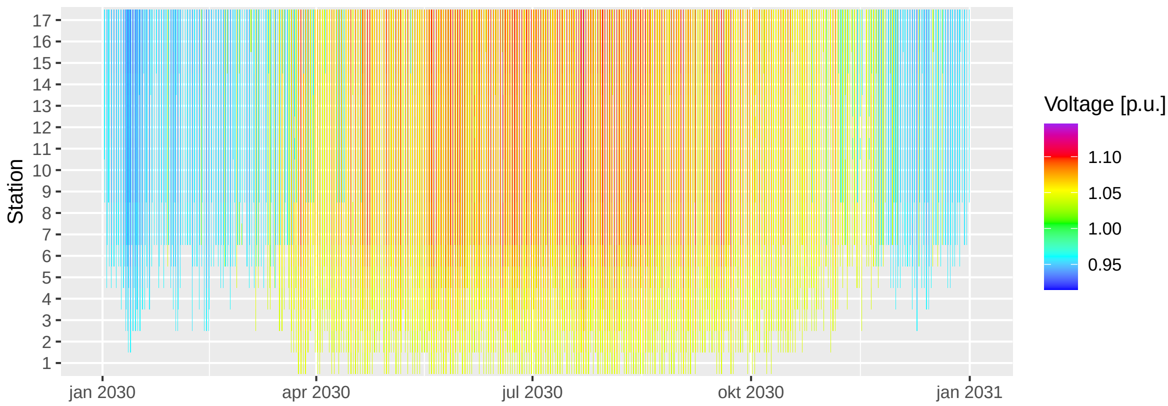


Figure 6.11: Yearly variation of the voltage violations of seventeen nodes in a relatively weak grid. The seventeen nodes are all connected in the same string, showing a very high simultaneity. The limits are set according to the simulations in section 4.2.2.

Challenges towards more large-scale system integration of P2G in the concept of MES have so far been the legal framework. However, the CEP and upcoming Dutch implementation in the form of the "Energiewet" are already more heavily focused on enabling integration of the gas- and electricity systems [93]. Thus, the concept is promising but still very immature.

Temporal constraints, in general, are difficult to take into account and also difficult to determine. Whether, for instance, a battery can solve a bottleneck, of course, relates to the absolute magnitude and duration of the excessively exchanged energy relative to its capacity. However, not solely. Several sources describe that using battery storage solely as a peak shifting alternative to alleviate overloading and voltage problems will prove not profitable [48, 68, 86]. Stecca et al. [76] have also shown that for batteries, pursuing multiple services results in an overall increased revenue stream. Sizing a battery along these numbers therefore does not guarantee sufficient capacity when the battery is also applied for different objectives, as it does not guarantee an optimal initial SoC.

This difficulty also shows in other temporal constraints. Zhang et al. [19] perform an elaborate model consisting of different types of residences, a large database of occupation profiles, and thermal models to demonstrate the application of their performance metrics. These performance metrics are created to provide insight for specific parties, as the energy retailers, aggregators, customers, and system operators. An important parameter here is the available flexibility, which depends on the states of the flexible resources, their rated power, and the temperature of the heated object in relation to its temperature limits. Furthermore, Zhang et al. warn for what they call the synchronisation of operation, where the concurrent operation of multiple HP in residences with similar thermal characteristics results in a higher simultaneity.

In the model of Zhang et al., a centralised control approach resulted in absolute knowledge of all equipment. In reality, that will often not be plausible. However, it becomes clear that many factors influence the available power, and determining it requires extensive communication and connectivity.

6.3.5. Present potential

The future present potential of flexible resources in Stedin's grid is highly uncertain and likely to show a large dependency on the scenarios as shown in Chapter 3. A scenario materializing influences the integration rates of certain technologies. The AM.2021 scenario materializing will result in a large integration of residential DRG relative to the installed power of large DRG. Such a development will likely positively influence the demand for the controllability of residential DRG as it would entail an overall large impact. Similarly, a materialization of IA will likely negatively influence the demand for controllable EV-chargers relative to the materialization of ND.

Peters [94] models different compositions of the future flexible resource-pool fulfilling the demand of the aFRR-market. The thesis demonstrates three scenarios: one where the pool of flexible resources remains similar to that of 2016, one where wind curtailment is added, and one where large scale storage is introduced. The results show that the introduction of new technologies, especially the integration of storage, the prices are significantly reduced. This will likely further reduce the attractiveness for more expensive units, as gas-fired CHP, to join, and therefore further influence the composition of the pool.

One would think that the composition could also influence the market for flexibility. Higher DRG integration leads to a stronger influence of intermittency, this stronger influence leads to more short-term imbalances, and more imbalances lead to higher demand for flexibility. However, Peters also modeled the influence of improved weather and DRG forecasting and showed that this is of relatively less influence.

Characteristics	Technology				
	Combustion engine	Gas Turbine	Steam turbine	FC	Microturbine
Technical data					
Size [MW]	0.01-10	0.03-450	0.5-500	0.001-3	0.05-0.25
Electric efficiency [%]	30-45	24-36	5-40	30-50	22-28
Total efficiency [%]	77-83	66-71	80-90	70-90	63-70
Fuel	Natural-/Bio-gas	Natural gas, light oil	Coal, biomass, waste	hydrogen, natural gas, methanol	Natural gas, liquid fuel
Flexibility data					
Minimum load [%]	20-30	25-40	18-45	ca. 20	ca. 50
Startup-time [hr]	0.03-0.05	0.25-2.5	0.25-10	3-48	0.02-1
Ramp-rate [%/min]	100	15-25	4-10	100	100
Grid level	MV	IV	IV	N/A	N/A
Application					
	Industrial, commercial, residential, DH, Horticulture	Industrial, DH	Industrial, DH, Garbage disposal	Commercial, residential	Commercial, residential
Available decentrally installed potential (national)					
2019 [GW] [95]	3.14	0.80	1.14	N/A	N/A
2019 [GW] [27, 96]	5.80	1.43		N/A	N/A
2030 [GW] [27, 96]	4.36-5.10	1.08		N/A	N/A

Table 6.2: Different types of CHP and their properties [27, 81, 95]. The estimates from [27, 96] include waste incineration with CHP, Large CHP, and small CHP. The share of central/decentral is taken to be equal to that of [95]

The presence of flexible resources is also likely to differ based on the geographical properties of the location. For example, CHP are located near locations with large heat demand. As shown in table 6.2, a prominent example in the Netherlands, and especially Stedin's service area, is horticulture. Other examples are large offices, institutes as hospitals, or DH. Overall, Combustion Engine Combined Heat and Power (CE-CHP) are most prominent. Large-scale DRG is likely to be located in rural areas, where urban areas are likely to contain more residential DRG. Emergency power plants are located near important buildings or institutes where significant damage could occur in case of (long) outages. As discussed in the previous subsection, the future locations of the demand-supply flexible resources are still subject of discussion.

As the scenarios are heavily tied to the composition of generators and consumers, estimates can be made for the present potential of flexible resources under these directions. Examples are DRG, CHP, batteries, EVs, and HP. Other sources are projections based on industry-specific scenarios. For example, the Dutch Data Center Association and REOS, the Dutch government's spatial development strategy organization, assumes an increase in installed capacity of 1.5 GW and 1.8-3.0 GW, respectively [97, 98]. Data centers typically install sufficient emergency power for long-term operation, which can estimate the emergency power generators installed.

For a large part of the resources, it is difficult to assess the share of the installed power that can be used as flexible resources. This will depend on the temporal constraints and variability.

6.3.6. Policy instruments

Policy instruments can be applied to enhance the flexibility of system users by providing regulatory incentives. The incentives can be set up to benefit certain categories as a result of political preferences or aid flexibility in general. The most straightforward way for DSOs to provide these incentives is through the change of tariffs. An example of this is the use of non-dispatchable demand response.

Non-dispatchable demand response is based on variable tariffs that reflect the scarcity or surplus of distribution capacity. Variable tariffs incentivize reducing consumption at peak consumption loading by increasing the tariffs for these periods and vice versa. This is then often accompanied by real-time telemetry feedback of consumption for reconciliation (several minutes time-frames), depending on the type of variable pricing. Three common variants are distinguished: Time of use pricing, Critical Peak Pricing, and Real-Time Network pricing [18, 22].

Time of use-pricing predetermines prices for different time-slots. It is set for a specific period and therefore not prone to changing very often. Therefore, it cannot quickly adapt to changes in the energy system. Critical peak pricing can do just that; it is implemented when a capacity shortage is forthcoming. Real-time network pricing reflects the current scarcity in network capacity in real-time.

A significant barrier towards any variable pricing is that all such strategies are incompatible with the tariff structure currently present in the Netherlands [22]. The current structure is mainly focused on a non-discriminatory and fair distribution of costs. The applications of such structures may lead to discrimination among system users based on their location while simultaneously affecting all connected system users differently [69]. Overall, this could provide DSOs with an unfair power towards system users (for more information on tariff structure, *see:* [22, 68, 69]).

A second significant drawback in applying non-dispatchable demand response is that it is unclear beforehand what the impact of the response to dynamic pricing on a specific bottleneck will be[18]. The impact of dispatchable demand response on system users is higher than that of non-dispatchable, but its effects are clear and, to a certain extent, guaranteed beforehand.

Due to the incompatibility with overall grid operation and variable pricing in network tariffs with the basic foundation of the current tariff structure, non-dispatchable demand response through variable tariffs is deemed unfit for application in the Dutch distribution grid.

Recently, several initiatives have been set up to incentivize certain flexible behaviour from DRG through curtailment: dropping N-1 redundancy and cable pooling. These are specific cases where additional conditions apply to the transport and connection agreement [99].

As described in section 2.2, system operators maintain a level of redundancy in the grid. For TSOs, this redundancy is required by law. for DSOs, it is maintained for its economic security. In some cases, system operators are allowed to **drop the "N-1"-criteria** for generation and use the redundant capacity to allow higher integration levels of DRG. This is officially acknowledged in Dutch legislation from 2021 by a decree from 2020 [100]. For TSOs, this requires permission from the regulating authority. Dropping the "N-1"-criteria is not without conditions to the system operator. This does mean that in the event of maintenance or a fault in which the redundancy is addressed, measures are taken to curtail excess generation immediately. However, this decree does allow more DRG to be connected.

Cable pooling combines the intermittency and the low simultaneity of different types of DRG to use the capacity of a connection more effectively. This is enabled by a decree from 2017, allowing more allocation/measuring points on a single connection [101]. A common example is that of wind turbines and PV. Using this method, both a wind and a PV-plant can be connected behind the same physical connection to the DSO. In the case of simultaneous peak production, the connection limits the amount of power that can be delivered to the grid. However, due to the intermittency and the low simultaneity of the producers, occurrences of simultaneous peak production are rare and curtailment is therefore only rarely required. Especially for existing connections, access to the grid for the new party can be realised much faster and often without the need for reinforcements of the distribution grid. Curtailment is still applied in simultaneous peak production but without any intervention needed by the DSO. Such a construction does require specific agreements between the different market parties owning the assets.

Aside from policy instruments through regulatory organisations such as the ACM or the Dutch government, DSOs can also promote more efficient grid usage initiatives. They can, in advance, aid or lobby industrial or general large consumers to invest in increasing the controllability of their installation. An example is the electrification of loads, which can increase the versatility of cases in which the load can be connected. Overall, the electrification of the industry is a large pillar in the scenarios of Netbeheer Nederland [102]. An example of this is also given by Netbeheer Nederland, where farmers with or near large solar installations use the peak production hours to power electric water pumps to irrigate their lands instead of diesel-fueled pumps [99].

6.4. Summary

Using section 6.2.2, the risk of a bottleneck and the application of flexibility can be calculated and weighed against the allowable risk. The levels of the probabilities used in assessing the unavailability of a resource will differ for each resource. The information available to the DSO, such as load and generation profiles of the resource and the assets providing insight into the bottleneck, can be used to quantify the levels of P_b, respectively. P_a and P_c may differ per bottleneck and resource and should be determined accordingly.

Table 6.3 shows an overview of the flexible resources discussed in this chapter. Something that stands out is the brackets used in the first column, the *Levels of Influence*. These brackets are used similarly as in the second chapter, where they signal certain conditions. In general, these conditions refer to an important discussion in applying flexibility; local/congestion flexibility versus system/balancing flexibility. However, this discussion's scope can be broadened to flexibility on different levels in general.

The studies consulted for this and the previous chapter shows that several conditions must be fulfilled for flexibility to act as an alternative to grid reinforcement. An important condition is insight and controllability. The preparatory action in the form of requesting flexible resources requires accurate insight on when and where a bottleneck will arise. This, in turn, requires accurate load and generation prognoses and insight into the state of the network. Especially for LV grids, the evaluated studies have shown that this condition is not sufficiently met. The drawbacks of residential demand response (dispersed and limited participation and significant impact of the uncertainty of states and loads at low aggregations) deem it unreliable and insufficient for deferring investment and reinforcement on the LV level. The exception in these situations being automatic control methods, for instance, those based on droop, even though these also have significant disadvantages that would need to be addressed.

This begs the question at what level sufficient communication infrastructure and aggregation are obtained to mitigate these uncertainties and make impact at a reasonable price. This deliberation is furthermore connected to the integration of new resources in the grid. Local storage and P2G, for instance, to a certain extent can defer reinforcements in lower distribution levels. However, if eventual reinforcement is inevitable, the business case of this decentralized storage decreases significantly, and its flexibility might be limited by access to upper grid levels.

These considerations actually draw the discussion of congestion flexibility versus balancing flexibility wider by also considering congestion on different grid levels. An important assumption mentioned in section 5.2.2 says that problems should be solved at the lowest social costs. DSOs might determine that facilitating the full installed capacity of flexible resources for upper grid levels (including transmission) may be more socially beneficial than utilizing the flexibility locally. Such a trade-off is difficult to generalize. It depends on local pricing, bottleneck characteristics, price elasticity, and reinforcement costs, which will need to be evaluated for all included grid levels. Reinforcement for facilitating flexibility is increasingly important when more flexible resources are unlocked, as the utilization of flexible resources is inherently highly simultaneous.

	Levels of influence	Instantaneous abilities	Availability constraints	Temporal constraints	Installed potential	Primary Objective
Supply side						
Diesel generators						
- Emergency power	(LV)-IV	P: + Q: +/-	• Mainte-nance	• Fuel (Days)	NA/ NA	-
- Peakshaving	(LV)-IV	P: +/- Q: +/-	• Mainte-nance • Applica–tion	• Fuel (Days)	NA/ NA	Max. grid utilization
CHP						
- CE-CHP	MV-IV	P: +/- Q: +/-	• Mainte-nance	• Shifting • Rebound • Thermal inertia	NA/ 4.36 - 5.10 GW	Heat provision
- Turbines	IV	P: +/- Q: +/-	• Mainte-nance	• Shifting • Rebound • Thermal inertia	NA/ 1.08 GW	Heat provision
DRG						
- Small scale	LV-IV	P: - Q: +/-	• Weather	None	1.6-3.8 GW/ 12.2-25.5 GW	MPPT
- Large scale	MV-IV	P: - Q: +/-	• Weather	None	1.8-3.8 GW/ 12.2-25.5 GW	MPPT/ Market
Demand side						
Res. demand response						
- Appliances	(LV)-IV	P: +/- Q: 0	• User participa-tion	• Operation Duration	NA/ NA	Comfort
- EV	(LV)-IV	P: + Q: 0	• Plugged in	• Battery capacity • Departure	0.1-0.22 GW/ 0.5-1.1 GW	Sufficient SoC
- Hybrid HP	(LV)-IV	P: + Q: 0	• Temp.	• Thermal inertia	0.9-2.3 GW/ NA	Temp. control
- Electric HP	(LV)-IV	P: +/- Q: 0	• Temp.	• Thermal inertia	1.1-5.3 GW/ NA	Temp. control
Ind. demand response						
- Load shedding	(MV)-IV	P: + Q: 0	• Uncertain	• Operation duration • Maximum delay	NA/ NA	Production
- Load shifting	(MV)-IV	P: +/- Q: 0	• Uncertain	• Operation duration • Maximum delay	NA/ NA	Production

Demand/supply						
Energy storage						
- Gen. Battery storage	(LV)-IV	P: +/- Q: +/-	-	• Battery Capacity	NA/ 2.1-14.3 GW	Uncertain
- V2G	(LV)-IV	P: +/- Q: +/-	• Plugged in	• Usable Battery Capacity	0.1-0.22 GW/ 0.5-1.1 GW	Sufficient SoC
System integration						
- P2G	(MV)-IV	P: - Q: +/-	-	• Other vectors	NA/ 1.0-5.0 GW	Uncertain
- Fuel cells	(MV)-IV	P: + Q: +/-	-	• Other vectors	NA/ 0.0-1.4 GW	Uncertain

Table 6.3: The constraints and capabilities of potential flexible resources.

Using a similar structure as with the evaluation of the impact of ETTs on the identified operational problems in Chapter 2, the potential resources are also rated on their impact on the operational problems. The presence of the resources is not considered in this analysis, only the impact of utilizing the resource as a flexible resource. Table 2.1 is transposed to form table 6.4, as in this case, not the problems but the solutions are evaluated sequentially. The table is accompanied by the below clarification, referencing some of the notes applied in the table.

(1) Overall, the application of flexibility is unlikely to mitigate topological capacity problems, as the flexible resources are generally already connected and available. The exception is, of course, cable pooling. This also applies to the fault currents and unintended islanding. The exception is the application of emergency generators. These are not connected under normal conditions.

(2) Dropping the redundancy will provide the DSO with additional capacity to facilitate distributed generation. Still, it will not alleviate voltage problems or actual physical congestion, as the physical characteristics of the grid or the power flows do not change.

(3) Of the PEID, small residential PV is shown to emit a higher level of harmonics with lower power levels. Curtailing of small-scale DRG is therefore likely to increase harmonics, including DC components [103]. As uncontrolled chargers are normally also operated at nominal power, it could be that these would demonstrate the same effects. However, I did not find research to confirms or disproves this.

(4) The aforementioned automatic droop-based regulating strategies can mitigate the effect of voltage asymmetry. However, if a more centralized and communication-based strategy is maintained, the effects would depend on the control strategy. The same applies to the other LV flexible resources.

(5) Reverse power flows decrease with a decrease of generation or an increase of load. Curtailment is therefore always likely to decrease reverse power flows. However, the other flexible resources may also be applied to compensate for consumption overloading at higher voltage levels, effectively increasing reverse power flows.

(6) The risk of a cyber-threat is likely to increase with the application of any of the flexible resources. An exception is the application of CHP as flexible resources. These are generally already connected to a form of distributed control for their flexibility in other markets.

that

	Effects										
	Capacity		Power quality				Safety				
	Thermal	Topological	Voltage dips and swells	Harmonics and distortion	Voltage asymmetry	DC components	Shock hazard protection	Reverse power flows	Unintended Islanding	Fault currents	Cybersecurity
Supply side flex	(1)	(1)	(1)	(3)	(4)	(3)		(5)	(1)	(1)	(6)
DG:											
- Peakshave	Probable	Unlikely	Probable	Unlikely	Unlikely	Unlikely	Unlikely	Context	Unlikely	Unlikely	Negative effect
- Emergency power	Probable	Unlikely	Probable	Unlikely	Unlikely	Unlikely	Unlikely	Context	Negative effect	Negative effect	Negative effect
CHP											
- CE-CHP	Probable	Unlikely	Probable	Unlikely	Unlikely	Unlikely	Unlikely	Context	Unlikely	Unlikely	Negative effect
- Turbines	Probable	Unlikely	Probable	Unlikely	Unlikely	Unlikely	Unlikely	Context	Unlikely	Unlikely	Negative effect
DRG											
- Small	Probable	Unlikely	Probable	Negative effect	Probable	Negative effect	Unlikely	Probable	Unlikely	Unlikely	Negative effect
- Large	Probable	Unlikely	Probable	Negative effect	Unlikely	Negative effect	Unlikely	Probable	Unlikely	Unlikely	Negative effect
- Cable pooling	Probable	Probable	Probable	Unlikely	Unlikely	Unlikely	Unlikely	Probable	Unlikely	Unlikely	Negative effect
- Drop N-1	Probable	Unlikely	Unlikely	Unlikely	Unlikely	Unlikely	Unlikely	Negative effect	Unlikely	Unlikely	Negative effect
Demand side flex											
Res. Demand Response											
- Appliances	Probable	Unlikely	Probable	Unlikely	Context	Unlikely	Unlikely	Context	Unlikely	Unlikely	Negative effect
- EVs	Probable	Unlikely	Probable	Unsure, research needed	Context	Unsure, research needed	Unlikely	Context	Unlikely	Unlikely	Negative effect
- HVAC (HP)	Probable	Unlikely	Probable	Unlikely	Context	Unlikely	Unlikely	Context	Unlikely	Unlikely	Negative effect
Industrial demand response:											
- Load shedding	Probable	Unlikely	Probable	Unlikely	Unlikely	Unlikely	Unlikely	Unlikely	Unlikely	Unlikely	Negative effect
- Load shifting	Probable	Unlikely	Probable	Unlikely	Unlikely	Unlikely	Unlikely	Context	Unlikely	Unlikely	Negative effect
Demand/supply flex											
Storage											
- Gen. Battery storage	Probable	Unlikely	Probable	Unlikely	Context	Unlikely	Unlikely	Context	Unlikely	Unlikely	Negative effect
- V2G	Probable	Unlikely	Probable	Unlikely	Context	Unlikely	Unlikely	Context	Unlikely	Unlikely	Negative effect
System integration											
- P2G	Probable	Unlikely	Probable	Unlikely	Unlikely	Unlikely	Unlikely	Context	Unlikely	Unlikely	Negative effect
- Fuel cells	Probable	Unlikely	Probable	Unlikely	Unlikely	Unlikely	Unlikely	Context	Unlikely	Unlikely	Negative effect

Negative effect | Unsure, research needed | Context | Probable | Unlikely

Table 6.4: The impact of the flexible resources on the problems identified in Chapter 2. This table shows the impact of utilizing the resource for its flexibility to cancel or defer grid investments, not the impact of the resource itself.

7

Financial feasibility

The definition of the distribution grid provided in Chapter 2 ended with the phrase: *"...at the lowest possible costs"* [28]. In combination with the current regulatory methods described in Chapter 1, this signals that cost-efficiency is an important aspect of the distribution grid. Chapter 6 showed several solutions able to contribute to more efficient grid operation as flexible resources. Whether the application of such resources can be regarded as a valid alternative depends, among others, on the financial validity. To be able to quantitatively compare the flexible resources to reinforcement and determine which flexible resources are feasible, the value of flexibility for the DSO needs to be determined.

How can the value of flexibility for DSO's like Stedin be determined and quantified?

The value of a solution that uses flexibility for a DSO typically relates to the business case in comparison to an investment that acts as an alternative for comparable outcome conditions. The costs, however, depend on the agreements made between the resources and the DSO. This chapter therefore starts with the description of the costs of flexibility and the methods of contracting. Following, the assessment of alternatives is evaluated.

OTE's 'Reinforce unless' specifies a cost-benefit analysis from the view of the DSO for financial feasibility, the Grid Operator Cost-Benefit Analysis (Netbeheerder Kosten-batenanalyse (NKBA), in Dutch), through which the willingness to pay for the DSO can be determined. Aside from a cost-benefit analysis, another method used in grid planning is Least Worst Regret-assessment (LWRA). Where the NKBA aims to provide an average indication of the costs and its possible spread over the different scenarios, the LWRA aims to be the least wrong whichever scenario will prove most right. The latter, although not considered in the framework, seems to capture some of the values implicit in the NKBA.

7.1. Costs of flexibility

The costs of applying flexible resources as an alternative for reinforcement, of course, differ for many applications. Firstly, they depend on the regulatory structure that is used to obtain sufficient flexibility. Second, the price can vary over different types of resources, different use of the resources, and dependencies of the resources on policies as determined by transcending regulations (*see: Social Cost-Benefit Analysis*, section 7.2).

7.1.1. Cost structure

The costs of flexibility depend on the way flexible resources are addressed. The resources' capacity can be periodically contracted to guarantee their availability (to a certain extent). This option reduces the probability that insufficient flexible resources are available. Another possibility is to operate along a free market structure, where flexible resources can bid their flexibility to offers by the DSO in the form of bottlenecks. The DSO can then pick the cheapest alternatives for sufficient impact. However, this approach does not guarantee the DSO of sufficient available flexible impact.

To evaluate the structure that is most likely to succeed, a comparison is made with current market-provided ancillary services in the grid. These services are currently mainly contracted by the TSO, however, applications as redispatch have been contracted by DSOs as well. The Dutch TSO TenneT currently contracts the following services [104]:

- **Frequency containment reserve (FCR)** or primary frequency control is a balancing service contracted to maintain the frequency of the grid in the event of sudden changes in the system. The providers of this service are required to linearly adjust their withdrawn or injected power with the deviation of frequency from its nominal set point. ENTSO-e, the European Network of Transmission System Operators for electricity, rules specify TSOs to maintain a certain level of available capacity. Capacity is contracted day-ahead without guarantee of sufficient availability. Payment is capacity-based and reconciliation is based on measurements of the resource.
- **Frequency Restoration Reserve (FRR)** is a balancing service that can be subdivided into secondary and tertiary frequency control:
  - Automatic FRR (aFRR) is contracted to restore the balance in the event of power mismatches on a national scale (i.e., unallocated exchange with neighboring systems). Capacity in the form of energy bids is contracted day ahead. The providers of this service adjust their output based on a real-time set point. Sufficient capacity is guaranteed through capacity contracts, obliging contracted parties to bid their contracted capacity. Payment is energy-based and reconciliation is based on measurements of the resource.
  - Manual FRR direct activated (mFRRda) is activated to restore the balance in the event of incidents or long-lasting deviations. Capacity in the form of power is contracted through daily bids. Upon addressing the resource, the full contracted capacity must be available within a specified time. Payment is energy-based and reconciliation is based on measurements of the resource.
- **Reactive power** or voltage control can also be subdivided into two services. The first, primary control, operates through a droop curve along the voltage to provide initial robustness to the system. It is a constant uncompensated service provided by all connected, generating parties. Secondary control is contracted annually through a tender. As reactive power control is location-specific, the resources are addressed based on their location and availability and not a specific market procedure. Payment and reconciliation are based on measurements of the resource.
- **Redispatch** is contracted under the term 'reserve power for other purposes'. The service is used to spatially shift levels of generation or consumption to solve transport problems or congestion. Bids can be submitted seven days in advance. Due to the spatial aspect, this service requires specifying the location of the system user in the topology (often through its European Article Numbering (EAN), a numbering system used for identification of grid connections). TSO TenneT does not necessarily follow a standard procedure for addressing the resource and reconciliation. However, recently GOPACS was set up with this exact goal.

Based on the above evaluated services, the services with the highest similarity are 'Redispatch' and 'Reactive power'. The main relevant aspect is that the services are bound to the location of the provision. The high dependency on location will mean relatively few flexible resources will be available. Also, especially in mitigating voltage problems, a market-based approach for solving structural bottlenecks through flexible resources will likely continuously benefit the same asset(s) due to their preferential position.

The service of 'Reactive power' is a special case where the TSO is generally the only customer in the market. Also, the reactive power exchange of grid-connected generators is generally kept at zero, meaning its reactive power capabilities are fully and solely available to the TSO. Active power exchange on the other hand is of course bound by general usage and possibly also the balancing markets.

The similarities with 'Redispatch' are most obvious, and a similar approach therefore seems most fitting. However, the TSO benefits from the obligation for system users with a contracted capacity higher than 60 MW to submit redispatch-bids. Where TSOs are relatively certain of sufficient redispatch offers, DSOs, aside from Congestion Management, do not have this privilege and neither does prospective legislation offer any additional perspective in this field [105, 106].

Evaluation of the two most similar processes both show significant drawbacks, and this does not end yet. If flexible resources are aware of their preferential position (in network topology or as a monopolist/near monopolist), they might try to abuse this condition. This is called gaming. A simple example is demanding high compensation for the offered flexibility. However, if the resource becomes too expensive, the alternative methods of guaranteeing sufficient capacity become more attractive for DSO. Another, more cautious method, is purposely withholding, limiting, or overpricing the application of the flexible resource under certain conditions to trigger a redispatch action from the DSO. When this redispatch action is triggered, the flexible resource bids its flexibility and thus obtains its own desired result in the process while also obtaining income from the DSO. This, however, requires the provider to be aware of the 'certain conditions'. The problems originating from gaming decrease with the size of the bottleneck due to higher market liquidity and level of competition [69].

Gaming is hard to counteract. Cramton, a Professor of Economics focused on researching market design, describes several methods towards decreasing gaming in a local flexibility market, the most important are named as *Transparancy, Simplicity, Competitiveness, and Robustness* [107]. The key aspects translate themselves in a market with sufficient competition to mitigate the influence of single parties, where transparency on high prices and simplicity allow new players to enter the market, and where robustness safeguards sufficient capacity in the event of insufficient liquidity in the market.

The safeguarding of sufficient capacity through capacity contracts is supported by Poudineh and Jamasb [57] in their study towards flexibility as grid capacity enhancement and can be realised through DSOs contracting resources with sufficient capacity for obligated bidding. This guarantees DSOs of sufficient capacity to mitigate the bottlenecks at reasonable prices for events when the liquidity provided by the market is insufficient. This is also supported by the prospective change in the Netcode (Congestion management amendment proposal [105]), which specifies that DSOs are allowed to contract system users obliging them to provide offers similar to the aFRR contracts.

Such contracts however do differ from aFRR and mFRRda agreements. They oblige the resource to bid the remainder of capacity in the agreed direction, not to reserve the complete capacity. After all, the resources are selected such that (part of) their collective implementation guarantees sufficient capacity under all expected conditions. In theory, this allows the resources to still be used in the aFRR market, only solely in the congestion mitigating direction. Predetermined prices agreed with these resources act as a backstop, an upper limit of the flexibility prices. These prices can possibly be built up the same way as mFRRda prices, by also considering a possible minimum factor over the EPEX spot price, but can also be determined through for example a descending clock auction [57].

Unfortunately, the predetermined backstop again does not fully eliminate the possibility of gaming. Even though the backstop eliminates high prices, the frequency of occurrence can still be influenced by manipulating transport prognoses. This, however, does decrease the probability that the gaming party will also be the one benefiting, and thus decreases the incentive to try.

Sagdur [108] specifies another possibility to disincentivize gaming in his thesis, which includes maintaining a fixed and a variable price for the capacity contracts. In this case, the variable price for the application of flexibility can be made small in comparison to the fixed price to limit the incentive for gaming. This, however, diminishes the effect of the free market, as the marginal prices of non-contracted flexible resources are likely to be higher than those of the contracted resources.

Based on the evaluation in this section, the application of flexible resources as an alternative to reinforcement is further limited by possible market conditions and the possibilities of gaming. Overall, a combination of several of the currently used procedure seems to be most promising. When considering that FRR and Redispatch procedures are now contracted by the Dutch TSO TenneT simultaneously, the procedure seems to show a high resemblance to aFRR. The following is proposed:

The combination is made to form a free market in which DSOs can make an offer in the form of a bottleneck, to which flexible resources can offer bids in the form of power exchange. The DSO can award the resources with the highest mitigating impact per monetised value. To guarantee sufficient impact to solve the bottleneck, the DSO procures the 'obligation to bid' from flexible resources through capacity contracts. Both non-contracted and contracted parties are allowed to offer bids, where contracted parties are limited to an upper-price level agreed beforehand, referred to as a backstop-price.

Reconciliation is based on the market-clearing price and the demanded and realised beneficial deviation from its profile.

7.1.2. Pricing

Strategic and stochastic bidding by balance responsible parties would allow to implement simultaneous market propositions in aFRR and congestion markets, especially due to the spatial indifference of aFRR. However, only to a certain extent. The addition of extra demand for flexible resources from DSOs to the already increasing demand for flexibility from TSOs results in an expected increase of the price of flexibility.

At a certain price, flexible resources will become more expensive than the reinforcement alternative. The DSO is then no longer realizing sufficient capacity at the lowest possible costs. Therefore, DSOs need to determine when this 'tipping point' is reached, as to when an alternative (e.g., reinforcement) becomes more economically efficient. Also, DSOs need to determine this 'tipping point' well in advance considering the lead times of certain reinforcements.

As specified earlier, making accurate predictions about the grid of the future has always been difficult but increasingly so with the dynamic and unpredictable nature of the energy system. Also, the prices of flexible resources are highly dependant on the type of resources. The procurement and contracting method chosen eventually resembles that of aFRR. Logically derived, aFRR will be the main competitor for the service. The price of flexibility is therefore assumed to show similar variations as that of aFRR.

The thesis of Peters [94] describes a model of the Dutch aFRR market under different scenarios from 2015 to 2030. This model uses the projected imbalances as a consequence of among others DRG forecasting errors, load forecasting errors, and outages. This model is used to identify the sensitivity of the imbalance duration curve and the imbalance prices, towards changes in the flexible resources and their characteristics; and towards changes in the forecasting of DRG.

Peters uses several assumptions to make a prediction on the prices of flexibility for the future. The author specifies that the model was made for the purpose of scenario assessment, therefore, it does not provide perfect representations of the prices of aFRR in the upcoming years. One major conclusion is that the prices of flexibility are likely to rise to high levels for the current providers of flexible capacity (i.e., conventional generation). However, the introduction of new flexible resources as battery storage and DRG curtailment under the determined conditions may lead to severe reductions in these prices. This results in levels and variability near equal to those modelled for 2015 under lower DRG penetrations.

The prices of aFRR are for a large portion determined by the pool of flexible capacity. The marginal costs can vary greatly for different types of resources. A pool that largely consists of DRG-curtailment, demand response, and battery storage has a low dependency on fuel and CO_2 prices. This pool, however, has dependencies on weather changes and customer behaviour and may therefore show strong variations in season and time. If the pool is to consist of mainly flexible gas-generators, the fuel and CO_2 prices become more important.

Gathering estimates from prices from the curves provided in the thesis of Peters would not be justified. Firstly, because non of the curves provided show a combined scenario, but more importantly because the results are highly dependant on the input. For instance, the liquidity and composition of the market in the future.

As Peters specifies, the model does not sufficiently capture the complexity of the market for use in business applications. However, signalled by the low sensitivity towards DRG-forecasting errors and under the assumptions of the Netbeheer Nederland-scenarios showing higher integration of storage as used in the thesis, a larger portion of other 'new technologies' that can function as flexible resources, and a total mix of flexible resources showing a low dependency on fuel and CO_2 prices, the prices of aFRR and flexibility are likely to stay relatively constant.

7.2. Decision process

In line with the importance of *"...at the lowest possible costs"*, 'Reinforce unless' specifies that the decision for the most valid option should be based on costs and benefits. The cost-benefit analysis proposed in the framework is set up to integrate well with the biennial 10-year investment plan of the system operators in the Netherlands. As described in rule 9 of the ”Key policy and regulation principles for the development of the framework” in appendix B, the cost-benefit analysis of the alternatives can be done in two ways:

1. The NKBA focuses solely on the socialised costs that the grid operator must incur to guarantee sufficient capacity through pursuing a specific option.

2. The Social Cost-Benefit Analysis (”Maatschappelijke kosten-batenanalyse”, MKBA in the framework) focuses on the overall social costs and benefits of the energy system as a whole when pursuing a specific option. This approach nears that of an integral energy system.

The NKBA is described as the minimal social cost-benefit analysis that can be performed. As the benefits of all the options are the same, only the costs that are incurred to supply sufficient capacity are compared. The NKBA acts as a financial comparison for the costs incurred by the DSO and passed on to the system users.

The **Social Cost-Benefit Analysis** can range from considering multiple grid levels to nearing the approach of MES. This results in an optimization problem highly dependant on policies and requirements set to promote or discourage certain fields of operation. In general, the Social Cost-Benefit Analysis was found to transcend the overall scope and goal of this analysis. Such an analysis is generally more fit for a higher level, to determine guidelines and set policies that present themselves in the NKBA. Examples of this are the monetization of greenhouse gas emissions, the monetization of risks through the risk matrix, and legislation, as the CEP’s Redispatch Article (Article 13, paragraph 5a of EU directive 2019/943 [2], *see:* section 5.2.2).

Aside from a cost-benefit analysis, another method used in grid planning is **Least Worst Regret-assessment (LWRA)**. The LWRA has a similar structure as the NKBA where only the costs are considered in the analysis. However, where the NKBA awards the solution with the lowest average costs over the different scenarios, the LWRA awards the solution which exhibits the lowest difference in costs in comparison to the optimal solution for the scenarios. It is therefore a minimizing regret-based strategy, where regret is defined as the difference between the optimal result and the chosen result [109].

The framework argues that the chosen cost-benefit analysis allows DSOs to choose the solution that realises sufficient capacity at the lowest costs. Furthermore, the analysis is said to aid in quantifying the ’implicit’ values of the alternatives; the value of deferring investment and the value of excess capacity. However, the effect on the actual financial risk and opportunities towards the DSO actually seem to remain quite implicit in the framework, only to be interpreted from the visualization in a bar graph. National Grid [109], an English TSO, has published a review of their Network Options Assessment, their methodology for assessing reinforcements and possible alternatives, using LWRA. This review shows that especially for the purpose of realizing sufficient capacity under uncertainty, such a methodology can provide insight into which solutions are likely to include underutilised capacity.

The first subsection describes risks and opportunities that need to be considered when comparing alternatives. The second subsection describes the valuation of a solution for a certain scenario as based on the socialised costs. It then follows up by using these valuations in both the NKBA and the LWRA. The last subsection compares the two methods on providing insight and the comparative assessment.

7.2.1. Financial risks and opportunities

The risk that applying flexible resources as an alternative for investment forms consists of two parts. The first is the risk described in section 6.2.2. The additional risk taken on by choosing flexible resources over investment, expressed in monetary terms, represents the yearly amount of ’reserve’ that has to be made to account for the taken risks. This essentially forms an additional expense. The second risk is the spread of possible expenses associated with possible solutions for different scenarios. Furthermore, the framework specifies an opportunity in deferring the value of investment

Risk Matrix

In the evaluation of eq. (7.3), the costs of risk is different from the others. DSOs should exert caution with this method as the factor $C_{yr,\ \omega,\ \text{risk}}$ is not actually part of the allowed, socialised costs. Processing the costs of risks in the socialised costs would provide a perverse incentive where DSOs are effectively rewarded for taking risks. Instead, the costs of risk are solely for the purpose of assessing different solutions. As the risks are combinations of probability and impact, they do not define actual costs. However, when evaluated on a top-level, if the risks are quantified correctly, the 'risk mitigation' based prioritisation of bottlenecks should result in yearly expenditure approximately equal to the calculated accepted risk.

In short, the risk that flexible resources add to the system should be accounted for as such. If mitigation is not deemed cost-efficient, the accepted risk may theoretically increase up to €3M. However, a valuation of €$10/kWh$ results in a relatively high willingness to pay for mitigation over accepting risk; the cost efficiency of risk mitigation is bound to be sufficient. The risk acceptance after applying flexibility may be no more than €3000, and is therefore not likely to be the determining factor.

Uncertainty costs

As described in the introduction, the number of bottlenecks and the required work and capital associated with it are large, while the capacity and budget to carry it out are in short supply. Furthermore, due to an increase in land-use speculation and overall less room for utilities, DSOs are finding it increasingly difficult to find sufficient feasible locations for new assets. A shortage of personnel, a shortage of budget, a shortage of available space, and an increase in bottlenecks combined are leading to increased lead times.

In the event of long lead times, the application of flexible resources might initially provide more leeway and time for the reinforcement to be realised. Therefore, when signalling the bottleneck, flexibility first originates as an opportunity. However, it is possible that this changes when flexibility is applied as a long-term alternative. Unexpected developments as a consequence of the dynamic behaviour of the energy transition and uncertainty of flexibility prices may lead to shifts in the comparison of the business cases of the alternatives.

The risk associated with longer lead times requires DSOs to be aware of the uncertainties in the price of flexibility. To be sure the possible risk is sufficiently captured and weighed in the comparative analysis, the spread, and more importantly specifically the maximum, of possible flexibility prices should be kept sufficiently large.

Deferring investment

The value of deferring investment consists of an explicit value and an implicit value. The explicit value can originate from a decreasing trend in investment cost or a discount factor (Weighted Average Cost of Capital, WACC) which is higher than the prospected increase of investment costs. In reality, these differences are not likely to return a positive result. Overall, the WACC estimate for the near future is relatively low in relation to the low interest, where prices of assets have been increasing [110].

The implicit value of deferring an investment is specified as the ability to reduce the possibility of unused capacity or disinvestments through a better understanding of the developments of the bottleneck [26]. However, it does this along a set of scenarios as if these would be frozen over time. As, in reality, such scenarios develop continuously along developments in the grid, this 'better insight' is highly circumstantial. As these projects typically have long lead times and investments are made for very long periods of time (regulatory lifetimes, i.e., up to fifty years [111]), the deferring of investment is unlikely to contribute to an increase in certainty [109], as they will have been replaced by new ones. Only in the event of specific uncertainties, e.g., is a soccer stadium going to be built or not or irrevocable political decisions, deferring may be beneficial.

7.2.2. Valuation

Financially comparing the application of flexible resources as an alternative to reinforcement requires the solutions to be monetised in a comparable value. As for reinforcement, the benefits are overall similar. The difference originates from the costs. The socialised costs over a specified time-frame are discounted to the Net Present Value using eq. (7.3), where the WACC represents the interest or return of the invested capital and ω represents the scenario. This calculation has to be performed for each of the alternatives, for each of the scenarios.

$$n_1 = \text{Number of energy scenarios} \tag{7.1}$$
$$n_2 = \text{Number of evaluated flexibility prices} \tag{7.2}$$
$$\omega = [1 .. n_1 * n_2]$$
$$NPV_\omega = \sum_{yr=0}^{z} \frac{C_{yr,\ \omega}}{(1 + WACC)^{yr}} \tag{7.3}$$

The yearly costs $C_{yr,\ \omega}$ can be determined through the method provided in eq. (7.5), based on the method provided in the framework. Based on interviews of colleagues working with ACM's regulatory accounting methods, it was found that the formula used in the framework included a mistake. Equation (7.5) corrects that mistake. This method expands on the method used in the framework by also considering the risk associated with applying flexibility or possibly even the risk acceptance of slight overloading. As described in the subsection before, DSOs should exert caution with the factor $C_{yr,\ \omega,\ \text{risk}}$.

$$C_{yr,\ \omega} = (C_{\text{capital}} + C_{\text{depreciation}} + C_{\text{operational}})_{yr,\ \omega} \quad (+C_{yr,\ \omega,\ \text{risk}}) \tag{7.4}$$

$$C_{yr,\ \omega,\ \text{capital}} = (GAW * WACC)_{yr,\ \omega}$$
$$C_{yr,\ \omega,\ \text{depreciation}} = \begin{cases} C_{\text{investment}}/\text{reg. lifetime}, & \text{if } (y \leq t \leq (y + \text{reg. lifetime})) \\ 0, & \text{otherwise} \end{cases}$$
$$C_{yr,\ \omega,\ \text{operational}} = C_{yr,\ \omega,\ maintenance} + C_{yr,\ \omega,\ flexibility}$$

$$GAW_{yr,\ \omega} = \begin{cases} C_{\text{investment}} * (1 - \frac{yr-y}{\text{reg. lifetime}}), & \text{if } (y \leq t) \\ 0, & \text{otherwise} \end{cases} \tag{7.5}$$

To compare the deferral of investment through flexibility, and possibly also the deferral of flexibility through the acceptance of the risk, three moments in time are identified: x, y, and z. The analysis starts at $t = 0$, this is the time in which a bottleneck starts to arise and the DSO starts to encounter a certain risk. This is followed by $t = x$, where the DSO starts to apply flexible resources to mitigate this risk. At $t = y$, the DSO counteracts this risk through reinforcement of the bottleneck. $t = z$ represents the end of the analysis. The different alternatives do not necessarily need to include $t = x$ and $t = y$, nor does crossing $t = y$ necessarily mean that applying flexibility stops. Combinations are possible.

Aside from the energy scenarios of Chapter 3, the costs $C_{yr,\ \omega,\ flexibility}$ should also include an additional variation based on the minimum and maximum possible prices of flexibility as described in the previous section. These prices can be varied per time frame in which flexibility is contracted based on the DSOs expectations and should be kept sufficiently large.

7.2.3. Grid Operator Cost-Benefit Analysis

The method specified by the framework is similar to the method used by system operators to compare reinforcement alternatives. It compares the Net Present Value (NPV) of the different alternatives over a specified time frame. The DSOs are required to assess and substantiate their reinforcement choices based on a variety of scenarios. For some of the reinforcement alternatives, for instance, the application of flexibility, the costs associated with resolving the bottleneck will differ with the amount of additional energy exchange to be facilitated and will therefore likely differ among the scenarios. For others, as reinforcement, the DSO is likely to apply a solution that complies with all possible scenarios.

The range of additional energy exchange to be facilitated as provided by the scenarios is the same for each solution. The minimum, most likely, and absolute maximum level of 'overloading' of a bottleneck to be facilitated using a solution can result in a spread in the costs of sufficient capacity to

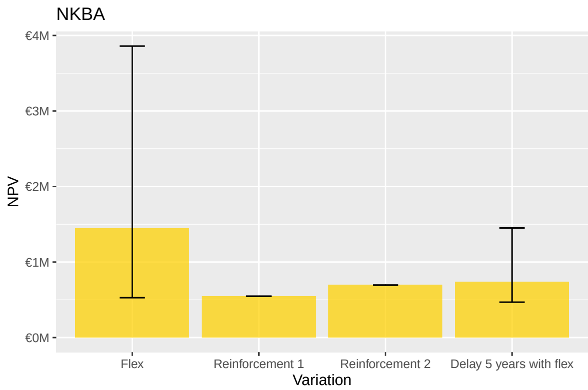


Figure 7.1: A visual representation of an NKBA as used in 'Reinforce unless' [26]. This example shows the spread for solutions using flexible resources and the constant factor for sole investments.

accommodate that scenarios. Based on the number of scenarios and the weight assigned to the result of the scenario, a probability can be assigned to a certain 'overloading' [26]. The minimum, absolute maximum, and most likely maximum level of 'overloading' can be approximated using eq. (7.6) [94]. The scenarios are sorted from minimal to maximal load, n is the number of scenarios, M is the level of overloading for scenario ω, and p is the weight assigned to the result of a scenario ω.

$$\{min(M_\omega), \quad sum\left(M_\omega * \frac{\sum_{i=1}^{\omega} p_i}{\sum_{i=1}^{n} p_i}\right), \quad max(M_\omega)\} \tag{7.6}$$

The NKBA requires this spread to be determined for each of the alternatives, resulting in a comparison of all three levels. The comparison used as an example in the framework is included as fig. 7.1.

7.2.4. Least Worst Risk-assessment

Using the approach of the NKBA, a lot of information gets 'lost'. The LWRA, also commonly called "Mini-max regret", shows that this information can be put to good use. Instead of taking the spread in loading and deriving the corresponding range in costs, the LWRA considers the NPV of the costs of all solutions separately. An example of such an evaluation is shown in table 7.1. The top table shows the NPV (costs) of the investments. The bottom table shows the regret, the difference between the optimal result (maximum NPV) for that scenario (combination of energy scenario and flexibility price) and the evaluated strategy. The strategy following from this analysis is that with the lowest maximum regret (i.e., Lowest Worst Regret).

The LWRA is said to show the attractive theoretical property of not wanting to be very wrong for whatever scenario will materialise [109]. Through this approach, the chosen solution will effectively result in a balance between the risk of over- and under-investment.

A closer review of the LWRA shows that in a simple comparison of the fixed investment costs or the variable flexibility costs, flexibility will be the chosen option as long as the possible benefits (less capital spend in the event of flexibility being cheaper than reinforcement) outweigh the possible costs (more capital spent in the event of flexibility being more expensive than reinforcement). This also results in this assessment being particularly sensitive to the extremes of the solutions. Because of this sensitivity, extreme caution should be taken to ensure that the weighed solutions are relevant and realistic [109, 112].

7.2.5. Comparison

TSO National Grid [109] argues that especially the weighing of scenarios when comparing different solutions shows significant drawbacks. The first of these is the use of weights in assessing the outcome of the scenarios. Assigning weights or probabilities to the scenario will likely be based on the projection of current knowledge, previous experiences, and expertise to relevant aspects of the scenarios.

NPV (as costs)								
Scenario:	**KA**		**ND**		**IA**		**AM.2021**	
	High	Low	High	Low	High	Low	High	Low
Strategy 1	€ 1287k	€ 3860k	€ 528k	€ 1583k	€ 546k	€ 1639k	€ 531k	€ 1592k
Strategy 2	€ 548k	€ 548k	€ 548k	€ 548k	€ 548k	€ 548k	€ 548k	€ 548k
Strategy 3	€ 695k	€ 695k	€ 695k	€ 695k	€ 695k	€ 695k	€ 695k	€ 695k
Strategy 4	€ 693k	€ 1451k	€ 469k	€ 780k	€ 474k	€ 797k	€ 470k	-€ 783k
Regret								
Scenario:	**KA**		**ND**		**IA**		**AM.2021**	
	High	Low	High	Low	High	Low	High	Low
Strategy 1	€ 739k	€ 3312k	€ 59k	€ 1036k	€ 72k	€ 1092k	€ 61k	€ 1045k
Strategy 2	€ -	€ -	€ 79k	€ -	€ 73k	€ -	€ 78k	€ -
Strategy 3	€ 147k	€ 147k	€ 226k	€ 147k	€ 220k	€ 147k	€ 225k	€ 147k
Strategy 4	€ 145k	€ 903k	€ -	€ 232k	€ -	€ 249k	€ -	€ 235k

Table 7.1: An example of the LWRA of an evaluated bottleneck. The values written in green represent the lowest NPV of the estimated costs for each scenario, red represents the maximum possible regret per strategy, and blue the minimum of the set of maximum regret.

However, the uncertainty and dynamic nature of the energy transition potentially causes this expertise and experience to be largely irrelevant. Especially because the energy transition may encompass revolutionary changes, expertise and previous experiences may be of significantly less value in assessing future needs.

The weighing of scenarios using probability factors to create a most-likely-average case is therefore based on information that does not necessarily have an objective argumentation. Furthermore, even if the weights of the scenarios are equal, the combination of the scenarios results in a case that is always somewhat right, but can still be very wrong. The most-likely-average does not actually represent a specific case. In reality, the most valuable information given by the NKBA is therefore the spread indicated by the graph through the maximum and minimum as to our best guess, each of these values is equally likely to occur.

'Reinforce unless' specifies the NKBA and its graphical representation in fig. 7.1 to indicate the value and costs of additional capacity and to be useful in minimising disinvestment. However, when converting the scenarios to a minimum, most likely, and maximum value, a lot of information is actually lost. Even the proposed valuation of disinvestment is actually misread from the graphical representation in the framework.

Whether the use of LWRA can result in overall lower socialised costs than NKBA is, to me, not sufficiently proven. Literature on the application of LWRA in dealing with uncertainty of complex energy infrastructure scenarios is available, however not widely applied. The concept may therefore be relatively old (according to [109], first originating in 1979), its application is not necessarily very mature. I do agree with National Grid and Konstantelos et al. that the theory has attractive properties and its manner of representation, especially in [112], is more insightful than that of 'Reinforce unless'. DSOs may therefore choose to substantiate their decision along a similar structure as shown in fig. 7.2. This figure from [112] shows the total regret of a solution and its decomposition in several forms of costs.

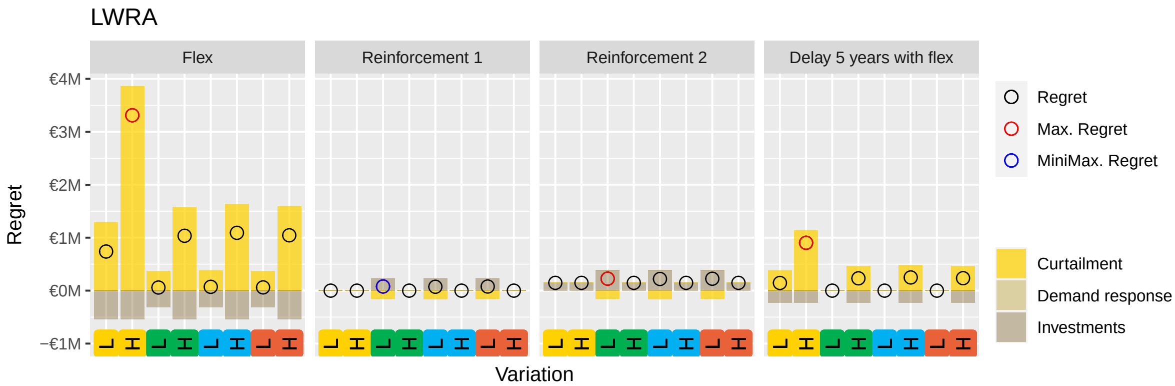


Figure 7.2: An LWRA of four different strategies under the four scenarios with Low and High flexibility costs. Konstantelos et al. adopts a slightly more intensive approach of LWRA which uses it as an optimization strategy instead of solely a comparison.

8 Conclusion

This final chapter concludes the research of this thesis. The first section answers the main research question based on the answers to the five sub-questions. In the second section, recommendations towards Stedin and possible future work are described.

8.1. Research questions

1. **What are operational problems that arise in the distribution grid due to the accelerated energy transition?**

This research question first defined the task of the distribution grid. Along this definition followed three main categories of operational problems expected to arise as a function of the energy transition; Capacity, Safety, and Power Quality.

Literature research identified eleven operational problems which were categorised among the three categories. Of these operational problems, 'Power quality: Voltage dips and swells'- and 'Capacity: Thermal capacity'-problems were identified as the operational problems most likely to be solved through the application of flexible resources.

2. **What are the root causes behind operational problems in the distribution grid and how can these be used to categorise the problems in the context of applying flexibility?**

Several LV and MV grids were modeled for the year 2030. One categorization of specific interest is that of the AD. This is due to the common conception that rural areas are more likely to experience voltage problems, where urban areas are more likely to experience capacity problems. The models are created by projecting three complex energy scenarios from Netbeheer Nederland and one from Stedin on Stedin's service area. The projections were, in turn, created by SETIAM and converted for use in Stedin's LV and MV grid analytic tools through newly developed scripts. Among other benefits, the conversion scripts extend the use of SETIAM's data from solely assessing capacity through radial addition of active power flows to performing complete load flow analyses.

The models of both the LV and the MV grids showed increased problems compared to the base-case scenario for all scenarios. The scenario-specific results showed only a small correlation between the experienced problems and the AD for LV grids. The correlations that were found were initially counterintuitive but were put into perspective by further analysis of the cables, the input data, and the analysis of the MV grid. The analysis of the MV grid revealed it to be primarily responsible for the described conception.

It was shown that capacity and voltage problems were highly correlated, especially for the LV grid. Both problems also seem primarily dependent on active power flows. This was explained by the properties of the cables used in the distribution grid. Mitigating these problems, therefore, mostly requires flexible resources capable of exchanging active power, where reactive power exchange is of less influence in MV grids and significantly less influence in LV grids.

3. **How can the feasibility of solving or delaying specific operational problems through flexibility be determined?**

Quantifying the feasibility of impacting operational problems through flexibility is similar to the objective of "Reinforce Unless"'s Quick Scan. Therefore, Chapter 5 starts with assessing the approach used in the Quick Scan. However, the approach of using key figures and additional, not-quantifiable check questions for the initial minimal feasibility assessment showed some inconsistencies and limitations. Therefore, this thesis proposes to adopt the approach to evaluating the operational feasibility and the financial feasibility.

The bottlenecks can be expressed in nodal mismatches of active and reactive power. These mismatches can be reduced by exchanges of active and reactive power by flexible resources. By expressing the sensitivity of bottlenecks towards active and reactive power exchanges at the nodes in the network, voltage and capacity bottlenecks can be quantified on the required, flexible impact in both active and reactive power exchanges.

The benefit of this approach is twofold. First, known flexible resources can be evaluated for their impact on experienced bottlenecks. Second, nodes with significant impact on the bottleneck can be identified and evaluated for new flexible resources afterward. Finally, the total Flexibility Availability as constrained by the RSO can be assessed for its sufficiency to solve the bottleneck.

By evaluating the required impact in active power levels [MW] along with the duration [h] and yearly occurrence [y^{-1}], the bottlenecks can be quantified in the amount of additionally locally generated, used, shifted, or omitted energy [$MWhy^{-1}$]. Using an estimated price as determined in Chapter 7, the financial feasibility of applying flexibility can be assessed.

4. **What solutions in the form of flexibility can be applied to solve or delay operational problems?**

Chapter 6 follows up on the structure of OTE's "Reinforce Unless" on the demands set in the form of 'sufficiency criteria'.

The framework determines that no degradation in the security of supply is allowed. However, the addition of 'more links in the chain' is certain to decrease this security somewhat. The question to the DSO is determining if the risk associated with this decrease in certainty is acceptable according to its company values.

Sufficient security of supply can be quantified in the form of acceptable risk. The level of this acceptable risk is determined using Stedin's Risk Matrix and is set at a level of $€3000/year$. As identified in the quick scan, the flexible resources in the network can be evaluated on their Flexibility Availability (i.e., the potential technical impact to be made by the resource) and the combined unavailability of the flexible resource as a function of several probabilities.

By combining the Flexibility Availability and combined unavailability, for all resources, for each exceedance of the bottleneck, the maximum unavailability of the required combined flexible impact can be determined. This unavailability and the impact on Stedin's company values can be converted to a risk using the risk matrix, which can be compared to the maximum risk acceptance.

Furthermore, this chapter addresses the characteristics of potential flexible resources and addresses several barriers to applying flexible resources as an alternative to investment. The main barriers discussed originate from the trade-off between facilitating and using flexibility. Especially at lower levels, it might not be possible to reach sufficient levels of aggregation to make a sufficient impact. However, such a trade-off requires extensive insight into markets and the bottleneck its upper grid levels.

5. **How can the value of flexibility for DSOs like Stedin be determined and quantified?**

To determine the value of flexibility, the procurement scheme for the DSO has to be known. Based on existing service procurement schemes used by the Dutch TSO, a structure is proposed that allows

DSOs to contract sufficient flexible power at reasonable prices while maintaining the possibility for non-contracted resources to bid their flexibility. Reconciliation is based on the market-clearing price and the beneficial deviation from its profile.

With such an approach, the contracted flexible resources act as a backstop guaranteeing a reasonable price. However, this does not fully rule out gaming. By influencing their prognoses, resources can still trigger redispatch actions. Sufficient participants do reduce the probability the gamer will actually benefit. Overall, sufficient market offers from flexible resources are a necessity to guarantee sufficient availability and reduce gaming.

Financial risks associated with the application of flexibility mostly originate from the uncertainty in the pricing of flexible resources and its combination with long lead times. Unfortunately, the uncertainty of pricing is not easily solved or mitigated, as accurate predictions are tough to make. As the NKBA was found to represent the risks associated with this uncertainty insufficiently, I propose to add a graphical representation of LWRA to provide more insight into the risks the uncertainty may bring.

What ‘flexibility’-methods can DSO’s like Stedin pursue or contract to solve or delay congestion and retain stable operation of its grid over the course of the accelerated energy transition?

This main research question has been subdivided over the different sub-questions, where each of the sub-questions partly provides the means to answer this question. The first sub-question defines *”stable operation of its grid”* and provides an overview of what problems can be mitigated with the use of flexible resources. The second sub-question projects *future energy scenarios* on Stedin’s grid defining the wide range of possible changes *over the course of the accelerated energy transition*. This projection is used to determine the extent of these problems and with the aim to provide means of categorization for the encountered bottlenecks.

The third and fourth sub-questions provided the means to assess bottlenecks for their feasibility of being solved through flexibility and assess resources for their ability to solve bottlenecks. The approach of translating the sensitivity of problems towards the nodal mismatches of active and reactive power allows for fast determination of required, flexible impact. This resulted in the means for DSOs to substantiate whether flexibility can *solve or delay congestion* and thus act as a technically sufficient alternative to reinforcement.

The last sub-question provides the means for DSOs to substantiate whether flexibility can also act as a financially feasible alternative to reinforcement and the *methods* Stedin can *pursue or contract* for the use of flexibility. The value of the service of flexibility is hard to predict. However, using the provided NKBA and LWRA, the risks of this uncertainty can be mitigated, and the most efficient solution can be chosen. Furthermore, using a flexibility market with a backstop provided by sufficient capacity at a reasonable price decreases the incentives for system users to game the system.

8.2. Recommendations

Over the different subjects encountered in this thesis, several recommendations for future work are made.

- Especially for LV-grids, voltage problems act as predecessors of capacity problems. Voltage droop-based control, as often investigated and also mentioned in section 6.3.2, and power-based reactive power control, therefore, seem cheap and promising solutions that should be further investigated. Especially the low need for measurements, control, and predictability of load are beneficial properties. However, the unfair advantages of linear droop control, decreased user comfort, and the possible reconciliation are just some of the possible barriers that could stand in the way. To some extent, it may be up to the DSO to lobby for the implementation of such types of control. Especially in mitigating problems through automatic control, as mentioned above, DSOs would be the main/sole advocates. That such methods can alleviate bottlenecks in LV grids is shown, whether it can feasibly be applied and under which conditions remains a topic for further research.

- An important discussion on flexibility is the trade-off between the use by DSOs for flexibility for capacity or flexibility for power. This thesis showed that even in the use for flexibility for capacity, DSOs should investigate at what level flexibility should be applied as an alternative for reinforcement and at what level reinforcement should be applied for the facilitation of flexibility. This is especially relevant in the distribution of new resources as utility-scale batteries and P2G. That example, however, can only be influenced by DSOs to a small extent. This remains a topic for further research.

- During research on possible verification and validation methods, the possibility to use smart meters was shot down due to privacy regulations. DSOs are currently limited in their access to the measurements of the smart meter. DSOs do have access to counters that measure the number of times the smart meters detect voltage dips and swells outside of the limit of the Netcode. Contrary to the Netcode, however, these counters only count dips and swells with a duration longer than thirty seconds. In theory, this should be enough to detect inverter trips due to overvoltages. However, several practical examples showed the contrary. It was therefore chosen not to follow this route. It is unclear why these trips are not detected. However, it further decreases the insight DSOs believe they currently obtain and is definitely a possible subject for future work.

Aside from the recommendations for future work, the following recommendations are made to Stedin regarding their operation and data provision.

- Using solely the 'not delivered'-energy to assess the impact of bottleneck simplifies the assessment of the mitigated risk through flexibility. To compare the costs of risk mitigation (dR/dC) for capacity measures to the risk mitigation of quality measures, this approach is insufficient in capturing the whole risk. However, the application of the risk matrix as a whole also has significant drawbacks. The matrix was essentially used for portfolio-level. This, for instance, includes the risk of prolonged use of a depreciated type of assets. This example, valued for multiple assets in the whole of Stedin's service area, is allowed to cost the same as every single bottleneck where flexibility is applied. This approach does not seem justifiable and requires further research.
- SETIAM can be a potent tool, yet there are some significant drawbacks in its current mode of operation. One of the main drawbacks I noticed was that the people using its results were insufficiently aware of the assumptions and the origin of data used in the model. Even the basic assumptions of the scenarios were proven to be somewhat unclear. It would aid in discussing some of the results and the assumptions themselves if more awareness was created.
- For this thesis, a script was created to apply SETIAM's projections in Stedin's grid analytic tools. Several departments in the company showed interest in using this tool and its results for their own means. I believe that interchanging SETIAM its current radial addition with the available grid analytic tools can result in better quality insight in bottlenecks and higher and wider applicability of the available information. I also believe that this will help the previous recommendation as it will provide more insight into causes and details for currently unaware users.

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A

Assumptions in modelling

To simulate the effect that SETIAM's modelled ETTs have on the grid, simulations are run using the Phase-to-Phase Gaia and DIgSILENT PowerFactory. The software is used to evaluate the following expected issues:

- Power quality
  - Voltage stability (deviations per distribution level).
  - Voltage asymmetry (limited extent)
- Capacity issues/component or cable overload
  - Changes in existing connections
  - Cable overloading
  - Transformers overloading

As the model uses information from SETIAM, assumptions made in the digital twin are also taken over to the model. SETIAM is a very information-intensive algorithm developed in-house by Stedin. Not all information regarding this algorithm can be disclosed, nor is all relevant for this thesis. The following assumptions are noted for data originating from SETIAM:

Each type of DRG is assigned a characteristic profile, spatial differences and possible differences in orientation are neglected. According to the technology, a characteristic load or generation profile is combined with the rated power of the connection to create a power flow profile. For general loads and generators, a constant load profile of the rated power is generated. The user is notified that if more information is available, this profile can be altered manually.

1. SETIAM assumes a radial power flow with an hourly profile. The loading profile of an asset is calculated by aggregating the profiles of the assets behind it. This is shown in fig. A.1.
2. The power-profiles of loads and generators can be generated in three ways:
   - A normalized power profile. This is among others used for the profiles of PV, wind turbines, and high power EV-chargers. This profile specifies the power as a ratio of its peak power output. For example, PV: SETIAM uses a characteristic profile for PV-production which takes into account a standard efficiency and downsizing of the inverter, resulting in a maximum AC power output of 70% of the installed peak panel power. A profile is obtained by multiplying the peak power output of the panels with the normalized profile.
   - A normalized energy profile. This is among others used for the power profile of small consumers. This profile takes the total annual consumption of a connection in the base year as input and multiplies this with a profile specifying the share of the annual consumption that is being consumed in that hour. The profile is specified per type of connection and assumes certain levels of aggregation.

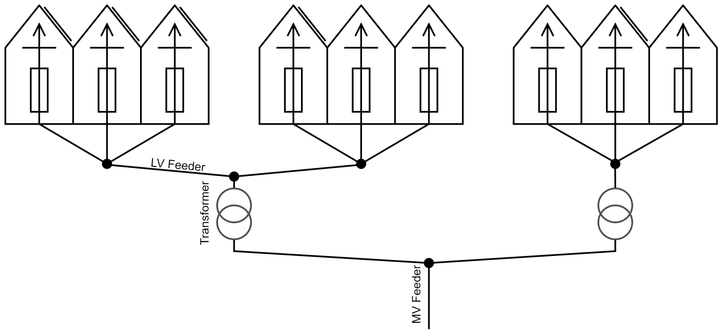


Figure A.1: Radial power-flow in SETIAM

- A profile based on probability. This is among others used for the profile of small EV-chargers. This profile is generated by a probability distribution per time-step, that specifies which of the EV-chargers behind a certain asset are currently charging a vehicle. The nominal power of these chargers is added for each time-step, resulting in an hourly profile.

3. The starting situation (n=0) is actualized each year with the most recently available information.

4. How a building belonging to a certain EAN is heated is determined from a number of factors. For the first year or as indicated by history, heating by gas is assumed. This is because there is no obligation to register an alternative source of heating and therefore little information is available. For the years following the changes of switching a source of heating are derived from the type of housing, the chance of a nearby collective heat source, and the year of construction. If an EAN is assigned a heat pump, the corresponding thermal heat pump power is calculated using the yearly gas consumption according to appendix A. This method is noted as questionable but not yet changed. New houses are assumed to be built with either a full electric HP or collective heating, always without connection to gas. Although the rated power is the same, the profiles that are used in SETIAM differ.

5. Electric cooking is assigned in combination with the perceived availability of the gas connection. If an EAN will switch to either a full electric heat pump or collective heating, it is assumed that it will also switch from gas-cooking to electric cooking.

6. PV is distributed using a probability and peak installation-power that is assigned to each EAN. The higher the probability, the earlier the connection will be assigned PV. The peak installation power depends on the available roof surface. The PV is assigned to the highest probabilities until the cumulative sum reaches the objective.

7. EV are distributed using a probability function that is assigned to each EAN. The higher the probability, the earlier the connection will be assigned PV. A distinction is made between Plug-in Hybrid EV and a Battery EV, where Plug-in Hybrid EVs are limited with a lower charging power of 3.7 kW and Battery EVs with a higher charging power of 11 kW. The assumption is made that 58% of all EVs are Plug-in Hybrid EVs, this assumption has been noted as outdated but not yet changed.

8. Annual consumption is derived from the measurements of the base-year combined with constant growth factors specified by the scenarios. This presents itself in SETIAM through a consumption profile that specifies the share of the annual consumption that is being consumed in that hour.

9. Large scale DRG is assigned based on RES and local subsidy requests, of which the proposed connections to the grid are cross-referenced with the responsible manager for that area (Gebiedsverantwoordelijken Elektriciteit, GV-E).

Aside from the assumptions made in the data provided by SETIAM, several assumptions and changes have been made to enable the modelling in Gaia. Some of these include actions that are taken in SETIAM further down the process, others are implemented to counteract assumptions that did

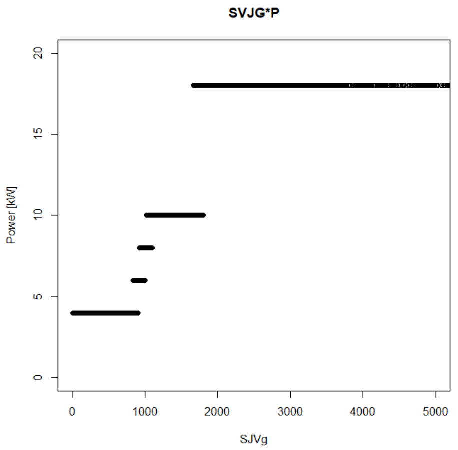


Figure A.2: Full electrical heat pump assignment

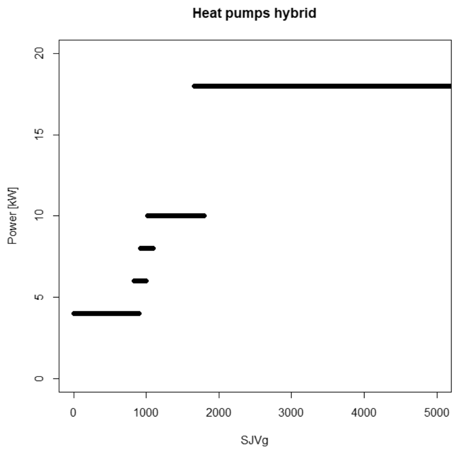


Figure A.3: Hybrid heat pump assignment

not seem plausible.
In general, SETIAM calculates the loading of assets using hourly profiles. Gaia can only perform this for a relatively low number of calculations, either short periods with short intervals or long periods with long intervals. In Gaia, the profiles are projected to two extreme scenarios called 'Evening'; corresponding to 100% load and 0% generation, and 'Noon'; 30% load and 100% generation. This corresponds to the maximum and minimum values used in the profiles.

8. The grid topology and connection information is actualized with the most recent available information and models. Due to an internal information mismatch, the information regarding the currently installed PV in SETIAM differs from that in the Geographical Information System which the grid analytic tools use. For this, the information in the grid-analytic tools is kept as the standard, where SETIAM only contributes the yearly added power for the future.

9. SETIAM uses a characteristic profile for PV-production. Gaia uses a maximum value that corresponds to that of the PV profile.

10. SETIAM uses a characteristic profile to convert the standard annual consumption to a load profile. Gaia uses the standard annual consumption combined with Strand Axelsson-calculations to calculate a peak power value per household.

11. Electric cooking is processed in SETIAM as an increase of the standard annual consumption, presenting itself in the power flow through the standard consumption profile. In Gaia, electric cooking is added as an additional load with a nominal power of $250W$, corresponding to Stedin's observation-based key figures.

12. The profile of a hybrid and full electric HP in SETIAM are derived from a normalized gas-consumption (energy-)profile. Due to the fact that HPs operate along a different strategy as conventional heating because of their lower thermal power rating, these profiles differ in reality. Because of this, the peak electrical power of the HP, as a key figure used by Stedin, is assigned to the connection instead of the gas consumption converted to electrical power.

13. Although the current sales trend clearly shows the yearly share of Plug-in Hybrid EV diminishing, the outcome in 2030 is highly uncertain. There are no projections available for the Dutch ratio of Plug-in Hybrid EV and Battery EV stock in 2030 and opinions on the European stock differ hugely. As no better alternative was found and the data corresponded to that of the IEA [113] no corrections were made in the data. There is a change made in the charging power of the EVs. For this, the assumption was made to keep the charging power for Plug-in Hybrid EVs at 3.7 kW and change the charging power of Battery EVs based on the type/power of the connection. These powers can range from 3.7 kW for a single-phase connection to 22 kW for a three-phase 35A connection (or higher).

14. Newly constructed and demolished buildings and public chargers are not included in the LV-grid analysis. This is because implementing these new connections cannot be done automatically, resulting in a lot of manual work. Therefore, newly constructed and demolished buildings are assumed to be connected to new distribution transformers. Because public chargers will have a relatively high share of all charging operations in high address density-areas, I found it important to include these one way or another. The public chargers were therefore assigned to connections that, until then, had none. The downside of this assumption is that its impact could be decreased by the rated power of the connection.

15. The assignment of HP-power based on their annual gas consumption does not seem plausible, especially if the application of better insulation is taken into account (as is often done when switching to an HP). This method has also led to other strange results, as large gas connections (G25) receiving the smallest size HP. Stedin's standard method for calculating the load of heat pumps is based on key figures that relate to the type of housing. This method is adopted. Hybrid HP are assigned a rated power of a factor 5 less [114]. The simultaneity of HP consumption differs among sources, varying from 0.85 to 1 [114]. Using the key figures and referencing to a study in the Netherlands for a relatively mild [115] and a relatively cold winter [116], the key figures seem to take into account the measured simultaneity quite well.

16. If the rated power of a HP or PV installation exceeds the rated power of the connection, the type of connection is changed to one that is sufficient. If an HP is assigned the connection is assumed to switch to a three-phase connection. This is based on the notion that single-phase HP are rare and the rated power of an HP will most likely exceed that of the single-phase connection with the highest rated power. If the rated power of a PV installation exceeds 5 kW, the connection is assumed to switch to a three-phase connection based on regulation in the Netcode [29]. The number of connections with changed capacity is kept as metadata, the capacity of connections will only increase.

17. SETIAM only models active power flows. Gaia specifies the reactive power flows of general consumption and different ETTs with characteristic phase angles based on common practice in the software and on common technical properties.

    - HP: $\cos\varphi = 0.9$ ind.
    - EC: $\cos\varphi = 0.9$ ind. (because of the addition to the HP profile)
    - EV: $\cos\varphi = 1$ -.
    - PV: $\cos\varphi = 1$ -.
    - General consumption: $\cos\varphi = 0.9$ ind.

Several assumptions and changes have been made to enable the modelling of SETIAM-data in PowerFactory. Most of these relate to assumptions that are irrelevant for SETIAM but need to be specified in PowerFactory.

18. Due to SETIAM's radial power flow assumption, SETIAM holds a topology of the MV-grid that consists of an HV/MV-station feeding several distribution stations (MV/LV) through 'feeders'. Possibly, a feeder from an HV station can be subdivided by another station that also has several feeders feeding several distribution stations. In PowerFactory, the actual looped/meshed structure of the grid is modelled using the most recent available information regarding the topology. Because of this, several feeders which will present themselves as overloaded in SETIAM might not be in PowerFactory and vice versa.

19. Because of the radial power flow assumption, SETIAM assigns new MV-connections ranging from 175 kVA to 1.75 MVA to a feeder in general instead of a specific distribution station on that feeder. To which feeder the connection is assigned depends on its location, where the nearest feeder is chosen. Because a station is not specified, the assignment to a station in PowerFactory is either done based on the address of the request (if specified) or based on a random station on the specified feeder (if only the neighborhood is specified based on the scenario data).

20. The connection information in both PowerFactory as in SETIAM is actualized with the most recent available information and models. Due to release-time mismatches between the two, the information regarding the currently installed PV in SETIAM can differ from that in PowerFactory. For this, PowerFactory is automatically checked for existing installations that SETIAM still notes as unfinished.

21. The changes made in the LV simulation to counteract assumptions in SETIAM that were found improbable are not implemented to correct the load profiles of the distribution transformers. This required extensive knowledge of SETIAM and collaboration with the team, which was not doable during the course of this part of the assignment. Most of the changes relate to the simulation in extreme scenarios instead of profiles, these will not have an impact on the PowerFactory-model. Assumptions [13], [14], [15] will have a significant impact on the power flow, resulting in a different minimum and maximum loading of the transformers than encountered in Gaia.

22. SETIAM only models active power flows. PowerFactory specifies the reactive power flows through reactive power profiles, voltage-based regulation, or constant phase angle. The RfG specifies that DSOs are allowed to specify levels of reactive power to DG [58]. At the moment, this is only done by Dutch DSOs in specific cases. As plant operators do not obtain any benefit from deviating from unity themselves, the phase angle of DG is kept at 0. The same applies to high-power EVs. In general, Stedin specifies a constant power factor of 0.98 for its MV connections. This is applied to the remaining connections.

    - DG: $\cos\varphi = 1$ -.
    - High power EV: $\cos\varphi = 1$ -.
    - Distribution transformers: $\cos\varphi = 0.98$ ind.
    - Unspecified system user connections: $\cos\varphi = 0.98$ ind.

B

Reinforce unless: key principles

Key policy and regulation principles for the development of the framework

1. The price of the delivered flexibility is determined by free-market operation. Providing flexibility is voluntary.

2. The regulatory environment is such that the DSO can retrieve both investment costs for reinforcement or expansion as it can retrieve operational costs for the application of flexibility.

3. The current system principle based on the three market-freedoms stays intact. The application of flexibility as an alternative for reinforcement or expansion cannot act as a limitation.

4. Future legislation and regulations have been drawn up in such a way that "gaming" is prevented by market parties so that abuse of the assessment framework is prevented, market freedoms can be guaranteed and fair pricing can be established.

5. This framework determines two ways flexibility can be utilized as an alternative for grid reinforcement:
   (a) As a temporary measure to avoid congestion management in the event that a reinforcement cannot be realized in the given time-frame;
   (b) As an alternative for reinforcement.

6. Generic measures that can influence the desired transmission capacity, such as tariff structures, cannot be used as a solution in the assessment framework, but are a given in the estimation of the desired transmission capacity and the use of the assessment framework.

7. Only the technical characteristics of the exchange with the electricity grid by the flexible capacity and the security of supply of this flexible capacity is used as input in the assessment framework. In this way, the assessment framework is neutral according to the origin of the flexibility (for example, storage, conversion to other energy carriers, etc.) and the assessment framework only assesses the effect on the capacity of the electricity grid.

8. Sustainable does not receive a beneficial treatment over unsustainable solutions. It is assumed that the current emission trading system and policies stimulating sustainable energy will sufficiently competetise these technologies.

9. The social effectiveness of the use of flexibility can be assessed in two ways:

    (a) An assessment in which only the costs and benefits socialized by the network operator are compared. This is a Network Operator Cost-Benefit Analysis;

    (b) An assessment in which the comparison under (a) is extended to a total social costs and benefits analysis of the entire energy system. This is a Social Cost-Benefit Analysis.

    The assessment framework must be suitable for both considerations. Which consideration is ultimately implemented is a policy choice.

10. For the deployment of flexibility as an alternative to grid reinforcement, the socialized costs of the deployed flexibility must be lower than the socialized costs for grid reinforcement.

11. The assessment framework must fit within the principles as formulated in the OTE report ’Nieuwe Spelregels’.

C
Instantaneous abilities of flexible resources

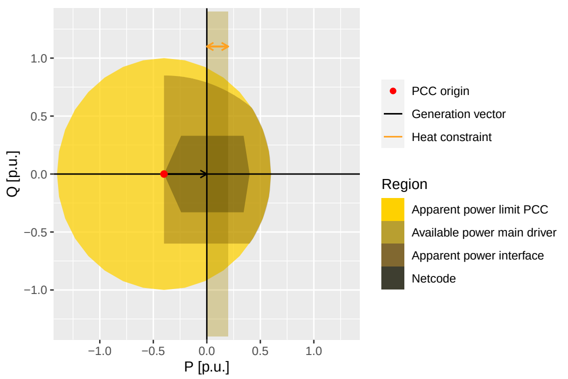
The following figures indicate typical situations and constraints set on the flexible operating region of flexible resources. Context on the construction of these figures is provided in the captions, along with the description of the instantaneous abilities corresponding with table 6.3.

The flexible resources can be categorized into PEID, synchronous generator interfaced generation, and discrete loads. PEID can typically operate in each quadrant (four-quadrant operation) but are additionally limited by the mode of operation; the direction power can flow. Power electronics interfaced generators can only operate in the two 'Generating' quadrants where vehicle chargers can only operate in the two 'Motoring' quadrants.

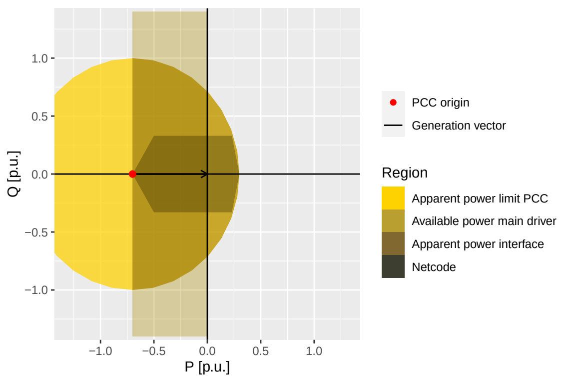
Synchronous generators operate in the two 'Generating' quadrants. Furthermore, the generator is constrained by stability limits, excitation limits, and apparent power limits (armature current) [117][118].

Discrete loads are operated in discrete steps of apparent power, most likely with a high share of active power relative to reactive power.

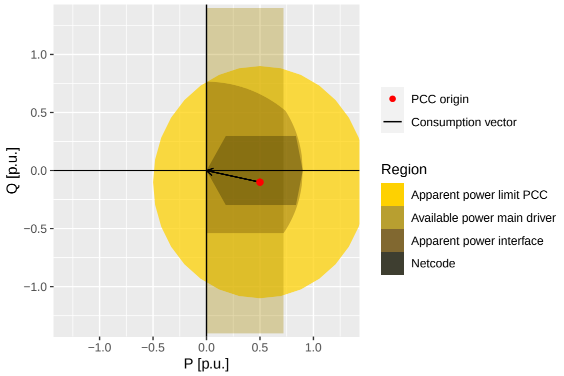
The share of flexible active power exchange is, as indicated in section 6.3.1, dependant on the 'Main driver'-limit determined by the flexibility of the feasible operating region in which flexibility can be provided. Depending on the controllability of the interface, this is either a discrete step (represented by an arrow) or a range (represented by the 'Main driver'-region). Depending on the standard optimization (e.g., MPPT, minimizing cost), a typical operating point is selected.



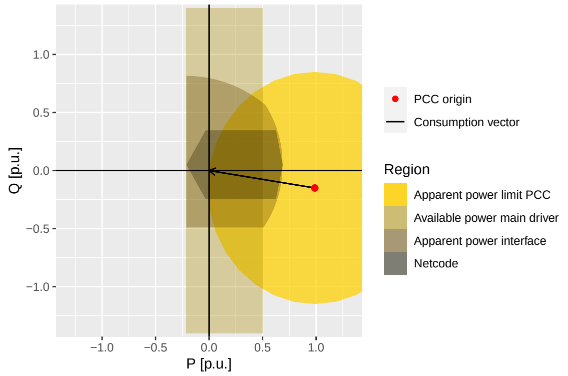
(a) Reactive and active power capabilities of a CHP with a synchronous generator. The 'Main driver'-limit is specified by the CHP its nominal electric power and the operating region defined by the heat constraint.



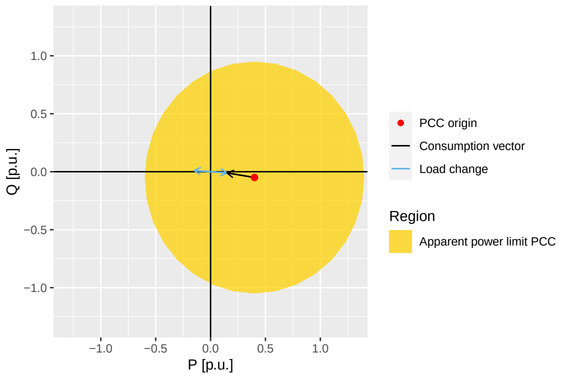
(b) Reactive and active power capabilities of a PV or wind plant (assuming power electronic interfaced generation). The primary objective of renewable generation is to maximise power production (MPPT); curtailment sets the constraints that limit this objective. Therefore, aside from cases where market-based curtailment was applied earlier, DRG can only be decreased, not increased.



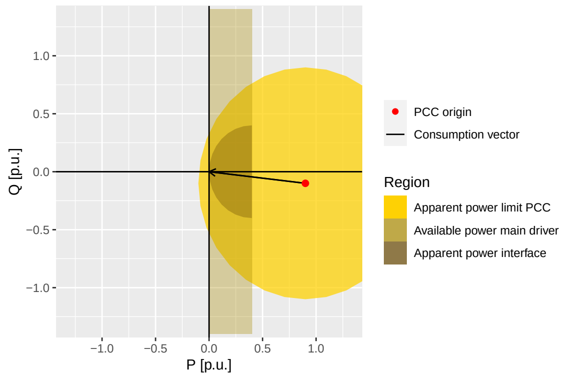
(c) Active and reactive power capabilities of a synchronous, emergency diesel generator. Emergency generators are sized to the requirements in the event of an emergency. For example, the installed rated power of emergency plants for Dutch hospitals in 2012 varies from 16-66% of that of the grid connection, where answers on what it should be range from 30-100% [119]. Data centers are likely to have sufficient installed power for full, long-term operation. The generator in this figure is sized to replace only a portion of connection capacity. The 'Main driver'-limit is specified by the diesel engine its nominal power. Its optimal operating point is based on the consumption vector of the system's connection.



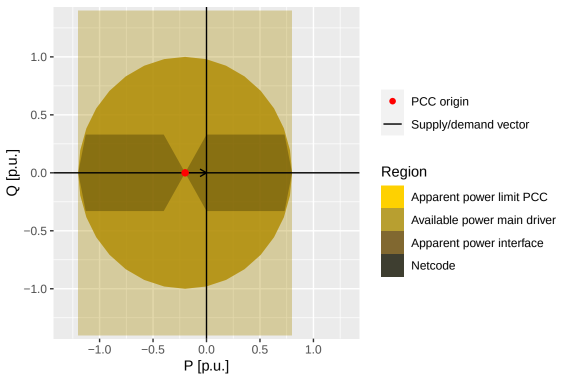
(d) Reactive and active power capabilities of a peakshaving, synchronous, diesel generator. These applications can only provide flexibility by providing more apparent power than is required to keep the grid current below its maximum. Its activities are therefore limited by the vector of consumption which is continuously changing. The 'Main driver'-limit is specified by the diesel engine its nominal power. However, in simultaneous operation this resource is likely to be limited in potential impact.



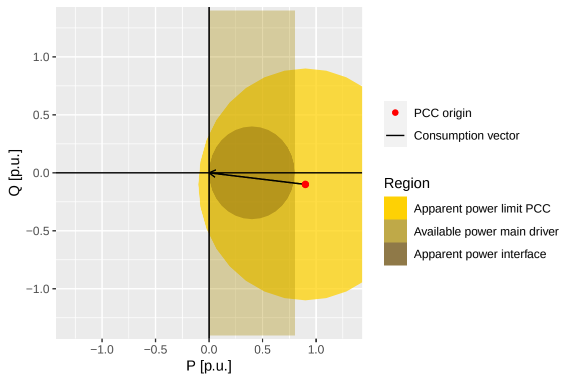
(e) Reactive and active power capabilities of demand-responsive load. This category entails residential demand response of household appliances and HVAC equipment, and industrial load shifting and shedding. The resource is controllable in one or more discrete steps of apparent power.



(f) Reactive and active power capabilities of an EV-charger. The rated power of the charger will demonstrate itself in the constraint of apparent power. The 'Main driver'-limit is firstly constrained by the active power limit of the battery and furthermore by the temporal constraints related to the SoC of the battery. A standard charger can only operate in the two 'motoring' quadrants.



(g) Reactive and active power capabilities of a battery (utility-scale) or combined P2G-fuel cell. Batteries are coupled to the grid by a PEID which can operate in four quadrants. The 'Main driver'-limit is firstly constrained by the active power limit of the battery and furthermore by the temporal constraints related to the state of the storage. The dPF constraints are set equal to that of a generator of similar rated power (according to Art. 2.16, Netcode [29])



(h) Reactive and active power capabilities of a V2G EV-charger. The rated power of the charger will again demonstrate itself in the constraint of apparent power. The inverter will now be able to operate in all four quadrants. The 'Main driver'-limit is firstly constrained by the active power limit of the battery and furthermore by the temporal constraints related to the SoC of the battery.

Figure C.1: Instantaneous abilities of flexible resources