Impact of LV connected DER steerability on HV and MV networks

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by

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Preface

With this thesis, titled *"Impact of LV connected DER steerability on HV and MV networks"*, my masters study in Sustainable Energy Technology comes to completion.

The research into power grids came from multiple projects which were energy system focused. As it is not straight forward continuation of my master track (Electric Mobility). I would like to thank the Integrated Electrical Power Grids (IEPG) group for providing this research opportunity together with Stedin Group.

Special thanks go out to Pedro Vergara Barrios, Weijie Xia, Sjors van der Heijden and Paul Bierling for their constant support and availability during this research.

Last but not least I would like to voice my appreciation to my family and friends for providing continuous support during my whole studies. Especially for the weekends which provided the much needed distraction, with a good chat and a drink. The RAIN-department drinks were also an unforgettable part of my studies.

To all people having played a role in getting to this point, Thank you.

V.J. Schonk BSc
Rotterdam, September 24, 2024

Abstract

Climate change results in governments making policies for more renewable electricity generation. At the same time, electricity prices are rising. These factors result in an increasing number of photovoltaic (PV) systems being installed and connected to the low voltage (LV) grid. More than half of the areas in The Netherlands have capacity issues related to distributed power generation, which can be solved by reinforcing the electricity grid or reducing the combined power being fed into the grid. This thesis aims at investigating the possibilities and effect of reducing PV power put into the grid.

Grid reinforcement can not happen instantly and requires a considerable investment while currently not enough skilled labourers are available. Together with this labour shortage and time delay, a large cost is associated with this action. Another factor is the eventual over generation from distributed energy resources (DER's) reducing power grid stability. All these considerations provide the basis for research into the possibilities of LV PV curtailment. There is a significant amount of research on the effects of curtailment, however this research mainly focuses on the LV effects or looks at not technically feasible curtailment options.

The current overloaded grid can be solved by different ways of curtailing LV PV alongside medium voltage (MV) and high voltage (HV) curtailment. Different options result in more curtailed energy correlated with lower grid loading or less curtailed energy but more residual network loading. The current German-implemented method sets a power limit of 70% of the installed power for small PV systems and requires a gradual curtailment possibility for larger systems. This approach has proven to provide a good trade-off between loading reduction and generation losses for now. Other curtailment may be more effective in the future. Therefore the research question of this thesis is *How will LV connected PV curtailment affect the loading of the MV and HV network?*.

In order to determine the impact of different curtailment methods a simulation based approach was chosen. Further on in this thesis the generation of power consumption and generation data will be discussed, as well as the implemented and explored curtailment methods. The selected networks are based on the amount of LV PV present together with the network capacity relative to the total amount of installed PV generation.

At the moment MV to LV transformers are the main bottleneck, which can only be solved by installing larger transformers or curtailing LV connections. When analysing all other assets an optimisation approach reduces grid loading the most, however this is far from necessary. In order to keep MV cable loading and HV to MV transformer loading within limits any form of curtailment is functional, even curtailment methods which do not impact LV connections.

The main takeaways from this thesis are that curtailment will become necessary in the coming years. Combined with the fact that LV curtailment has to be implemented within 10 years in order to avoid overloading the MV to LV transformers.

All in all a system wide approach is preferred, as this reduces loading with minimal energy curtailment. This can be achieved with an optimisation approach or propagating rules associated to the maximally loaded asset. Considerations, which should be explored further, are the financial impact, social impact of curtailment and complexity of the system. As these impact customers both directly and indirectly.

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Nomenclature

In this research the terms line and cable will be used interchangeably. Most connections in the Stedin network which was analysed consists of underground cables.

Abbreviations

Abbreviation	Definition
PV	Photo Voltaic (Solar panels)
LV	Low Voltage (below $1kV$)
MV	Mid/Medium Voltage ($1kV$ to $25kV$)
HV	High Voltage (over $25kV$)
DER	Distributed Energy Resources
RES	Renewable Energy Sources
DSO	Distribution System Operator
TSO	Transmission System Operator
KNMI	Koninklijk Nederlands Meteorologisch Instituut
EV	Electric Vehicle
HVC	Huis Vuil Centrale
PHEV	Plug-in Hybrid Electric Vehicle
BEV	Battery Electric Vehicle
ENTSO-E	European Network of Transmission System Operators for Electricity
TNO	Nederlandse Organisatie voor Toegepast-Natuurwetenschappelijk Onderzoek
IHA	International Hydropower Association
LCOE	Levelised Cost Of Electricity
PGM	Power Grid Model
CDF	Cumulative Distribution Function
SDE	Stimulering Duurzame Energieproductie
GHG	GreenHouse Gasses

1 Introduction

1.1. Renewability

Climate change is a prevalent issue in modern society, as more greenhouse gasses (GHG's) pollute the atmosphere and the temperature continues to rise [1]. With this rise in temperature, global impacts like wildfires, floods and droughts can be observed. Aside from environmental impacts global warming also impact socially relevant subjects. Even impacts on health, education and industry can be observed as results from global warming [2]. Fossil fuel consumption needs to be reduced in order to limit or even reverse this process. The sector which contributes most to GHG emissions is the energy sector, mainly producing electricity or heat [3].

With the Paris Agreement and other climate goals GHG emissions are being reduced each day [4]. Going into a renewable direction results mostly in improving efficiency and electrifying energy consumption [5]. Together with the sustainable generation of electricity instead of using gas, coal or oil in power plants. Renewable energy sources are primarily based on wind and solar power, as these are energy resources which are highly available. Policy and societal factors result in the fact that these sectors are expanding rapidly [6][7]. The aim for more solar and wind energy generation is also reflected in the Dutch climate plans [8].

1.1.1. Development of LV connected distributed energy resources (DER)

The development of wind energy is very important to achieve climate goals. As wind power can be produced during the night and has a different seasonality profile from PV [9]. When combining wind and PV generation the peak loading only goes up slightly due to the different moments of generation. Thus connecting both to the same cable results in more effective usage of that connection [10]. In the II3050 climate plan, which is supported by the Dutch government, it is expected to have wind generation grow from $4GW$ in 2019 to $30GW$ in 2030 [11]. As wind power connections are usually created from scratch and connected to the TenneT transport network the impact on the Dutch electricity grid is small.

Aside from the wind power development PV development is also expected, the prognosis in the II3050 climate plan states a growth from $6.2GW_P$ in 2019 to $40 - 75GW_P$, which constitutes a 6 to 12 times increase [11]. Figure 1.1 shows the rapid and extensive development of PV systems over the past years and into the near future. All scenarios represent around 67% of this capacity being installed on buildings. This high level of building-installed PV is expected as it is preferred from government policy, called the "zonneladder"[1]. As these PV systems are connected onto existing electricity connections this development poses significant issues to the electricity grid.

[1]The order in which to prioritise the placement of PV systems.

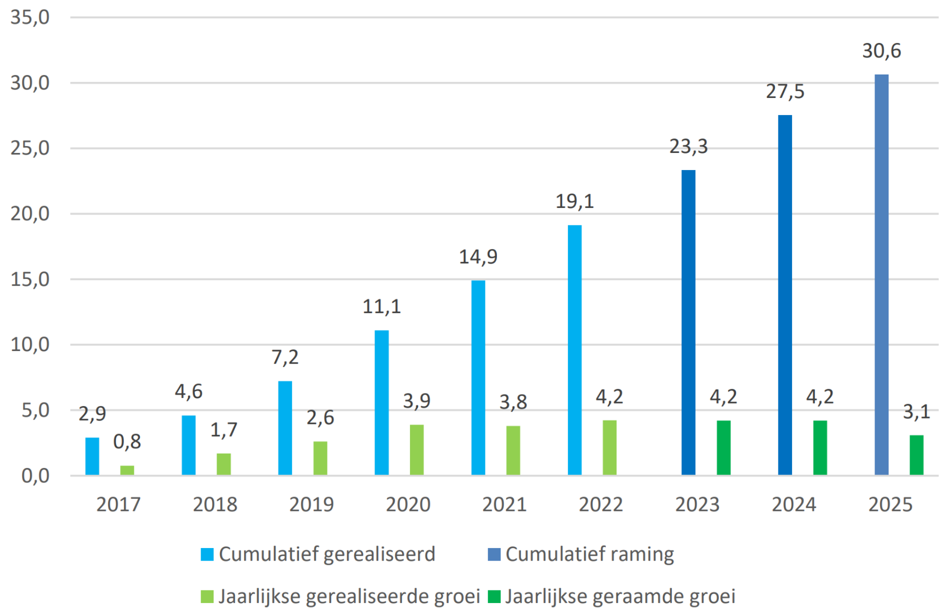

Figure 1.1: Past and prognosed PV development in The Netherlands [12]. GW_P installed on the vertical axis, Blue is the total installed capacity and Green is the added capacity.

1.1.2. Congestion

The Dutch electricity grid was not designed for all this distributed generation capacity [13]. This results in network congestion, which is already presenting itself [14][15][16]. Congestion is the situation that components are overloaded. For grid operators that maximum level is at 70% of the rated capacity in order to guarantee system stability and robustness. This thesis takes the nominal component value as the limit for congestion, as PV production can be reduced in non-standard grid conditions.

As component overloading increases degradation and ageing, overloading is an undesirable situation. In light cases components have to be replaced before the expected date. With severe cases causing fires and blackouts due to sudden breakdown of transformers and cables.

Figure 1.2 shows the current state of the Dutch power grid, most of The Netherlands deals with a lack of grid capacity. Due to this lack of capacity voltage issues in the low voltage network are already present. This is determined by current measuring devices in the network, most of which are analog and register a maximum value. However, most of the network is migrating to being actively digitally sensed, measured and controlled.

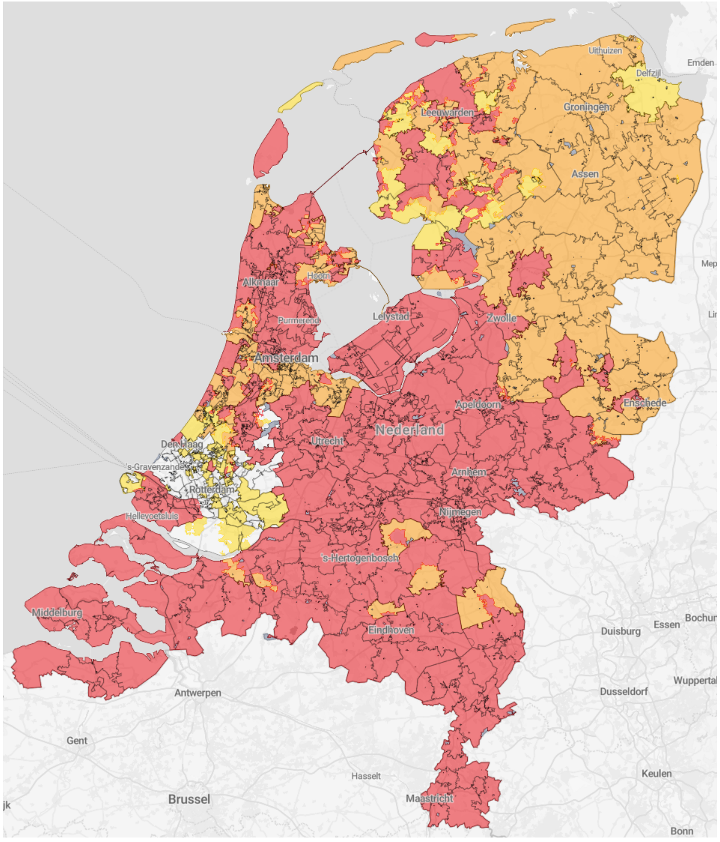

Figure 1.2: Map showing MV and HV grid capacity for DER generation [17].
Yellow: limited capacity | Orange: no capacity, curtailment research ongoing | Red: no capacity, curtailment not possible.

1.2. State of the art

In order to perform research on a technical subject the existing literature has to be reviewed. An in depth literature review can be found in Chapter 2. A research gap emerges from three requirements for this research. These requirements are; technically implementable LV curtailment, congestion modelling and LV curtailment its impact on MV and HV grids. Surrounding this gap are research into the HV and MV impact of theoretical curtailment options in the LV network, together with extensive research into the curtailment impact within the LV network [18][19].

1.3. Research questions

The primary objective of this thesis is to determine the effect LV curtailment will have on the loading of MV and HV networks. The expectations are a significant reduction in MV and HV congestion as there will be a reduction in power generation. This research does not analyse LV assets, the results are analysed including and excluding MV to LV transformers. As these are a significant bottleneck in the current network.

This research objective is formulated to provide insight and basis for development of curtailment methods. The pressing matter of congestion makes this an essential stepping stone on a pathway to curtailment implementation and development in The Netherlands.

Closing the research gap which is thoroughly analysed in Chapter 2. This research gap is created by the lack of research into implementable LV curtailment its impact on HV and MV congestion. Surrounding this gap are research into the HV and MV impact of theoretical curtailment options in the LV network, together with extensive research into the curtailment impact within the LV network [18][19].

Because demand response, load shedding and storage solutions are not feasible with the current social and technical state of the Dutch power grid, steerability is assumed to only include PV curtailment. In order to make this research more comprehensible and structured multiple sub questions have been formulated; namely:

- Which curtailment methods exist and are implementable? *(Section 2 and 3.4)*
- What is the impact of LV-connected low-carbon technologies on the HV and MV power flows? *(Section 3.3)*
  > How will DERs on the LV network develop until 2035? *(Section 3.3.1)*
  > How will loads on the LV network develop until 2035? *(Section 3.3.2)*
- How do different curtailment methods compare to each other? *(Section 4)*

The answers to these sub questions gives the inputs in order to analyse the impact of LV curtailment on MV and HV networks. As power flow simulations require the amount of power consumption and/or generation as inputs. These power generation amounts are scaled according to the curtailment method being analysed. This outline is explained more extensively below.

1.4. Thesis outline

In this section the outline of this thesis will be summed up and explained. The report is laid out in the same way as the research was performed. First the input of the power flow tool is explained, followed by an explanation of the chosen tool, finished by an explanation and analysis of the results.

In this section the outline of this thesis will be summarised and explained. The report begins with a literature review, followed by an overview of the simulation methodology. After which the input data for the power flow model is explained, lastly the results are analysed in the discussion. To close this thesis off the conclusions and recommendations chapter is presented last.

Curtailment and Congestion
Before this thesis dives into the subject at hand an in-depth literature has been performed. This is shown in Chapter 2, the literature review shows what policies and technologies are currently in use. As well as the gap presented by current research which this thesis will close to some extent.

Methodology
The whole research process, with power flow calculator, input data and output data will be discussed in Chapter 3. Simmulation results will be discussed in-depth in other chapters explained below.

Used cases, representing HV or MV stations with the connected networks are explained in section 3.2. With the different criteria, metrics and relevant background information.

For power flow calculations the input data is essential, this is the basis for any power flow calculation. Section 3.3 explains how these loads associated to each connection are calculated, from PV and wind generation to heat pump consumption.

Curtailment implementation is extremely relevant for the results. This implementation is explained in section 3.4, with the calculation methods and how the methods came to be.

Discussions
The output data from the used power flow model is analysed in Chapter 4. The different curtailment methods will be compared to each other with different metrics and visualisations.

Conclusion and Recommendations
Finally all the analysis and comparisons are combined into a conclusion in Chapter 5. This also gives insight into possible implementations of this thesis and future research.

2 Curtailment and Congestion

This chapter presents an overview of current implementations and theoretical research related to congestion and curtailment. Firstly the current implementations in other countries and operation limits will be discussed. Followed by a review of the existing literature related to network congestion and congestion mitigation possibilities.

2.1. Current implementations

Firstly a background of current state of affairs will be presented, giving insight into current network issues, implemented measures and state of the system.

Currently in The Netherlands the Real-time Interface (RTI) is being implemented on every power generating location with a generating capacity of over 1 MW [20]. This facilitates the communication of a power or voltage set point in order to mitigate frequency or congestion issues. From the grid operator a signal is sent in order to limit power production. The Requirements for Generators (RfG) dictates the circumstances in which this is allowed [21].

The RTI currently does not support sub mega watt generators (LV generation), this is expected to be added in a future implementation. When this is implemented a signal can also be provided to steer consumption, which will not be analysed in this thesis. Current LV curtailment, in The Netherlands, is only happening based on grid voltage, if that reaches the operational limits of an inverter ($184V < V_{grid} < 253V$). These disconnection limits are mostly triggered by over voltage, at moments of high irradiation and local (on street or neighbourhood level) congestion [22][23][24]. If voltages would exceed these limits an unsafe operating condition would occur.

As the voltage issues on the LV grid are solved by implementing thicker cables and making less connections per feeder, more power will be fed into the MV network from the LV network. As generation is less limited by voltage issues congestion problems become more frequent on the MV and HV network. With current infrastructure no feedback is being provided to LV connected DER from the MV grid loading or actions which need to be taken.

In Germany from the beginning of 2012 The Renewable Energy Sources Act (EEG) is in effect. This dictates that all power generating units of more than $800W_P$ shall be controllable by the grid operators. However, for units with a power of less than $30kW_P$ it is allowed to limit the power transfer to 70% of the peak power. If this option is chosen, the control ability requirement is not in effect anymore[25].

2.2. Possibilities and theoretical research

As demand response is not the focus of this study, nor is congestion due to power usage, this is not taken into account in the literature study. However, in future studies a full system analysis approach may be used in order to analyse load shifting implications. Inverters in PV systems provide a very gradual control over how much power is generated [23]. As power injection is controlled by pulse width modulation (PWM) of a direct current (DC) voltage bus, the resulting waveform is then filtered in order to create a sine wave. When the duty cycle at the peak gets larger the peak voltage will increase, resulting in power being injected into the grid. This duty cycle is easily controlled and therefore the power output is very easy to scale up or down.

This can also help alleviate voltage issues by injecting or consuming reactive power [26][27]. Reactive power control operates on a phase shift as current and voltage are not in phase with each other. If power injection is shifted from the voltage signal reactive power can be injected or consumed. This can compensate for cable inductance and other connected equipment which consume or generate reactive power. But the use of this gradual control in order to reduce asset loading is not yet implemented. However, it would provide a significant reduction of voltage issues [26].

Voltage based local curtailment is not a feasible solution for power based congestion. As this implementation would only work properly with extensive network knowledge and tailored inverter curves to each connection [19]. However, the research performed by A.T. Procopiou and L.F. Ochoa does provide basis as to the beneficial contribution of LV curtailment with respect to MV and HV congestion, what is also shown is the relevance of loading communication between the MV network and LV connections in order to maximally reduce overloading [19]. All in all this article provides basis for the relevance of LV curtailment for the eleviation of MV and HV congestion, while stating that their implementation requires full observably of the network and its connected assets.

In congestion control research from N. Shabbir et al., a fixed power injection limit is proposed as a congestion mitigating factor [18]. While showing promising results this study only focused on a LV network without taking impact on other voltage levels into account. This is the same case as the German regulations offer instead of providing curtailment access.

Table 2.1 shows a selection of curtailment methods and research presented in literature. As well as a quick review of the results of this thesis in the bottom row. This gives a quick insight into different existing curtailment methods. LV impact has not been shown as this is not the focus of this thesis, therefore not a fair comparison metric.

An in-depth explanation of the developed curtailment methods can be found in Section 3.4. A short summary of these developed methods is shown below.

- Curt. method 24: Optimisation of all voltage levels curtailment. (LV & MV & HV)
- Curt. method 25: Optimisation of MV and HV connections curtailment. (MV & HV)
- Curt. method 98: Curtailment based on maximally loaded asset. (LV & MV & HV)
- Curt. method 37: Curtailment based on maximally loaded asset. (MV & HV)
- Curt. method 50: LV connections capped at 70% of PV installed capacity with MV and HV connections being actively controlled.

The three curtailment methods from literature are reasonably self explanatory. The first one *"Peak percentage curtailment [18]"* limits the back feeding to a fixed percentage of the installed power, very much like the developed method 50 however it does not take the MV and HV assets and connections into account. Neither in the curtailing calculations, nor in the loading analysis.

The second curtailment method from literature *"Individual voltage based curtailment [19]"* analyses the interplay and relevance of LV and MV networks. This is based on a curtailment from the nominal voltage levels at the analysed nodes. As a practical solution this is less than desirable, due to the large amount of measurement and communication equipment needed.

The third literature based option *"Individual percentage curtailment [28]"* performs an optimisation calculation and determines in a LV network the optimal curtailment percentages. For a small scale network this is possible without needing too much measurement and computational equipment, however when scaling this up to the MV and HV grids the computations are not feasible to perform in real time. This option is closely related to the developed curtailment method 24, as this is a heuristic optimisation of the curtailment percentages over all the voltage levels.

The practical feasibility column in Table 2.1 represents the need for more measuring, communication and computational equipment before the curtailment option can be implemented. With the effect column giving a relative and simplified insight into general effect of the curtailment option. The last column of computational complexity gives a sense of the computational power needed for the implementation of the respective curtailment methods.

	Practical feasibility	Effect (MV & HV)	Computational complexity	Voltage level
Peak percentage curtailment [18].	+ +	?	+ +	LV
Individual voltage based curtailment [19].	- -	+ +	- -	MV, HV
Individual percentage curtailment [28].	-	?	-	LV
Developed curt. method 24 (Ch. 3.4).	- -	+ + +	- - -	HV, MV, LV
Developed curt. method 25 (Ch. 3.4).	-	+ +	- -	HV, MV
Developed curt. method 98 (Ch. 3.4).	-	+ +	-	HV, MV, LV
Developed curt. method 37 (Ch. 3.4).	+ +	+	+	HV, MV
Developed curt. method 50 (Ch. 3.4).	+	+	+/-	HV, MV, LV

Table 2.1: Comparison of literature suggested curtailment methods. + is positive and - is negative, for ”computational complexity” - means it is more complex.

This gap in analysis, combined with the observability need resulting from the research performed by A.T. Procopiou and L.F. Ochoa, provides the basis for this thesis [18][19]. As limited impact analysis is performed on MV and HV networks from LV curtailment. Combined with the research which was performed not considering a multitude of curtailment options with technical feasibility in mind.

2.2.1. Network congestion

The currently available research with respect to PV systems mainly focuses on LV network problems. This research focuses on the MV and HV network implications as that is less researched and it is expected that congestion issues will rise in the MV and HV network [29]. Germany has already implemented some LV PV curtailment [30], this may function as a stepping stone for Dutch regulatory and technical implementation. PV installations with an installed power up to $30kW_P$ have to provide a curtailment interface or are only allowed to back feed up to 70% of their connection power in Germany.

One of the two network issues are voltage related. As PV systems get installed on a LV feeder the generated voltage in order to put power back into the network rises [31][32]. If this voltage gets above $253V_{AC}$ the inverter stops generating power [33]. This is often the case in The Netherlands currently, resulting in the grid operators organisations publishing a best practices document to reduce the occurrences [34][24]. Various control methodologies have been researched in order to mitigate this problem. A control strategy, which is commonly employed in large power generating facilities, is droop control. With droop control the generated power drops with rising voltage and vice versa [26]. Other research suggests defining a maximum generating power for a connection which is lower than the maximum consumption power [35][18]. A more sophisticated approach, which impacts each connected party equally, is to limit the back feeding power by a percentage of the installed PV capacity or the connection capacity [28]. These limiting methodologies were used as a basis to determine which limiting strategies to research, those curtailment methods will be explained thoroughly in Section 3.4.

The other issue which energy networks may experience is congestion, this is when more current flows through a component than it is rated for. At the moment, the MV network is beginning to experience congestion due to transporting the DER produced energy, Figure 1.2 shows which regions in The Netherlands have grid capacity for the installation of additional DER generation. Currents which exceed component ratings result in accelerated ageing or component breakdown. Thus at moments of significant PV generation curtailment is necessary in order to avoid power outages and black-outs. The

Dutch energy law does not allow for this and mandates that grid operators have to invest in the grid [33]. However, as climate targets are being achieved by electrifying appliances and placing rooftop PV systems [36], the grid can not be expanded and reinforced fast enough.

Research that is present shows that, without additional capacity, the MV will not be able to handle additionally installed DER generation [29]. Voltage problems, which are currently limited to the LV grid, may even expand to the MV network [37]. This research will give insight into the possibilities of curtailment to mitigate or reduce these problems.

2.2.2. Energy storage system

Storage is also an option to alleviate grid congestion, as this shifts power consumption to moments of low grid loading, thus reducing peak power flows [38]. One of the cheapest and currently largest storage technologies is pumped hydro storage [39]. This is gravity based storage by using water as the medium which is pumped to a higher reservoir when energy is being stored. When energy has to be supplied, the water flows through a turbine and thus generates electricity.

As congestion becomes a pressing issue more and more storage is being installed. This can not all be executed in the form of pumped hydro storage, as space is limited and some areas like The Netherlands do not have the necessary height differences. With the rapid development in battery based storage solutions, mainly driven by the automotive industry, this is becoming a feasible option for grid scale storage [38]. According to TenneT, the Dutch transmission system operator (TSO), batteries are an essential part in order to achieve the climate goals [40].

2.2.3. Curtailment

In energy systems, curtailment is defined as limiting power output which is usually associated with renewable energy sources. As renewable energy sources are less controllable than classical fossil fuel based power plants. For this report curtailment is used as reducing output of a power generating system.

Due to earlier discussed societal developments more and more LV connected PV systems are experiencing curtailment or periods of being switched off due to voltage issues [22][23]. This is because article 3.8.2 of the Dutch electricity law [33][41] that ensures safety for the system user, which dictates that PV systems switch of when the voltage reaches $253V$ at the inverter. As there is no feedback to the generating units with respect to network loading, it does not protect the network adequately from over powering assets. Due to recent developments with respect to grid operator's rights in The Netherlands a legal basis for switching off PV generation has been created [42]. Implementation would result in the grid operator being able to send out a signal, after which the generating unit has to stop putting power into the grid within 5 seconds.

This new implementation would, besides ensuring system loading requirements, also ensure minimal curtailment and an equally divided impact of over production on the network. Currently, frequency based power balancing is used, as more power is consumed from the grid, the frequency drops and generating capacity is scaled up [43]. In other countries an active power curve is implemented in the electricity law, this dictates that as the grid frequency rises above a certain level the injected power gets linearly reduced. In The Netherlands PV systems have to switch of when the grid goes outside of a certain frequency band (more than $30min$ below $49Hz$ or above $51Hz$ [33]). However, if more power is being fed into the grid than can be consumed, this may prove problematic in the future, this is out-of-scope for this research.

Curtailemt of PV systems is very sophisticated and can be regulated to a high degree [23]. With controlling the reactive power even more transport capacity may be freed up on the grid (this is also out-of-scope) [27]. However, as power output is reduced, connected customers incur an indirect financial loss [26]. Fairness of curtailment is a difficult subject, as it fully depends on what metric is chosen and which division is considered fair [44]. This difficulty in defining and choosing what is fair resulted in this thesis only looking into the technical effects of curtailment [45].

Beyond the societal choices the technical implementation of curtailment also has its own challenges. Technically, having full insight and controllability in the network is optimal [44][46]. Besides the investment needed in data infrastructure, inverter communication and measurement hardware the determination which connection to curtail is also computationally intensive. Thus a blanket rule for all low voltage connections as in Germany is favourable from an investment and computation point. However, MV and HV generation units have such significant power outputs that gradual curtailment is essential in order to limit societal impact, just like a fossil fuelled power plant. Figure 2.1 shows all the Stimulering Duurzame Energieproductie (SDE) subsidised projects with an installed capacity of $500kW$ or more [47].

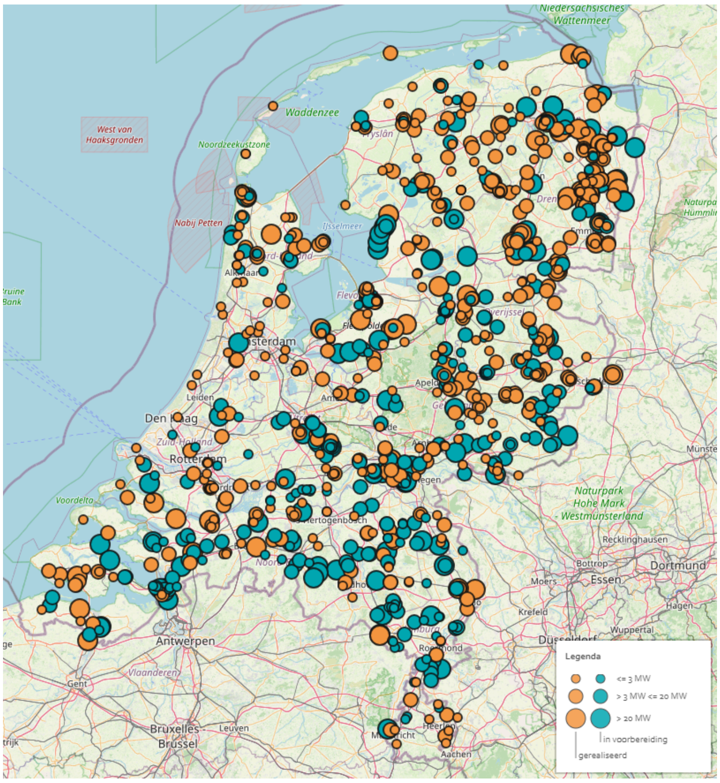

Figure 2.1: $500kW$ or more SDE solar projects [47][48].
In orange are completed projects, green projects are future developments.

2.3. Literature summary

Putting all these current implementations and the available research together. A research gap between the effectiveness of current LV limitations and their effect on higher voltage levels can be observed, as stated before. This thesis finds its relevance in the fact that LV curtailment impact on MV and HV grid components has almost no research at the moment, with the limited research being present not taking technical, social and financial feasibility into account. With rising amounts of DER generation being installed and the already congested electricity grid a need for research is presented. Combining this with the research being present for LV curtailment, technical feasibility and the MV and HV impact research, the research gap becomes clearly defined [18][19].

All in all this research will focus on comparing technically feasible solutions for LV PV curtailment and analysing their impact on the MV and HV grid. Providing basis for further development of curtailment implementation or policy related to LV PV systems.

3

Methodology

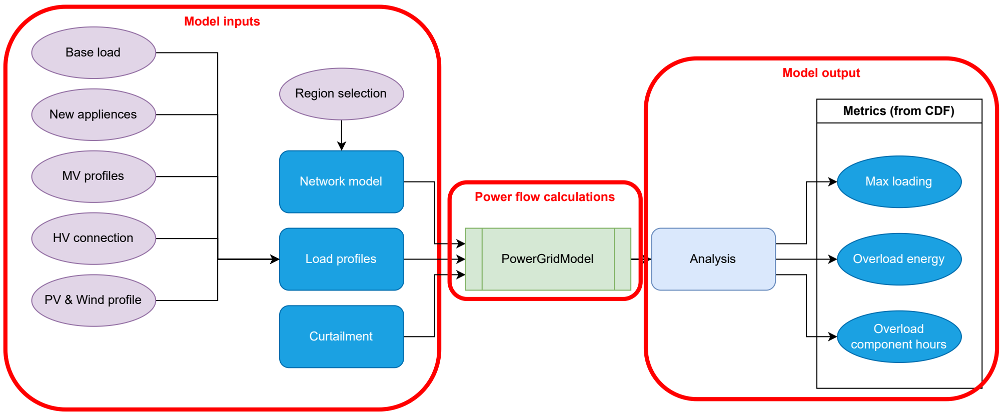

Figure 3.1: Simulation and analysis flowchart.

Figure 3.1 shows the process being followed in this research. This chapter will give a brief overview and describe the used power flow model as well as an explanation of the data generation for the power flow model. In depth analysis of simulation results will follow in Chapter 4.

This process was used as practically implementing curtailment on multiple LV connections is neither covered by the current legal framework, not desirable before analysis in a simulated environment. This thesis provides this theoretical basis for possible practical implementation of LV curtailment. Power flow calculations are performed by a power flow simulation model as this is the industry standard.

3.1. Simulation model

In order to determine power flows, asset loading and system dynamics a power flow model is needed to calculate large complex computations. As the main focus of this report is the PV generation in the grid an even distribution over the three phases and a generation power factor of 1 is assumed. Equal phase distribution is practically achieved by three phase connections or phase switching by Stedin, while the power factor of 1 is partially enforced by the electricity law and also desirable for maximal revenue for the PV system owner.

3.1.1. Model inputs

Power flow calculation models need a network file, which is automatically generated from the Stedin network, this will be explained in Chapter 3.2. Combined with the network file the power consumption or generation at each connection should be given. This connection or load power is calculated in different ways for LV connections compared to HV and MV connections. A full explanation of these calculations is given in Chapter 3.3.

In these connection powers load development, for example electric cooking, ev's and heat pumps, is taken into account. This is combined with development of residential areas and placement of more PV systems. Network development is not taken into account as planning until 2035 is not certain and will be impact by many factors.

3.1.2. Power flow model

In order to perform power flow calculations a lot of frameworks are available. The main differences are in the special capabilities of these tools. An in depth analysis will not be performed, but an overview of commonly used tools will be provided. The choice of model is not primarily based on performance as the power flow calculations are not very difficult and all the proposed models provide more than enough accuracy. Thus industry standards combined with whether or not the tool is open source provided a couple options, these are elaborated upon below.

Phase to Phase provides tools for power flow analysis on multiple levels [49]. These have been developed together with large industry stakeholders over the years. While providing good analysis their tools are not open-source.

PowerFactory is an application suite developed by DIgSILENT in order to provide easy and streamlined analysis and control of systems [50]. This development was driven from an industry integration and engineering point of view. However, these tools are also not open-source. DIgSILENT tools do integrate very well with the respective monitoring hardware and platforms.

Pandapower was developed on top of the PYPOWER and MATPOWER toolboxes [51]. Which gives it good system integration capabilities, high ease of use and makes it a great learning platform. This tool is even distributed under a 3-clause BSD licence, which provides a large use base, not only in industry, but also among engineering enthusiasts [52].

Power Grid Model (PGM) was eventually used to perform power flow analysis [53]. This tool was chosen as it will integrate and replace the Pandapower model, it is an open source implementation [52] and provides an easy to use python integration.

As pandapower has much more advanced network plotting capabilities this package was used to visualise loading within the network. For the analysis of longer time series pandapower was not used as calculation times are much longer than with power grid model [54]. However, loading figures in Cummulative Distribution Functions (CDF's) are extracted from PGM simulation runs.

3.1.3. Model output

The output of a PGM simulation contains the network components with the associated currents, voltages and loading figures. Output generated by the simulations provides the basis for the plotting of figures and numerical analysis. More about these metrics will be discussed in Chapter 4. The metrics analysed and plots generated are explained below.

As significant overloading in the network may result in instantaneous failure the maximum component loading is a logical number to analyse. However, this does not show the full impact, as a maximum loading figure could reach 150% at some points during the year with a system loading below 95% for the rest of the year. As component ageing and degradation is mainly contributed to thermal overload short time windows in which loading exceeds the nominal rating is acceptable. Thus analysing loading figures in Cumulative Distribution Functions (CDF's), together with some essentials like the overload hours, consecutive overload hours multiplied by the loading and the total overload hours multiplied by the loading. These metrics can be obtained from the component loading CDF, except the consecutive overloading. These figures are useful in order to present a visual progression and comparison, but for a theoretical analysis numerical values have to be extracted from this data. The main metrics which are of interest for curtailment effect are:

- Amount of hours for which curtailment takes place [$\frac{hours}{year}$]
- Amount of curtailed energy [$\frac{MWh}{year}$]
- Effectiveness of this curtailment [$\frac{MVAh}{MWh}$]

Besides metrics to determine curtailment effect the instantaneous maximum and average system loading are shown. As this gives a good visual representation of effect and provides a maximum value to analyse. For numerical analysis this should not be the primary metric, as it only determines the impact on a single instant in the analysis. One can call the instantaneous loading values a subjective KPI, as it is dependant on the rest of the curtailment performance.
To determine station overloading, with respect to the connection to the transport grid (25 kV and up), the power flow through the station is analysed. This only poses issues for stations with large amounts of power generation compared to the stations capacity. This loading is easy to analyse as it is comparing a power flow to a nominal rating from a single or 2 assets. No additional processing has to be performed for analysis.

The loading inside the networks, MV cables and MV connected transformers, is of much more relevance, as these limits are often reached before those associated with the station connection to a higher voltage level. There are usually a lot of cables, transformers and sometimes overhead lines in the network connected to a station. Due to the large amount of assets this creates a large amount of data to be analysed.

Appendix C.1 gives an extensive explanation of the used visualisation methods. However, the use of cumulative distribution functions and heat maps of loading are reasonably standard visualisation methods. The heat maps used have a nominal value which is white, with blue representing values closer to 0 and red representing higher values.

3.2. Network selection

In order to simulate power flows a network file, which describes network topology and assets, needs to be generated. This was performed by selecting a certain station from the already existing Stedin network file. First the criteria used to determine which stations to simulate are explained and analysed. After which the metrics of the selected stations are elaborated upon and determined whether these stations provide a good diverse set of case studies.

In order to select relevant regions with significant DER development impact the development needs to be analysed. Thus this section simultaneously shows the selection of simulated stations as well as answering one of the sub questions for this thesis, being *"How will DERs on the LV network develop until 2035?"*. Further in this section it will be shown that the ratio of LV PV to MV- and HV-connected PV will be largely between 50% and 70%, with some outlier stations. These station will mainly be situated in industrial areas where most customers have MV connections. It will also be shown that with current predictions the station transport capacity will not be reached at most MV and HV stations. Therefore cables and distribution transformers should be the main focus with respect to congestion.

3.2.1. Selection criteria

In order to limit the simulation complexity a selection of stations and grid parts to simulate has to be made. This section will explain which criteria were used to determine the stations and networks which were chosen.

The first criterion which was chosen is the amount of LV PV capacity with respect to the total installed PV capacity. Besides that the total installed PV capacity related to the station capacity is looked at, as this could result in station congestion at times of much PV generation.

These criteria are reviewed on a HV station (transport) level and on a MV station (distribution) level in order to determine bottlenecks on different levels. For these criteria the data from 2035 is used as this is the longest time span which is being analysed. This is far enough into the future that more loading is not expected before network expansion is performed.

To analyse the percentage of LV PV with respect to all connected PV two plots were created. One with the HV stations and one with the MV stations. Figure 3.2 shows the factor of MV station connected PV with respect to the total PV. As the focus of this research is LV curtailment high amounts of LV PV. The figure below (Figure 3.3) shows the same data for the HV stations. As to determine whether it is relevant to analyse the network at a higher level due to MV station aggregation.

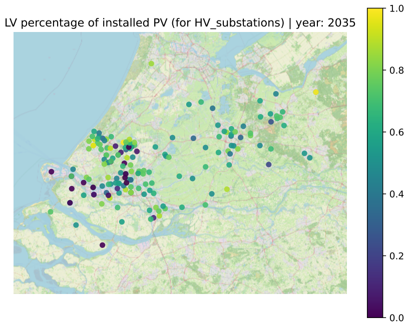

Figure 3.2: Percentage of PV connected at LV level $[\frac{kWp}{kWp}]$ per MV station in 2035. Large format of this figure in Appendix C

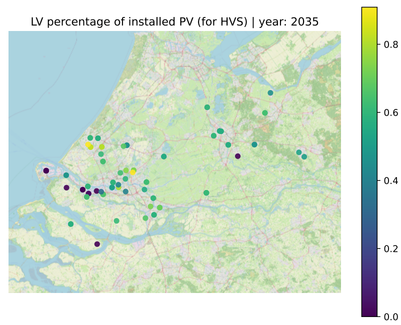

Figure 3.3: Percentage of PV connected at LV level $[\frac{kWp}{kWp}]$ per HV station in 2035. Large format of this figure in Appendix C

A different factor which was taken into account was the factor between station back feeding capacity and the installed amount of PV capacity. As this is a more relevant factor with respect to congestion at station level. When much PV power is produced the station may get overloaded with a PV generation capacity higher than 1.5 times the station capacity. The figures below show this ratio and thus the risk of station overloading due to back feeding.

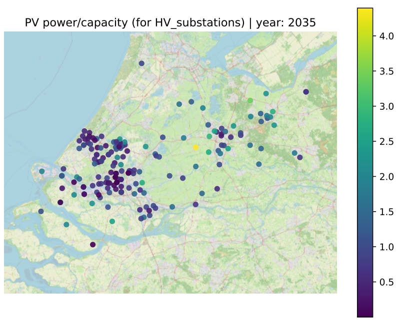

Figure 3.4: Percentage of PV capacity with respect to station capacity $[\frac{kWp}{kVA}]$ per MV station in 2035. Large format of this figure in Appendix C

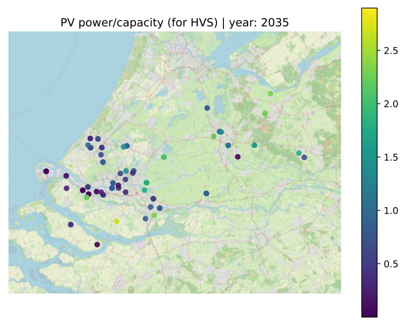

Figure 3.5: Percentage of PV capacity with respect to station capacity $[\frac{kWp}{kVA}]$ per HV station in 2035. Large format of this figure in Appendix C

3.2.2. Used cases

The part of the grid which is to be analysed is clearly connected via one or multiple assets to the station nodes itself. The segregation is done by determining the nodes to which the station is connected on higher voltage levels. From the initial station node each connected line, transformer and load is added to the network. Except for the assets which connect to the nodes higher up in the network as earlier explained.

Initially analysed regions were selected by region knowledge and non-data driven analysis. This resulted in the selection of the Dordrecht region, as explained in Appendix B, at that moment the region segregation was performed in a different way. Therefore the data from this initial research is not relevant as a result, but only to gain an insight into the relevance of the topic. This was part of the reason behind the choice to model the TT096, Dordtse kill, station. Below an extended explanation of why the chosen stations were modelled can be found.

Metrics

The used stations are individually analysed and explained below, together with some of the key figures. The metrics which resulted in the selection of the stations, *LV PV percentage* and *PV capacity percentage*, are plotted for the years which are simulated in Figures 3.6 and 3.7. It is clear that the selection has significant diversity in order to test the curtailment methods on different kinds of networks. However, the figures also show a clear clustering in the middle. This can be taken as a high level of the average development with respect to trends in the electricity grid.

Figure 3.6 shows the percentage of connected PV that is connected through LV connections. This metric provides insight into the distribution of PV systems with respect to size, as large PV systems usually have a MV connection. Most stations have a LV PV percentage between 50% and 70%, however two of the modelled stations have much higher or lower values. Station ”TT096” is an industrial area, where many businesses already have a MV connection and a large roof area which results in large PV systems. Combined with this fact multiple large scale PV systems are connected to this station, this results in the average system being so large that it gets a MV connection. On the other hand station ”TT024” has a large amount of residential buildings connected, this results in many small PV systems and possibly problems on the LV network.

The other figure shown below, Figure 3.7, gives insight into the PV power connected to a station relative to the station connection to the extra high voltage (EHV) or HV grid. Due to the addition of peak PV system powers it is not yet a large issue if this value gets above 100%. However, it does indicate more PV generation than the station is capable of transporting. Due to local consumption this is not a large issue at the moment, but will get increasingly problematic with more installed PV capacity. The general trend is visible at the bottom of this graph below the 200% level. Two stations which have significantly higher levels of PV are also selected in order to analyse the impact. Station ”TS047” is a substation of station ”TS041” therefore the combined outlier behaviour is expected.

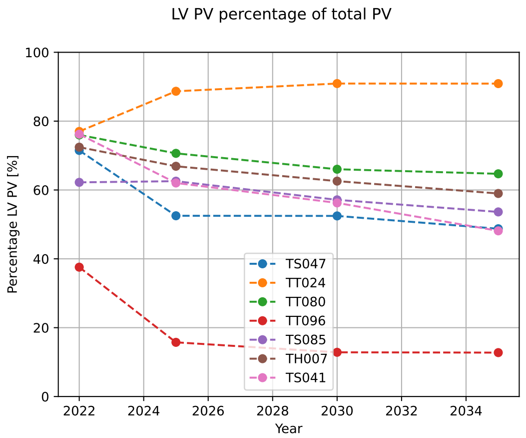

Figure 3.6: Percentage of PV that is LV PV. Large format of this figure in Appendix C

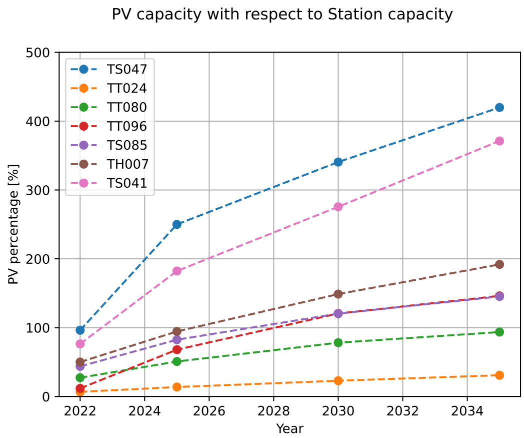

Figure 3.7: Percentage station capacity utilised by PV. Large format of this figure in Appendix C

3.3. Input power

In order to run power flow simulations, power consumption and generation numbers associated to connections need to be calculated. This section will explain the base generation and consumption power calculations. Based on grid operator data, weather profiles and standard calculation methods.

3.3.1. DER development

Wind profile

Wind power is determined as linearised power growth until the rated power from $3.5m/s$ to $12.5m/s$. When the wind speed is above $24.3m/s$ the turbine is shut down. These speeds were chosen as they are usual figures for modern large scale wind turbines [55].

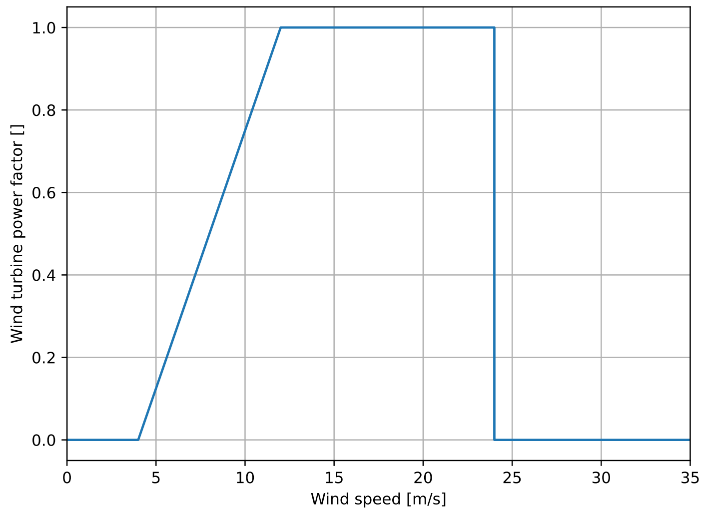

Figure 3.8: Wind turbine power factor curve [55]

PV profile

In order to model PV production the solar irradiation intensity in Rotterdam ($4.447E$ $51.962N$), the data is obtained from the Koninklijk Nederlands Meteorologisch Instituut (KNMI) [56]. This hourly profile is in $\frac{J}{cm^2}$, which does not directly translate to P_{AC} from PV systems. However, if that profile is normalised and multiplied by the mean specific yield (in $\frac{kWh}{kW_P}$) an hourly power output can be determined [57]. These yields can be seen in Table A.1.

At the beginning of 2022 the Stedin LV network had an installed PV capacity of $1.5GW_P$. This corresponds to a rooftop utilisation of 13.6%. The zonneladder, which sets the guidelines with respect to the order in which PV systems should be developed according to the Dutch government [36], dictates that rooftop PV should be placed before looking into utilising other land for PV generation.

If all rooftop potential ($892km^2$) [58] would be developed to have PV systems with an average panel efficiency of 20% [59] the total installed PV power would be $178.4GW_P$ (for the whole Netherlands). According to a study performed for Netbeheer Nederland [60] the installed PV power will reach between 38 and $125GW_P$ in 2050.

PV system growth is very difficult to predict, as past years have proven [61]. TNO (Nederlandse Organisatie voor Toegepast-Natuurwetenschappelijk Onderzoek) predicts that in 10 years the PV production will have gotten to 5 times the 2020 level [62]. This corresponds to an average growth of 17.5% per year. The climate goals result in a division of PV over different grid operators regions. As well as a division into types of PV installations (residential, utility and ground level PV systems). This input, together with subsidy applications, past developments and other societal factors are utilised as an input for a statistical model, developed by Stedin, to develop a growth prediction of PV systems in the network. This growth is used as the expected future PV integration.

In The Netherlands most residential PV systems are between $1.5kW_P$ and $3.5kW_P$. Figures 3.9 and 3.10 show a PV power generation curve during the middle of the year.

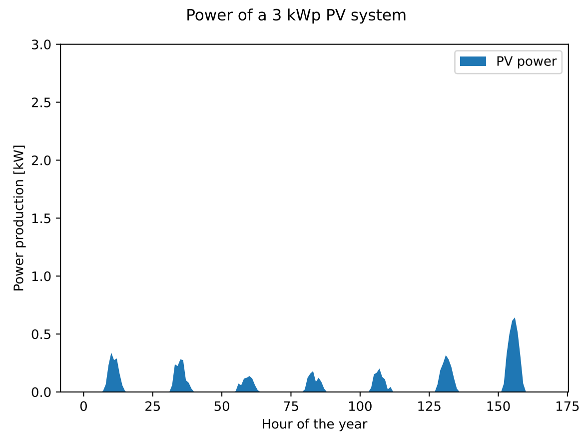

Figure 3.9: Winter PV power generation example of a $3kW_P$ PV system

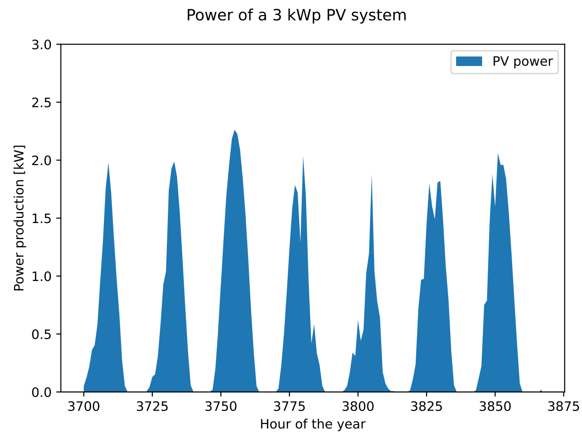

Figure 3.10: Summer PV power generation example of a $3kW_P$ PV system

3.3.2. Load development

As this research depends mainly on power flows, effort was put into the modelling of power generation and consumption. This was combined with societal trends towards electrifying energy consumption for heating, transportation and cooking as a consequence of the reduced usage of fossil fuels and natural gas.

Figure 3.11 shows a residential electricity connection with a heat pump, electric cooking and an EV charger being used. This is a week in the middle of the year and without any PV generation.

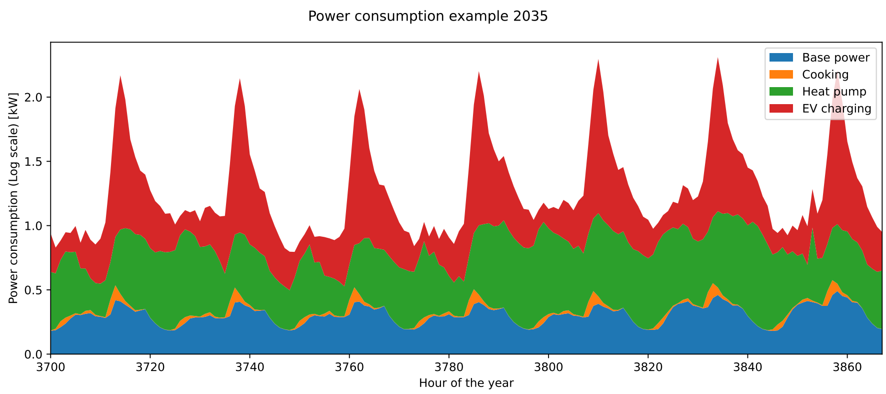

Figure 3.11: Stacked load powers for future calculations. The y-axis is on a logarithmic scale due to the large power associated with EV charging.

LV connections

Base load profile As explained in the introduction the base of the load profiles is determined according to the type of connection it is. These profiles are developed by the ”Marktfaciliteringsforum en Beheerder Afsprakenstelsel” (MFFBAS), an overarching organisation which aggregates and analyses grid data with the grid operators in The Netherlands. Thus profiles developed by MFFBAS are representative for the Dutch electricity connections [63].

As previously explained, a lot of load development is happening. Large energy consuming operations like heating, mobility and cooking are electrifying, these loads need to be taken into account in the power flow calculations. How this is done will be explained below on a per-item basis.

Heat pumps Heat pumps are the direction heating is going in The Netherlands. The government provides subsidies in order for people to replace their natural gas heating with heat pump installations

[64]. Climate change also results in summer days getting hotter and hotter, this increases heat pump installation even more due to their air conditioner capabilities [65]. This double use reduces the levelised cost of heating (and cooling) to below that of a natural gas furnace [66].

Stedin[1] has developed profiles for full-electric and hybrid heat pumps. These will be used in order to determine heat pump related electricity consumption. A total of 5 house types with each having 4 different insulation levels are determined. The average of these profiles is used as not each connection is modelled individually. This profile will be multiplied by the heat pump power which is expected to be appropriate in that specific house. For the adaptation probabilities for different renewable heating options have been computed, these do include district heating and renewable gas. If the probability of a non heat pump related solution is higher than that of a heat pump related solution it is assumed that no heat pump will be installed. The heat pump capacity is determined by an in-house algorithm which takes the type of house, insulation level and usage into account.

EV charging As electric driving is more efficient and costs less than driving fossil fuel cars it is expected that Plug-in Hybrid Electric Vehicles (PHEVs) are on average charged the same as Battery Electric Vehicles (BEVs). This is a daily cycle as it is expected that these people commute using their vehicle and when they arrive home, they connect it to the charger. With rising fuel cost and large scale adoption of EV chargers at homes and businesses the assumption is made that PHEVs are mainly operated as BEVs with respect to charging and energy consumption. As charging at slower speeds is more attractive with respect to electricity cost combined with the large amount of non-public charging points the assumption is made that PHEVs and BEVs will charge at these locations [67]. Combined with an average LV charging point capacity of $11kW$ the charging profile is implemented.

Electric cooking Cooking in The Netherlands used to be done on gas stoves, as gas prices rise, subsidies are provided and sustainability gets encouraged this is shifting towards electric cooking. Cooking consumes more or less the same amount of energy irrespective of the type of cooking appliance used [68]. This is assumed to be $210kWh$ per year, as not all electric cooking appliances are induction cook tops, but also deep fryers, microwaves and electric ovens. As cooking occurs at the same time of day for most people this curve has a distinct profile with peaks at breakfast, lunch and dinner.

Aggregation on transformer level

Load profiles and installed PV capacity are aggregated on a transformer level. This reduces computational intensity from tens of thousands of connections on the network to less than 10% of that amount, which does not reduce insight as this is all on the LV level. As for each connection an hourly load is computed, resulting in a significant impact on computational intensity.

MV and HV connections

MV and HV connections have a large impact, because they either have large loads or large generating capacity connected. Below the different types of MV and HV connections will be analysed and the corresponding methodology in order to develop load/generation profiles will be explained.

Most consumers which are already connected have profiles associated to their agreed upon capacity. These profiles are based on historical consumption measurements. When/where possible these profiles will be used as they represent the actual load the best. Future MV connections are difficult to estimate as it is often not known what the load profile will be. Therefore a standard load profile will be developed in order to estimate these connections their impact on the power flows.

High voltage connections are assumed to be consuming their contracted capacity. However in case of a PV system or wind turbine it is scaled with wind and irradiation figures as explained below.

3.4. Curtailment methods

Curtailment can be described in a multitude of ways. What they have in common is the reduction of power being fed into the grid. The different implementations can be formulated as an absolute power

[1] Stedin is a Dutch grid operator maintaining the gas and electricity grids in a large area of the Randstad.

level, a percentage, no power fed into the grid and some other options. Implementations in this thesis can be divided into a percentage of the installed PV capacity as a limit (static or dynamically) or selecting which loads are not allowed to put power into the grid at all.

After debugging and writing code to run the power flow simulations four curtailment methods proved promising and were analysed. These methods are explained below, their numbers originate from some debugging and experimentation with other curtailment options which proved to be not relevant to the research. A brief explanation of these methods can be found in Appendix D.

Curtailment 24 and 25: Heuristic optimisation This curtailment method is based on a heuristic optimisation. By running simulations with 0, 25, 50, 75 and 100 percent curtailment for each voltage level, resulting in 125 runs with one having a minimal over all loading. This combination of curtailment percentages is then refined in a similar manner until a one percent accuracy is obtained for all three voltage levels. This is assumed to be the optimal case with respect to system loading, as it presented minimal overload due to PV generation. The curtailment percentage is implemented as a back feeding limit related to the installed amount of PV power. For example, a connection with a $30kW_P$ PV system with 20% curtailment would be allowed to put a maximum of $(1.00 - 0.20) * 30 = 24kW$ into the grid. The equation used at each connected node is shown below.

$$P_{out} = max(P_{calc}, C_{factor} * P_{PV\,system}) \tag{3.1}$$

The difference between methods 24 and 25 is that curtailment method 25 only curtails HV and MV generation, while having no impact on LV connected assets. Contrary to curtailment method 24, which optimises over all connected loads and voltage levels.

Curtailment 98 and 37: Split network HV, MV (and LV) Curtailment methods 98 and 97 are based on the determination of the maximally overloaded asset in the network. From this location two sides, a power producing and a power consuming side, are determined. On the side that produces power flowing through this asset all connections are not allowed to put power into the grid anymore. With this change the simulation is ran again and this same analysis is performed until either all assets are analysed, none of the assets are overloaded or there is no significant improvement after curtailing. The difference between 98 and 37 is that in option 98 all connections are curtailed, while with option 97 only the MV and HV assets are curtailed. This provides clear insight in the difference achieved by including or excluding LV connections into a curtailment strategy.

Firstly the connected load powers are calculated and a base scenario power flow is ran. After which the nodes which will be curtailed are determined. If a node is in this list the associated load is set to 0 when it used to be negative (generating). If the load is positive it remains the same. This is continued until above stated conditions are reached.

Curtailment 50: German implementation In Germany PV systems have to comply with curtailment from the grid operator. However, PV systems with an installed capacity of $30kW_P$ or less are allowed to limit their output to 70% of this power and in turn do not have to comply with any further curtailment. This provides an easy, hassle free and attractive solution to small consumers while still maintaining grid capacity and operations. This method of a fixed back feed limit is applied to all LV connections, while MV and HV connections were turned of when contributing to the overload (as in curtailment method 37). The choice to apply the 70% limit to all LV connections is since the aggregation happens on transformer level a per connection analysis would be too computationally intensive. This is combined with the fact that the majority of LV connected PV systems have a capacity at or below $30kW_P$, as the average installed capacity of all PV systems in The Netherlands is $8.5kW_P$.

3.4.1. Curtailment comparison

In Table 3.1 shows an overview of key metrics related to curtailment implementation, Figure 3.12 shows an example network to provide context to the limit labels. It is shown that some curtailment options treat every connection similarly, while others make a distinction between HV/MV conenctions and LV connections. This difference is implemented to analyse the additional effect of curtailing LV generation.

Analysis and visualisation of simmulation results corresponding to these curtailment methods will be shown in Chapter 4

	Limit HV gen.	Limit MV gen.	Limit LV gen.
Developed curt. method 24	Iterative optimisation (minimising curtailment)		
Developed curt. method 25	Iterative optimisation (minimising curtailment)		No limit
Developed curt. method 98	Iterative based on max. loaded asset		
Developed curt. method 37	Iterative based on max. loaded asset		No limit
Developed curt. method 50	Iterative optimisation (minimising curtailment)		70% of PV_{kWp}

Table 3.1: Limits corresponding to labels in Figure 3.12.

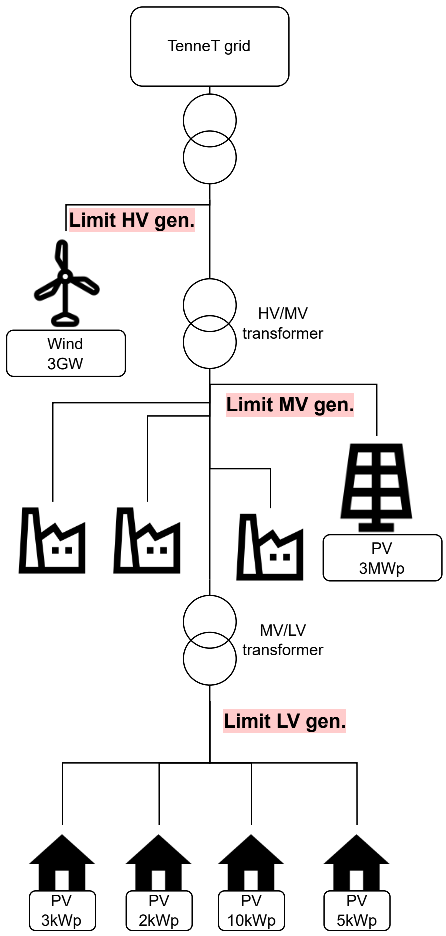

Figure 3.12: Visualisation of an example network to explain curtailment methods. Labels explained in Table 3.1.

4

Discussions

This chapter will provide an analysis of the network loading according to the metrics stated in Section 3.1.3. The loading will also be visualised in multiple ways to provide quick insight and a visual analysis. As curtailment method 24 is currently not practically implementable and has the best performance it is used as a base line for optimal curtailment. Figure 4.1 shows the average asset (over)loading in 2030 of all stations for which the chosen curtailment methods have been simulated. A clear reduction in overloading when curtailment is applied.

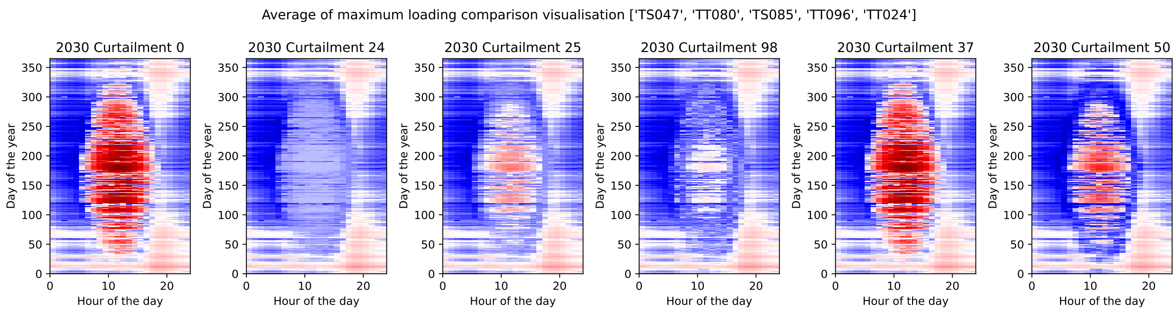

Figure 4.1: Average overloading over stations TT080, TS085, TT096, TT024 and TS047 for no curtailment and curtailment methods 24, 25, 98, 37 and 50 in 2030.

Besides a graphical representation of curtailment effect a numerical analysis is essential in the scientific comparison of curtailment methods. Table 4.1 shows the metrics associated with the visualisation in Figure 4.1. Curtailment option 24 clearly performs the best if only the mitigation of system overload is taken into account, which is shown in the loading figures. In Figure 4.1 it is clear that no overload due to PV remains when looking at instantaneous maximum loading. This is not noted as an explicit curtailment analysis metric, as this is implicitly integrated in the other metrics used. As well as it being used for intuitive analysis from the loading figures.

However, if the metrics in Table 4.1 are analysed a different conclusion can be drawn. While curtailment method 24 does mitigate all overloading due to PV it has a large impact on PV generation (shown in Table 4.8). When comparing curtailment option 24 to option 37 5 times difference in transformer effectiveness is observed when analysing 2030 results from Table 4.1. For curtailment option 37 this can be mainly attributed to the low amount of curtailed energy, as Table 4.7 shows only a small reduction in overload. Figure 4.1 shows that 99.7% of the overload remains present with curtailment option 37, especially MV to LV transformer related. The absolute amount of overload is properly represented by the numbers in Table 4.7. As for curtailment method 50 a high level of effect, over 90% transformer overload reduction and more than 50% cable loading reduction, both observed in Figure 4.10 as well as in Table 4.7, which indicates a more effective curtailment method. As the amount of curtailed energy is less than half of the other curtailment methods which effect LV connections (shown in Table 4.8). This reduces customer impact by curtailing less, while at the same time reducing system loading and investment needs.

	Curt: 24	Curt: 25	Curt: 98	Curt: 37	Curt: 50
Curtailed energy (GWh)	145.5	193.6	135.7	21.7	59.7
Overload reduction Trafo. ($MVAh$)	28978.81	25842.67	27587.68	13302.95	24765.40
Trafo. effectiveness ($\frac{MVAh}{GWh}$)	198.93	117.36	364.40	613.04	293.96
Overload reduction Cables ($MVAh$)	46.04	45.58	42.97	8.37	8.43
Cable. effectiveness ($\frac{MVAh}{GWh}$)	0.18	0.21	0.28	0.39	0.07
Average curtailment hours	4450.8 (50.8%)	6432.0 (73.4%)	3694.8 (42.2%)	245.8 (2.8%)	3541.4 (40.4%)

Table 4.1: Curtailment effectiveness (stations TT080, TS085, TT096, TT024 and TS047) in 2030, negative effectiveness means an overload increase.

4.1. Simulation results

Before going into an in-depth comparison of the implemented curtailment methods they are all analysed on an individual basis and the advantages and disadvantages associated with them are explained and shown. This is done in order to gain better insight into the absolute effect of these curtailment methods.

4.1.1. Curtailment 0: Base loading

Base loading simulations are relevant as comparison data and to analyse the significance of the problem. Figure 4.2 shows the significant amount of overload present in the different networks throughout the simulated years. The overload shown is present at the middle of the day (the red circle in the middle) which is caused by PV generation. The overload present more to the right of the figures is caused by consumption as PV generation goes down in the evening. This also shows the overload in the system due to high power consumption in the evening which this thesis does not address.

Besides the timing of the overloading it is visible that every year the amount of overload increases. This overload increase stagnates after 2025, which makes sense with the installed amount of PV capacity.

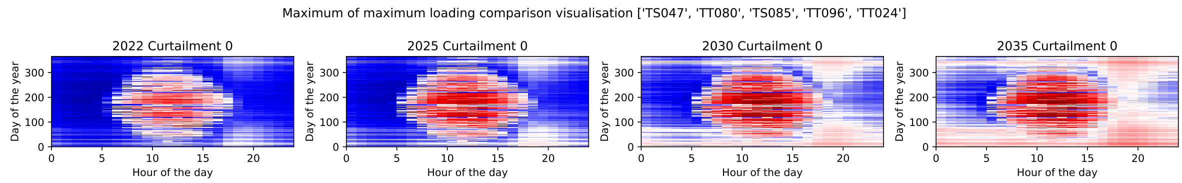

Figure 4.2: Maximum overloading over stations TT080, TS085, TT096, TT024 and TS047 for no curtailment.

Figures 4.3 and 4.4 show the overload inside stations or cables is not that relevant, as other overloading becomes a bottleneck before the station capacity. The numbers shown on the x-axis are the loading factors, this is the loading divided by the nominal capacity of the station or component. Thus anything above 1.0 is an overloaded state, which for a short time is acceptable until a loading factor of 1.5.

The analysis shows that until 2030 only station TS047 has significant overloading. This is due to a large amount of PV generation capacity, as Figure D.12 shows. Thus curtailment would be a good solution to delay the need of more station capacity.

When compared to transformer overloading, shown in Figure 4.5, a factor 8 difference can be observed. Due to this significance of transformer loading whenever a choice has to be made the transformer loading is the primary analysis metric. Unless curtailment methods only impacting HV and MV connections are analysed, as these do not impact the large amount of MV to LV transformers.

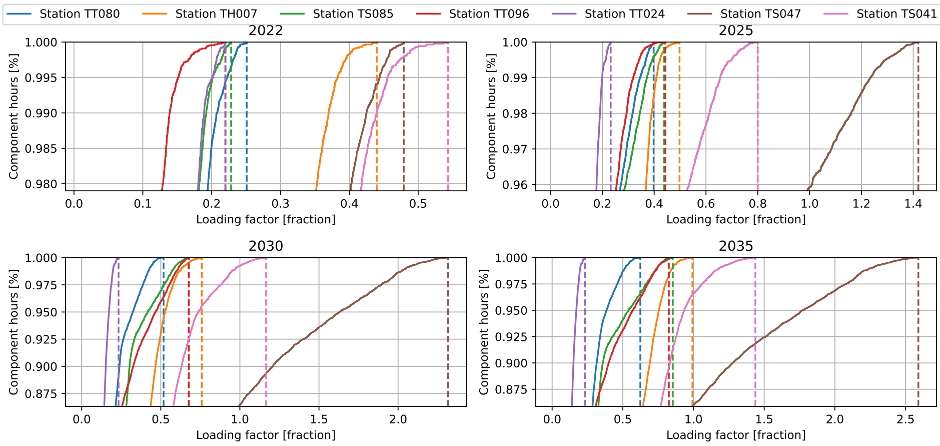

Figure 4.3: Station CDF's without curtailment for all stations in all simulated years.

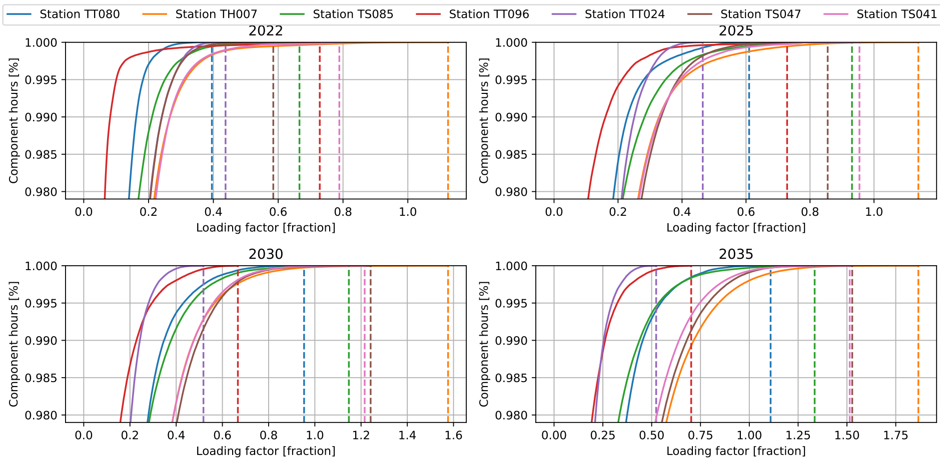

Figure 4.4: Cable CDF's without curtailment for all stations in all simulated years.

Figure 4.5 shows the transformers loading CDF's for the different selected networks. This CDF is the worst case scenario as no overload prevention is in place.

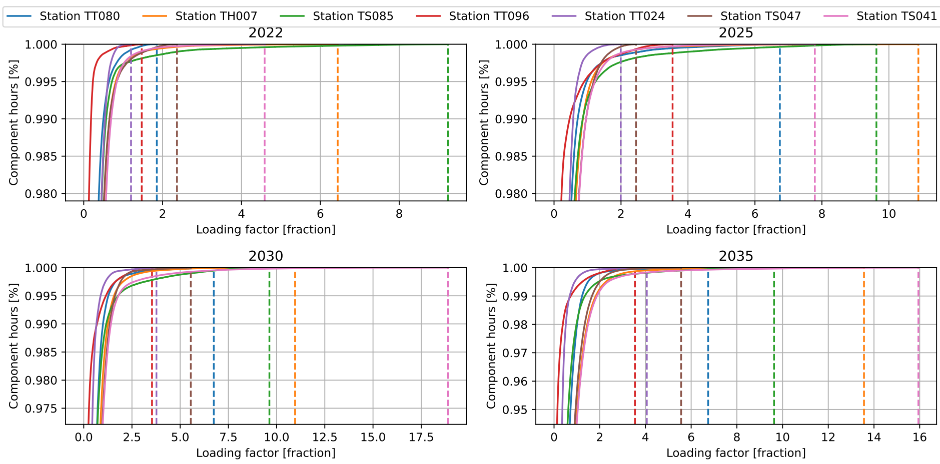

Figure 4.5: Transformer loading CDF's without curtailment for all stations in all simulated years.

4.1.2. Curtailment 24 and 25: Heuristic optimisation

Tables 4.2 and 4.3 show the metrics associated with these curtailment methods. These reduction metrics do not say much unless compared to other curtailment methods their metrics, this is explained in Section 4.2.

As curtailment method 25 does not curtail LV PV its effectiveness is reduced with 50 to 100% depending on the observed year. However, the amount of curtailed energy of curtailment method 25 is higher as less impact is achieved with respect to the total network.

This large amount of curtailed energy is a result of not being able to perform targeted or incremental curtailment, as MV and HV connections are usually more significant generation. As well as most overloading being created by LV backfeeding, which overloads MV/LV transformers. Thus if the whole system is analysed curtailment excluding LV connections is significantly less efficient and less effective than when these connections are controlled. This can be observed both in the Overload reduction row in Tables 4.2 and 4.3. As well as in Figure 4.6, which shows residual PV overloading when not curtailing LV PV and no residual overloading due to PV when LV connections are curtailed.

	2022	2025	2030	2035
Curtailed energy (GWh)	43.31	81.63	145.50	142.83
Overload reduction Trafo. ($MVAh$)	2065.03	9747.34	28978.81	35148.66
Trafo. effectiveness ($\frac{MVAh}{GWh}$)	94.84	126.10	198.93	209.85
Overload reduction Cables ($MVAh$)	0.00	0.00	46.04	302.61
Cable. effectiveness ($\frac{MVAh}{GWh}$)	0.00	0.00	0.18	1.39
Average curtailment hours	4044.6 (46.2%)	4740.8 (54.1%)	4450.8 (50.8%)	4469.2 (51.0%)

Table 4.2: Curtailment 24 metrics (stations TT080, TS085, TT096, TT024 and TS047), negative effectiveness means an overload increase.

	2022	2025	2030	2035
Curtailed energy (GWh)	79.46	112.44	193.59	184.33
Overload reduction Trafo. ($MVAh$)	2064.99	8912.93	25842.67	30754.56
Trafo. effectiveness ($\frac{MVAh}{GWh}$)	38.77	79.87	117.36	131.50
Overload reduction Cables ($MVAh$)	0.00	0.00	45.58	158.08
Cable. effectiveness ($\frac{MVAh}{GWh}$)	0.00	0.00	0.21	1.03
Average curtailment hours	5529.2 (63.1%)	5645.0 (64.4%)	6432.0 (73.4%)	6437.4 (73.5%)

Table 4.3: Curtailment 25 metrics (stations TT080, TS085, TT096, TT024 and TS047), negative effectiveness means an overload increase.

Figure 4.6 gives an intuitive insight into curtailment performance. As the overload at midday due to PV generation gets mitigated fully due to curtailment when using curtailment method 24, it clearly shows the effectiveness of this curtailment method.

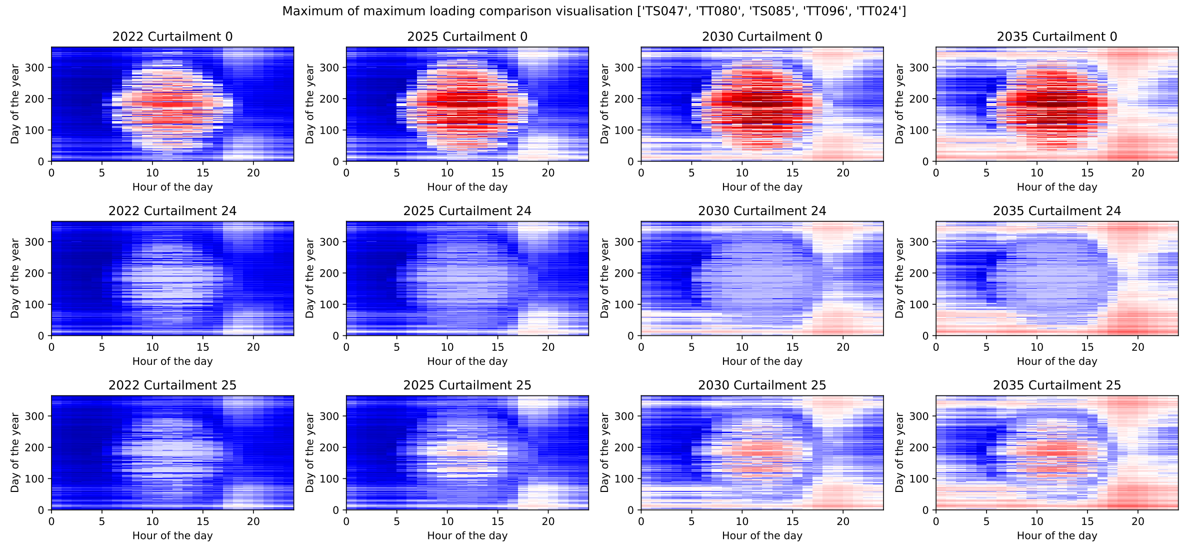

Figure 4.6: Maximum overloading over stations TT080, TS085, TT096, TT024 and TS047 for no curtailment and heuristic optimisation HV, MV (and LV).

4.1.3. Curtailment 98 and 37: Split network HV, MV (and LV)

These curtailment methods need more measurement equipment than currently present in the grid. Dutch grid operators are currently in the process of installing measurement equipment at each MV or HV location. This measurement equipment, combined with a communication strategy like the Real Time Interface, will facilitate the accurate and localised curtailment of over production due to PV generation [20].

Curtailment methods 98 and 37 should be compared to 24 and 25 respectively. As methods 24 and 98 include all voltage levels while 25 and 37 only curtail HV and MV systems. Figure 4.7 shows the effectiveness over the years, with option 37 not providing a noticeable reduction in overloading when taking MV to LV transformers into account. For analysis of the impact on the grid without taking MV to LV transformers into account Figure 4.11 can be looked into. This shows the effectiveness of curtailment method 37 for its intended purpose, however as its advantage over curtailment method 25 is only the computational complexity there needs to be ample reasoning behind that choice.

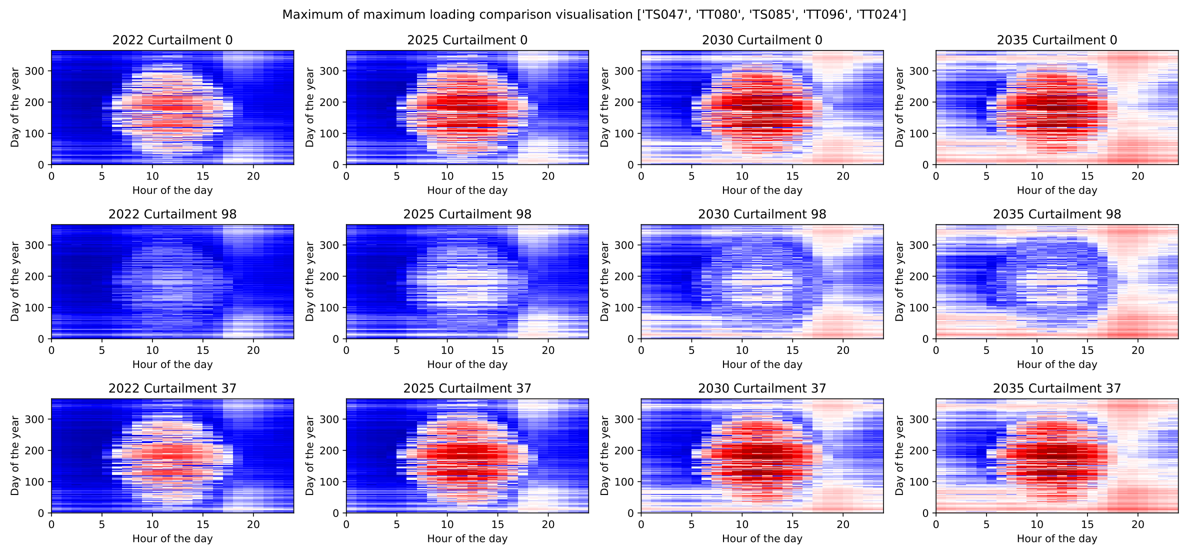

Figure 4.7: Maximum overloading over stations TT080, TS085, TT096, TT024 and TS047 for no curtailment and options 98 and 37.

Tables 4.4 and 4.5 show the progression throughout the years of curtailment metrics. This shows that these curtailment options provide good results with reasonable amounts of curtailed energy. It can be observed from Table 4.5 that with minimal amounts of curtailed energy the grid is not overloaded if MV to LV transformers are excluded.

	2022	2025	2030	2035
Curtailed energy (GWh)	6.22	21.94	135.65	170.64
Overload reduction Trafo. ($MVAh$)	2064.99	7913.61	27587.68	32411.82
Trafo. effectiveness ($\frac{MVAh}{GWh}$)	331.99	314.70	364.40	357.33
Overload reduction Cables ($MVAh$)	0.00	0.00	42.97	128.05
Cable. effectiveness ($\frac{MVAh}{GWh}$)	0.00	0.00	0.28	1.83
Average curtailment hours	1224.2 (14.0%)	2179.2 (25.0%)	3694.8 (42.2%)	4267.6 (48.7%)

Table 4.4: Curtailment 98 metrics (stations TT080, TS085, TT096, TT024 and TS047), negative effectiveness means an overload increase.

	2022	2025	2030	2035
Curtailed energy (GWh)	0.00	3.19	21.72	26.41
Overload reduction Trafo. ($MVAh$)	0.00	1063.93	13302.95	17277.00
Trafo. effectiveness ($\frac{MVAh}{GWh}$)	0.00	333.52	612.47	654.18
Overload reduction Cables ($MVAh$)	0.00	0.00	8.37	49.34
Cable. effectiveness ($\frac{MVAh}{GWh}$)	0.00	0.00	0.39	1.87
Average curtailment hours	0.0 (0.0%)	63.0 (0.7%)	245.8 (2.8%)	307.8 (3.5%)

Table 4.5: Curtailment 37 metrics (stations TT080, TS085, TT096, TT024 and TS047), negative effectiveness means an overload increase.

4.1.4. Curtailment 50: German implementation

The German implementation metrics are shown in Table 4.6. The effectiveness metric of this curtailment method is lower than that of curtailment method 37, it does however reduce overloading much more. Therefore these metrics should be analysed as a full set of metrics instead of on an individual level. Another good analysis method is the relative CDF area compared to curtailment method 24 as shown in Table 4.7. Those numbers show the high amount of effect from curtailment method 50. Resulting in over 90% transformer overload reduction and more than 50% cable loading reduction.

	2022	2025	2030	2035
Curtailed energy (GWh)	13.25	32.80	59.66	64.03
Overload reduction Trafo. ($MVAh$)	2065.03	8646.17	24765.40	28753.44
Trafo. effectiveness ($\frac{MVAh}{GWh}$)	155.85	263.63	415.08	449.05
Overload reduction Cables ($MVAh$)	0.00	0.00	8.43	52.60
Cable. effectiveness ($\frac{MVAh}{GWh}$)	0.00	0.00	0.14	0.82
Average curtailment hours	4137.0 (47.2%)	3957.8 (45.2%)	3541.4 (40.4%)	3367.4 (38.4%)

Table 4.6: Curtailment 50 metrics (stations TT080, TS085, TT096, TT024 and TS047), negative effectiveness means an overload increase.

Figure 4.8 shows the reduction in maximum loading due to curtailment method 50 across multiple stations. It shows the reduction of overloading, but there remains some overloading due to PV generation at peak hours. Figure 4.9 shows the relative effectiveness of this curtailment method, with only the heuristic optimisation out-performing it.

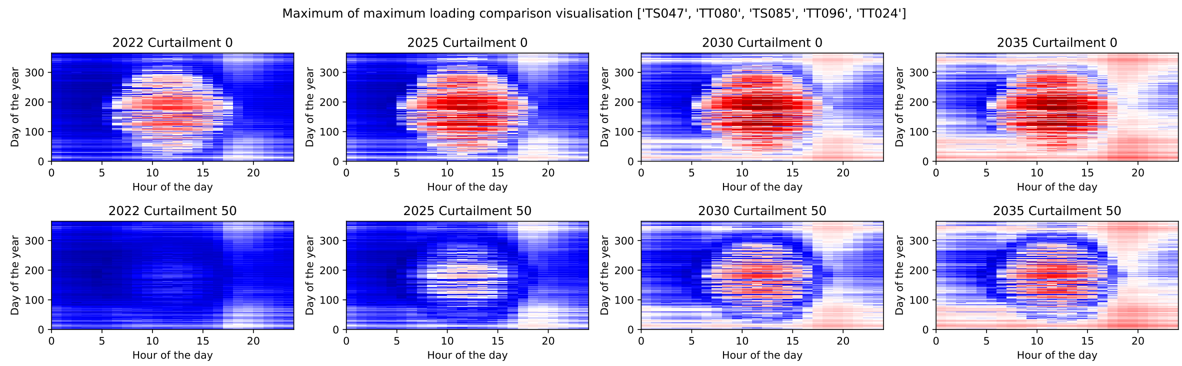

Figure 4.8: Maximum overloading over stations TT080, TS085, TT096, TT024 and TS047 for no curtailment and curtailment option 50.

4.2. Comparison

All in all individual analysis is important, but relative comparison is essential, especially in research based on case studies. Figure 4.9 shows the performance of the implemented curtailment methods over multiple (sub-)stations their transformers relative to optimal curtailment. This visualisation is made concrete in Table 4.7 with the relative surface of the different curtailment methods their CDF compared to the heuristic optimum.

Curtailment options 24, 98 and 50 all three are more effective with respect to transformer overload than options 25 or 37. This is due to the LV connections also being curtailed. The averages in Table 4.7 gives good insight into the fact that all these curtailment options reduce transformer overload significantly more than cable overloading. This characteristic comes from the difference in overloading between these asset types. Cable overloading is not as significant, as Figure 4.11 shows, due to the fact that every curtailment option simulated mitigates all cable overload present in the scenario without curtailment.

The most effective curtailment method which is implementable and does not increase cable loading is curtailment option 50, aside from the heuristic optimisation. Which in combination with the relative low amount of curtailed energy, shown in Table 4.8, makes this the best curtailment option currently implementable. For future expansion of PV generation other curtailment methods should be explored, prepared and possible implemented between 2030 and 2035. This relevance is shown in Figure 4.10, the presented future overload is due to LV PV as curtailment option 25 does not mitigate it.

For future implementation, with the measurement equipment currently being installed in mind, curtailment option 98 with sequentially analysing the maximally loaded asset would provide a good future solution. As computation power gets scaled up, measurement equipment gets installed and policy gets made for the curtailment of individual LV connections.

	2022		2025		2030		2035		Average	
	Cables	Trafos	Cables	Trafos	Cables	Trafos	Cables	Trafos	Cables	Trafos
Curt. 0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Curt. 24	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Curt. 25	12.660	0.085	3.834	0.165	1.910	0.392	1.470	0.397	4.969	0.260
Curt. 98	14.971	0.145	4.784	0.282	2.090	0.112	1.677	0.097	5.881	0.159
Curt. 37	1.000	1.000	0.994	0.999	0.953	0.995	0.918	0.994	0.966	0.997
Curt. 50	0.121	−0.591	0.333	0.042	0.601	0.403	0.651	0.462	0.427	0.079

Table 4.7: Combined (stations TT080, TS085, TT096, TT024 and TS047) residual PV load CDF area relative to curtailment 24 (no sun overload) and curtailment 0 (maximal sun overload). Derived from data visualised in Figure D.1 and 4.9. A low number represents a low amount of residual overloading.

The averages show the optimum of practically implementable curtailment being curtailment option 50. The only better option is the heuristic optimisation. However, this option is not practically implementable due to the lack of measurements and insight into the electricity grid.

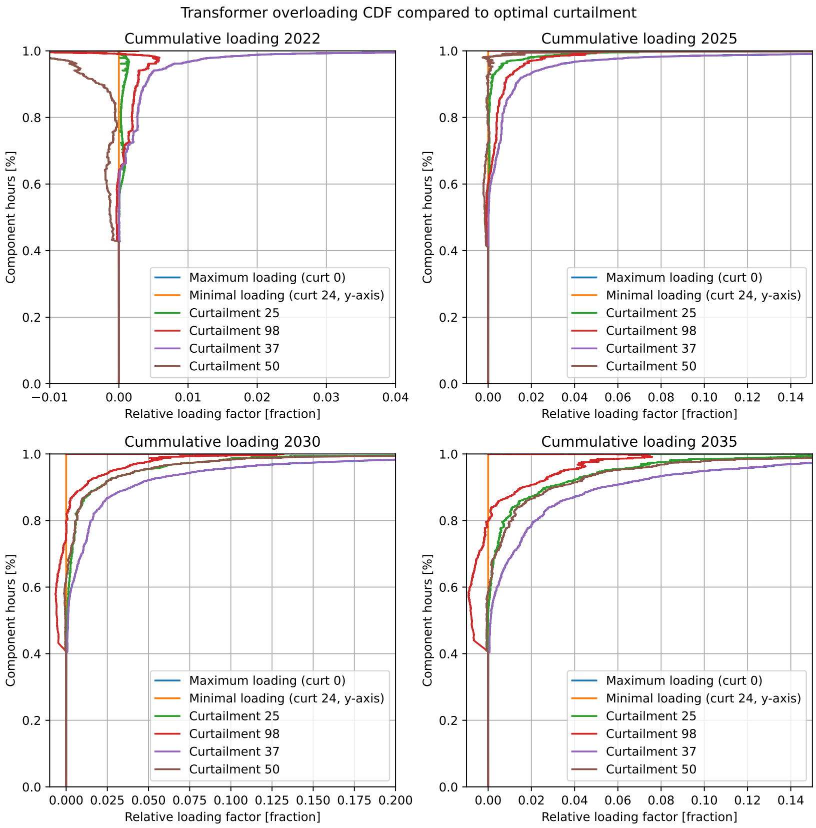

Figure 4.9: Relative transformers overloading CDF's of curtailment 0, 24, 25, 98, 37 and 50 for stations TT080, TS085, TT096, TT024 and TS047 combined.

	2022	2025	2030	2035
Curtailment 24	$43.2GWh$	$81.6GWh$	$145.5GWh$	$142.8GWh$
Curtailment 25	$79.5GWh$	$112.4GWh$	$193.6GWh$	$184.3GWh$
Curtailment 98	$6.2GWh$	$21.9GWh$	$135.7GWh$	$170.6GWh$
Curtailment 37	$0.0GWh$	$3.2GWh$	$21.7GWh$	$26.4GWh$
Curtailment 50	$13.3GWh$	$32.8GWh$	$59.7GWh$	$64.0GWh$

Table 4.8: Curtailed energy for stations TT080, TS085, TT096, TT024 and TS047 with different curtailment methods through the years.

Figures 4.10 and 4.11 show the general impact of curtailment on all assets and only transport assets respectively. These figures show that the heuristic optimisation reduces PV overload to 0. This same comparison shows the distinct difference between options 98 and 37, being the effect of curtailment 98 on the MV/LV transformers.

This also shows the necessity of LV curtailment in the comparison between methods 24 and 98 with the curtailment options 25 and 37. The first two methods include LV curtailment while options 25 and 37 do not, resulting in residual overload from PV power generation.

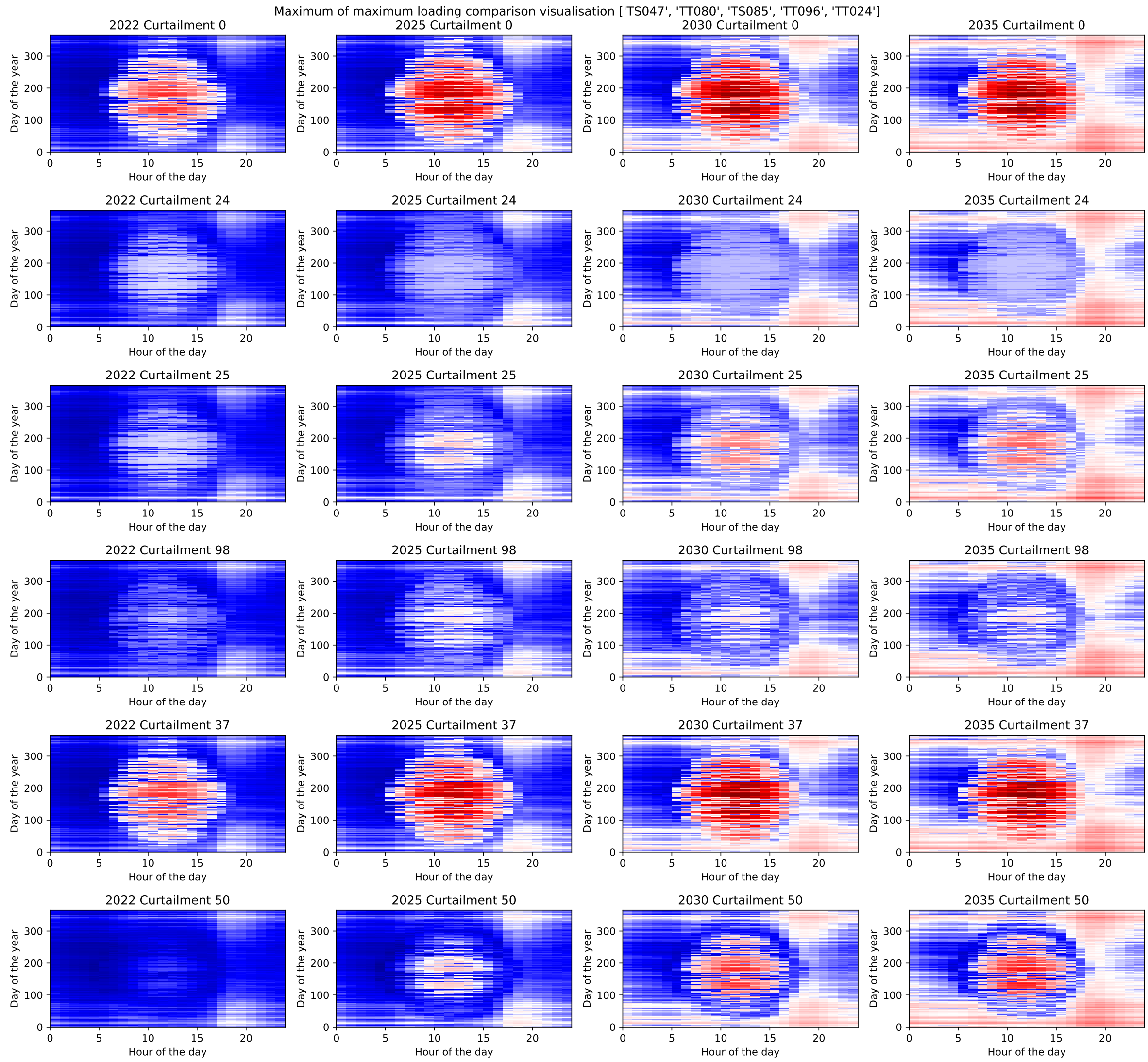

Figure 4.10: Maximum overloading over stations TT080, TS085, TT096, TT024 and TS047 for no curtailment and curtailment methods 24, 25, 98, 37 and 50.

Figure 4.11 shows the effectiveness of every curtailment method on the cables and transport assets. If MV/LV transformers are not taken into account any of the analysed curtailment methods is effective in mitigating HV and MV overload. Thus LV curtailment is not necessary, however it is beneficial, to HV and MV assets when excluding MV to LV transformers.

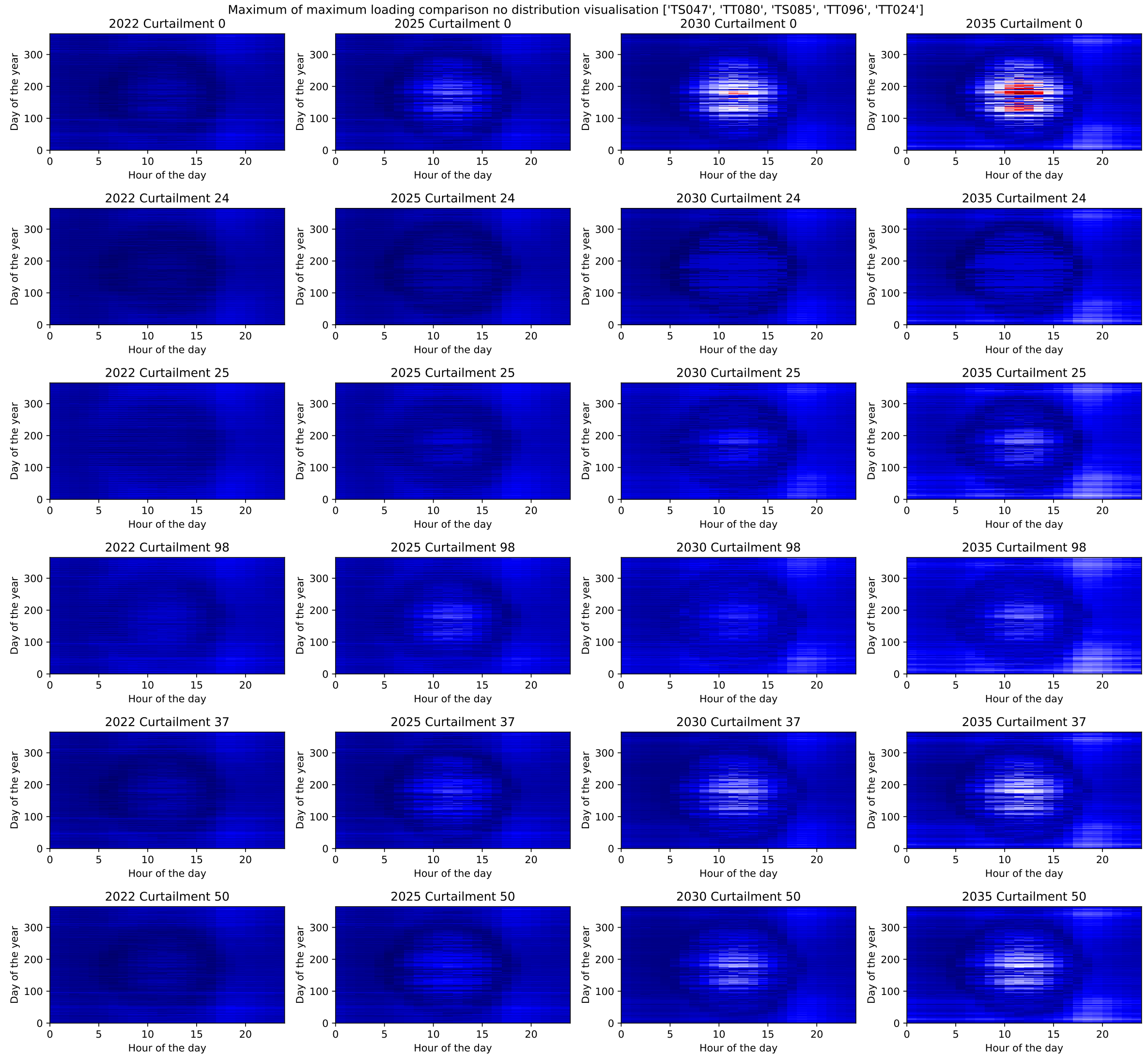

Figure 4.11: Maximum transport asset (MV/LV transformers excluded) overloading over stations TT080, TS085, TT096, TT024 and TS047 for no curtailment and curtailment methods 24, 25, 98, 37 and 50.

5

Conclusion and Recommendations

This thesis aims to close the research gap between LV curtailment research and theoretical curtailment implementations of LV curtailment to alleviate MV and HV congestion. As research into practically implementable LV curtailment effects on the MV and HV network was non-existent.

The subject has been divided into sub questions which, when the answers are combined and analysed, give an answer to the main research question. To summarise these sub-questions will be utilised as a framework, finishing with the main research question and the answer to it.

- *Which curtailment methods exist and are possible?*

  Chapter 2 gives an analysis of existing research and curtailment methods. With a comparison presented in Table 2.1. Furthermore Section 3.4 shows the implemented curtailment and the used methods, with an analysis in Chapter 4.

  The implemented and analysed options consist of an heuristic optimisation per voltage level, a selective curtailment based on the maximally loaded asset and one acting in a similar manner to the curtailment in place in Germany.

- *What is the impact of LV developments on the HV and MV power flows?*

  – *How will loads on the LV network develop until 2035?*

    Section 3.3.2 answers this sub-question. The large-scale adoption of electrification and green technologies results in the significant growth of electricity consumption by residential connections. This has a significant impact on grid loading, but only a minor impact on the overloading due to PV generation. While not being the focus of this thesis it can be observed in Section 4.1.1 that overloading due to these appliances is significant in the evening.

  – *How will DERs on the LV network develop until 2035?*

    Section 3.3.1 gives ample insight into the development of residential PV systems and other DER developments. This has a significant impact on network loading, as shown in Section 4.1.1. The prognosis of PV development is a five fold growth within ten years. If this takes place the power grid will become overloaded, both from a capacity point of view and with respect to generation stability. Therefore curtailment research is essential.

- *How do different curtailment methods compare to each other?*

  The comparison between different curtailment methods has been explored and analysed in Chapter 4. This, combined with the load and DER developments, gives an adequate insight into the role curtailment can play in reducing network loading.

  As generation is curtailed, the overloading due to PV can be reduced to 0. However, curtailment needs to be practically implementable, which is a consideration often not taken into account. Therefore the comparison presented in Chapter 4 is an essential addition to existing research.

- ***How will LV-connected DER curtailment affect the loading of the MV and HV network?***

In order to reduce network loading significantly, LV curtailment is essential, shown in Section 4.1. In the following comparison, it has clearly been shown that heuristic optimisation is the technically best option. However, this curtailment method is not technically feasible at the moment due to lacking insights into the electricity grid. A good option is the, in Germany implemented, curtailment method 50. Striking a balance between overload reduction and curtailed PV energy. With future expansion of the grid, market options and technical implementations facilitating a more complex and optimised curtailment approach.

If MV to LV transformers are excluded from the analysis conclusions present a different finding, shown in Section 4.2. Curtailment methods 50 and 24 are still both very effective. However, if curtailment methods 98 and 37 are analysed, it shows the lack of LV curtailment necessity to reduce HV and MV asset loading. In conclusion, the curtailment of LV is not essential for MV and HV assets if MV to LV transformers are not taken into account. Therefore either a system optimisation approach, which is computationally intensive, requires a lot of sensing and communication is required. Or a separate implementation for HV and MV curtailment should be implemented, with a different implementation for the LV connections.

The initially posed research gap "the lack of research into implementable LV curtailment its impact on HV and MV congestion" is closed as this thesis compares technically implementable curtailment options and their effects on the MV and HV networks. While also giving insight into the comparison between heuristic optimisation and feasible curtailment implementations.

The most effective form of curtailment is to control each voltage level independently, preferably per individual connection. However, the curtailment strategy implemented in Germany proved almost as effective, while only having one third of the impact on PV production. At the same time less insight into the grid is needed, which helps with the practical implementation of curtailment and provides possibilities of earlier practical implementation. As operational cost is directly related to curtailed energy this is a less expensive solution, both in operation and in technical implementation, as less insight into the grid is needed while also not creating the necessity of curtailment hardware at each connection. The German model requires a change of settings in inverters, while an optimisation approach would require a separate interface and data connection. With the added cost of implementing this and providing computational backing from the grid operator.

All in all an optimisation approach would be best to reduce grid loading. However, when implementation and impact are taken into account, it is better to adopt the German curtailment implementation while exploring alternative options. This provides almost as much grid relief, while significantly reducing downsides related to implementation. And if MV to LV transformers are excluded from the analysis LV curtailment has almost no benneficial impact on the analysed assets.

5.1. Future research

As controlling installations behind the connection point is a controversial topic research into societal support for different curtailment methods has to be performed. This should be combined with a financial impact analysis of reinforcing the power grid or compensating customers for curtailment. These matters, combined with this thesis, would provide the basis for a change in the Dutch electricity law or internal grid operator policy.

5.1.1. LV curtailment interaction

Further research into the correlation between different LV curtailment methods and HV & MV curtailment should be performed. As this research shows a significant impact on asset loading when these are correlated. Results from this research can be used as a starting point to look into the correlation between LV and HV & MV asset loading for different curtailment implementations.

5.1.2. Real life case study

In order to test the conclusions from this research a real-life implementation in a case study will be useful. This can be performed by changing the curtailment in cooperation with German grid operators or by implementing it in a selected region through an opt-in program. Special care needs to be taken in order to provide reasonable compensation to all parties cooperating.

To decide which station to use for the implementation case study, the results from the simulations in this report can be used. As observed an (almost) overloaded station with significant PV generation has the preference as curtailment has a significant positive impact for these stations.

5.1.3. Public support

In order to implement curtailment, public support needs to be created. This was proven by the rejection of the net-metering phase out from the Dutch Senate [69]. The conclusion that a 70% limit is nearly as effective, while being much more efficient will result in a higher level of social acceptance.

Further research into the societal impact of different curtailment methods needs to be performed before implementation. However, from this research, the general impact on network loading and curtailed energy can be used in further analysis.

5.1.4. Financial impact

The analysed connections of stations TT080, TS085, TT096, TT024, and TS047 account for 2.6% of all Stedin connections in 2022. If Table D.5 is combined with the average variable electricity cost in 2022 of €$0,4581$ per kWh it results in a curtailment cost between €$12.1milion$ and €$84.4milion$ euro per year, the exact numbers are in Table D.6 [70].

These numbers should only be used indicatively, when net-metering is ended the average price of electricity during sun hours will be significantly reduced. Especially as dynamic (based on the day-ahead market) electricity pricing becomes more prevalent in consumer contracts.

While this does give some sense of cost related to curtailment it should be contrasted by grid strengthening costs otherwise being necessary. This comparison should also be researched before any curtailment implementation takes place.

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A

Appendix

A.1. PV profile information

Year	Mean PV yield
2012	$896 \frac{kWh}{kW_P}$
2013	$899 \frac{kWh}{kW_P}$
2014	$931 \frac{kWh}{kW_P}$
2015	$952 \frac{kWh}{kW_P}$
2016	$939 \frac{kWh}{kW_P}$
2017	$886 \frac{kWh}{kW_P}$
2018	$1003 \frac{kWh}{kW_P}$
2019	$938 \frac{kWh}{kW_P}$

Table A.1: Table displaying Mean specific PV yield in The Netherlands [57]

B

Appendix Dordrecht region

B.1. Network statistics

The Dordrecht part of the Stedin MV network consists of many entities. A complete inventory of the power grid model (PGM) system can be seen in Table B.1. The network is split into two parts with a HV connection between them. This connection consists of a $50kV$ cable, owned by Stedin, and a $150kV$ cable, owned by TenneT. These cables are represented as links, which are connections representing very low losses. Links are chosen as no congestion is expected on the Stedin cable and the TenneT cable is out of scope.

Each connection point is represented by a load element. When power is being injected at a connection, the power of the load element is configured to be negative. A visual representation of the network can be viewed in Figure B.1.

Nodes	1400
Lines	695
Links	2
Transformers	710
Loads	675
Source	1

Table B.1: Component counts in the Dordrecht part of the PGM system

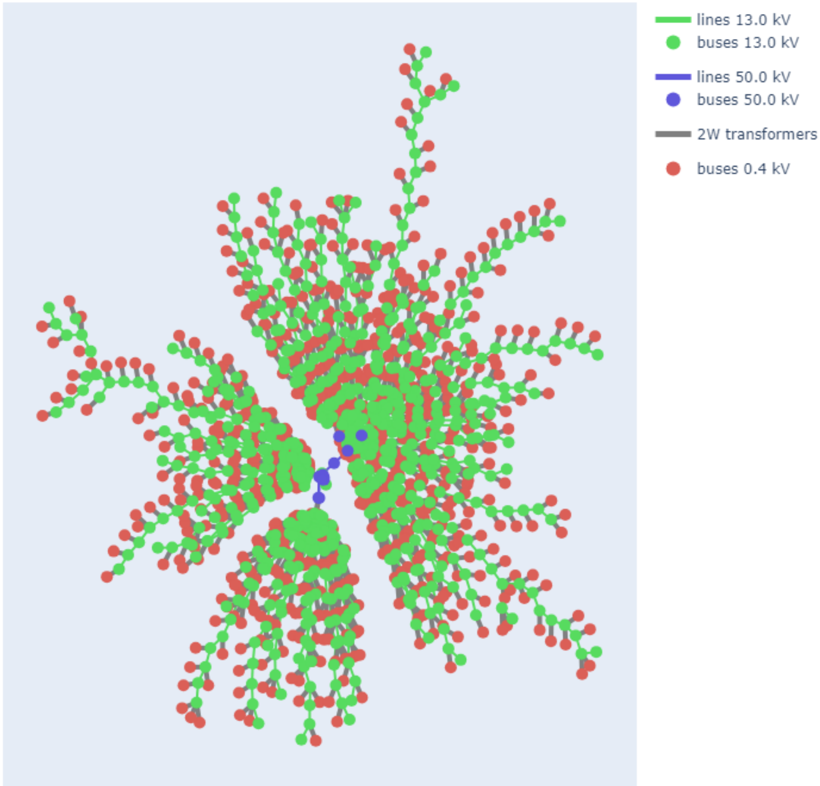

Figure B.1: Visual representation of the Stedin MV network from the Dordrecht region

B.2. HV grid connections

The external connections to the TenneT grid have a total transporting capacity of $5.6GVA$. This can only be fully utilised when no other power flows in the "Randstad 380 kV" grid are present, which is often not the case. The $50kV$ connections to the rest of the Stedin network have a combined capacity of $0.45GVA$. Combined does this constitute a theoretical export capacity of $6GVA$, thus when this back feeding limit is approached by type A [21] generation units curtailment will be essential in order to keep the grid operational.

B.3. Region selection

For the selection of a specific region, in order to speed up simulations, simplify the model and reduce analysis complexity, some criteria were chosen. These fall in the categories of; power generation, connection types and network state. The objective was to determine which region in the Stedin network has significant congestion issues and poses a diverse enough case to make analysis relevant. This was determined by analysing the Stedin network, shown in Figure B.2. One might suggest choosing the Utrecht region as there is a lot of congestion in that region. But the lack of a clear demarcation and the multitude of possibilities with respect to renewable technologies makes it a difficult case study.

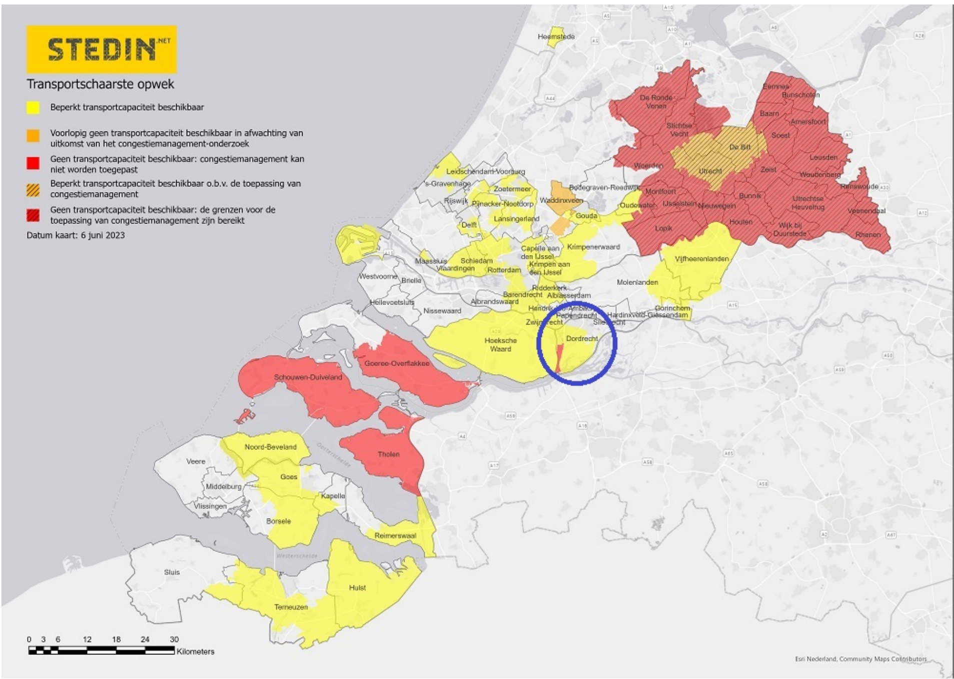

Figure B.2: Capacity map of the Stedin network with respect to generation [71]. Dordrecht region marked with a blue circle

As the island of Dordrecht has a clear demarcation, a multitude of connection types and a reasonable diversity of power generation this region has been chosen to focus and base this research on. Commercial warehouses, diverse house types and small commercial buildings are all present. On top of that some PV parks, wind turbines and a power plant, this creates a diverse generation scheme. Which may pose difficulties in the modelling, but is a substantiating factor of the results, is the fact that associated to this power plant a heating network is in use in the region [72]. Figure B.3 shows this region and its associated high voltage connections, cables and lines. The red and dark blue lines and connections will not be taken into account as these are TenneT assets.

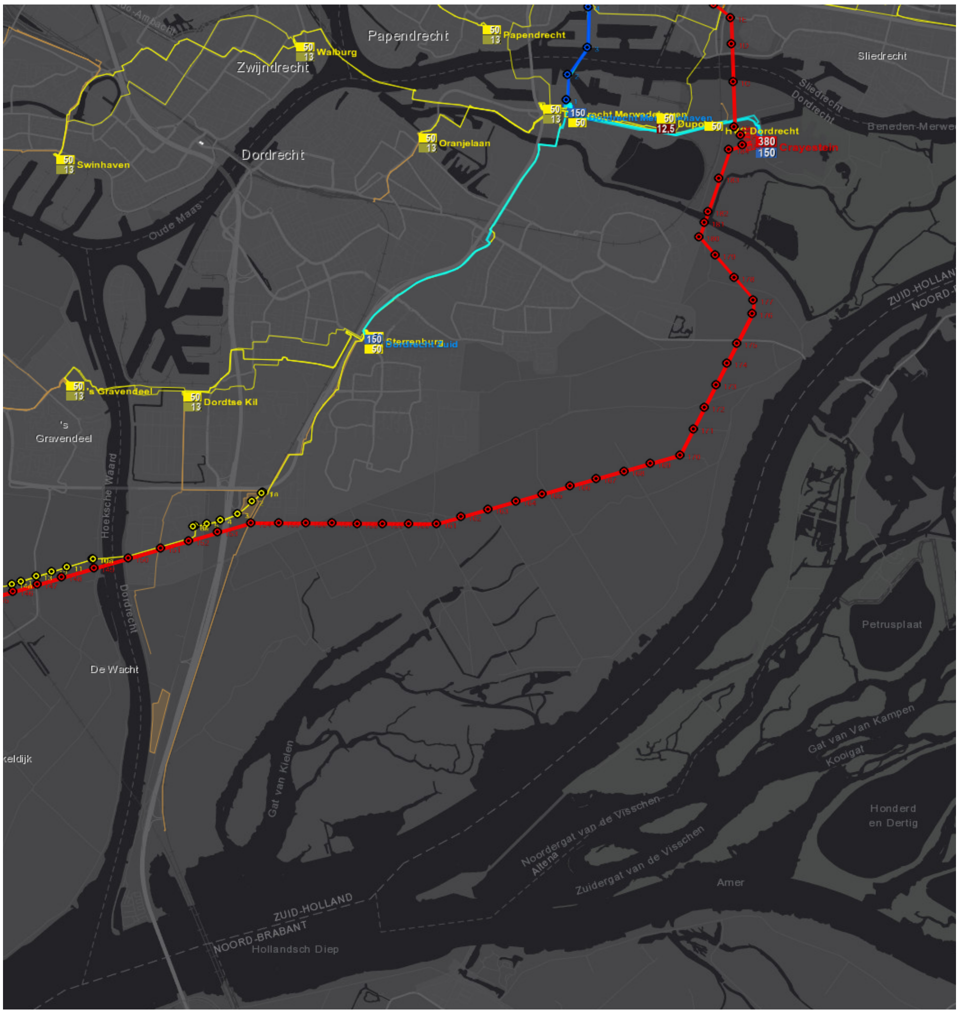

Figure B.3: Overview of the region that will be analysed, naturally demarcated by rivers (Nieuwe Merwede, Beneden Merwede, Oude Maas, Dortsche Kil) [73]

B.3.1. Region extraction from model

Two main nodes in the network, namely two HV/MV substations, were selected as starting nodes. After which adjacent components (lines, transformers, nodes etc.) are gradually added to the network. The components at the edges of the selected region have been determined by analysing the original model. These will not be added and once a loop has been ran without adding any components it is assumed that the sub-network is complete.

C
Figures appendix

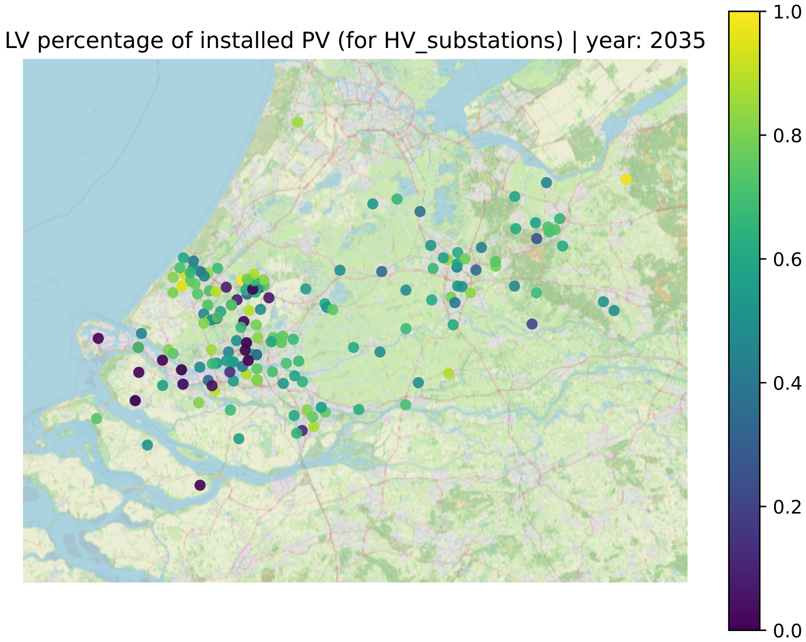

Figure C.1: Percentage of PV connected at LV level $[\frac{kWp}{kWp}]$ per MV station in 2035

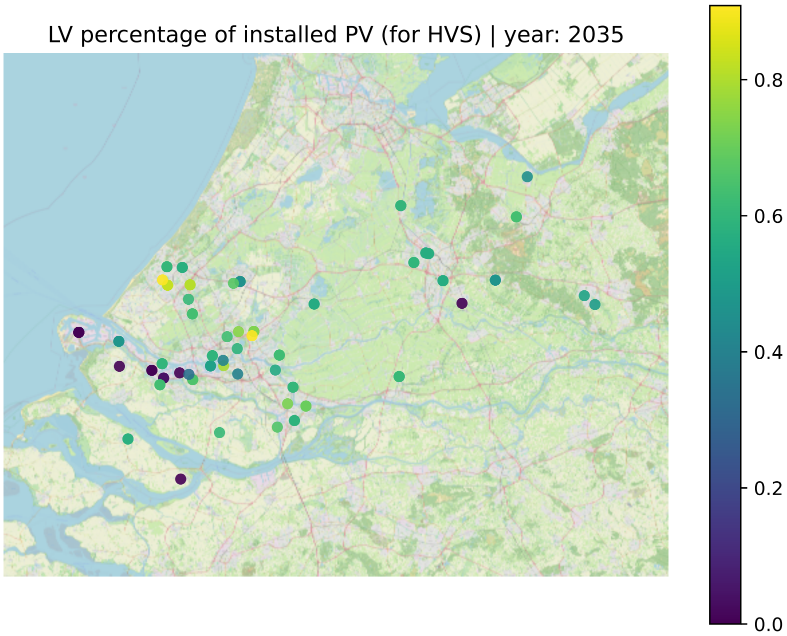

Figure C.2: Percentage of PV connected at LV level [$\frac{kWp}{kWp}$] per HV station in 2035

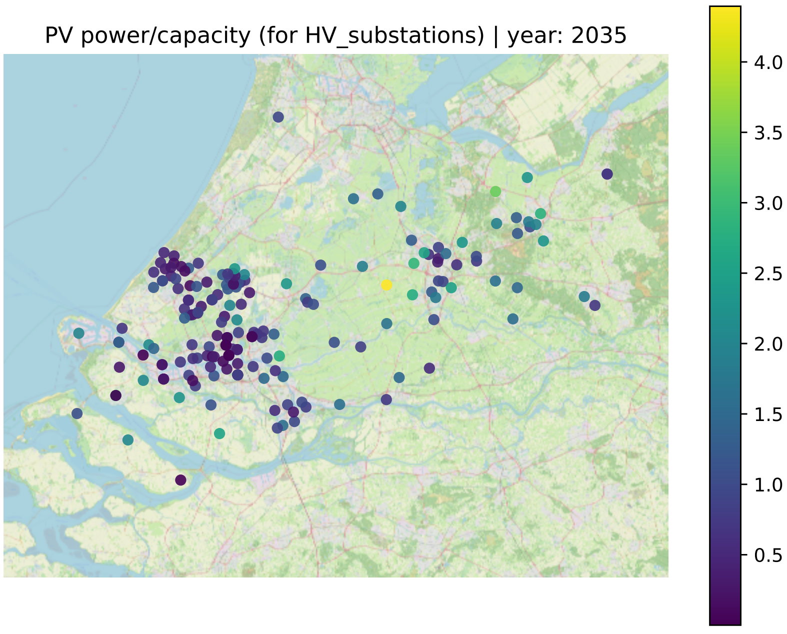

Figure C.3: Percentage of PV capacity with respect to station capacity [$\frac{kWp}{kVA}$] per MV station in 2035

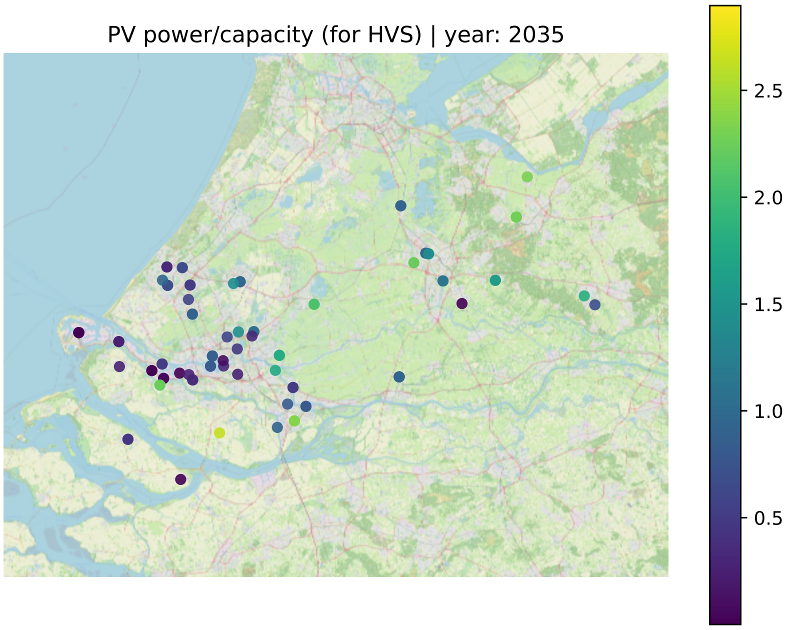

Figure C.4: Percentage of PV capacity with respect to station capacity [$\frac{kWp}{kVA}$] per HV station in 2035

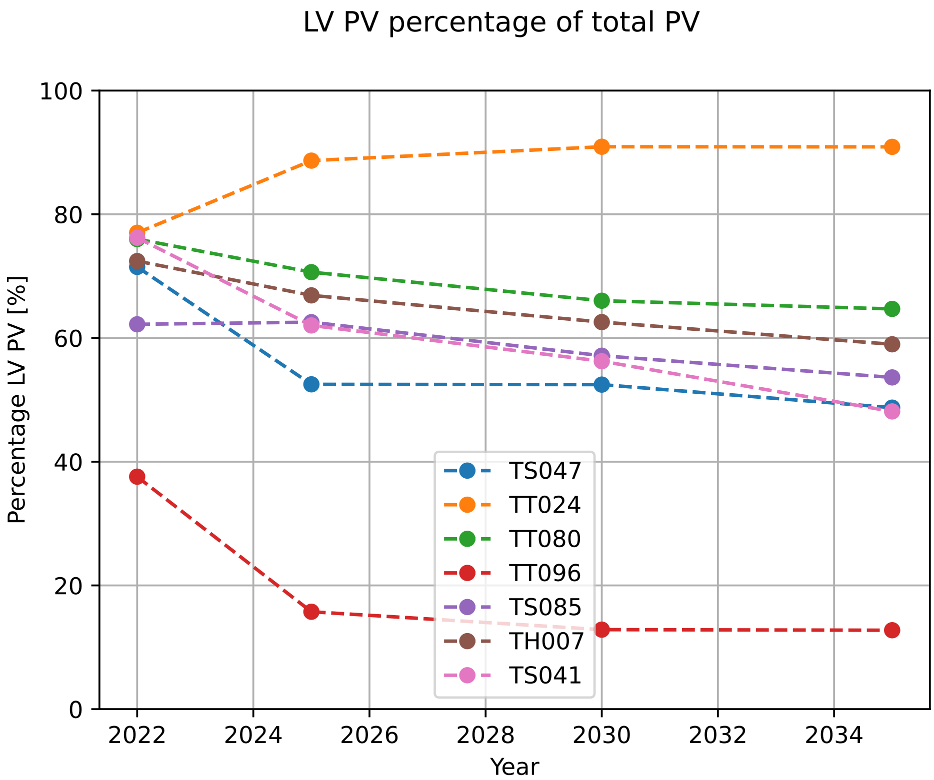

Figure C.5: Percentage of PV that is LV PV

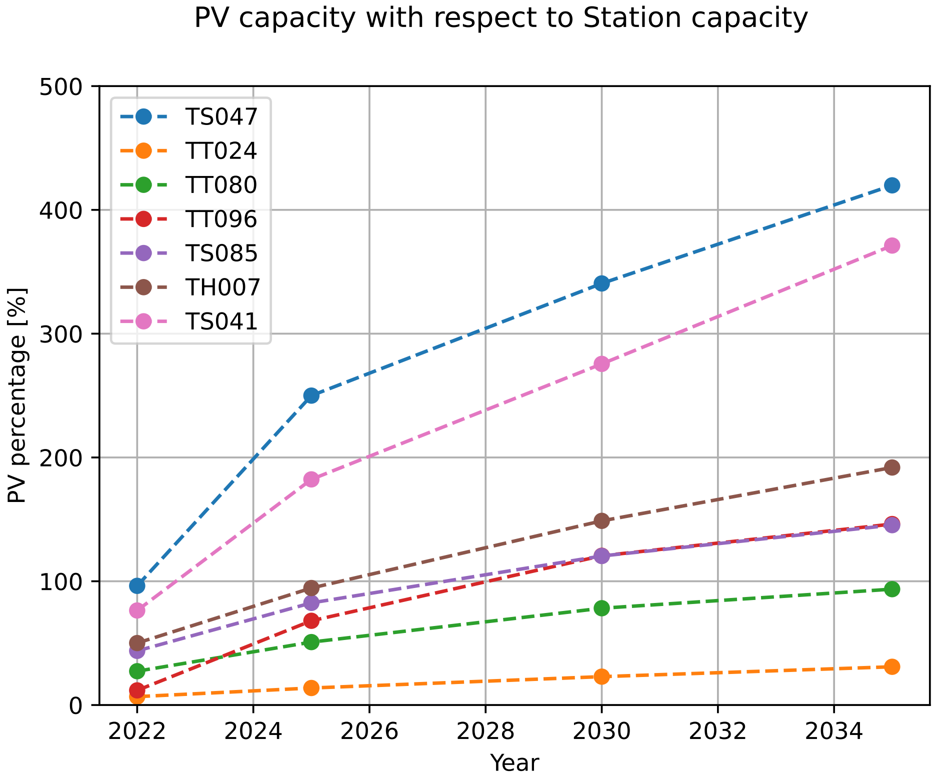

Figure C.6: Percentage station capacity utilised by PV

C.1. Visualisation methods

This appendix section explains the used figures and how to read them in a detailed way.

C.1.1. CDF's

The first visualisation method is plotting the CDF of component loading data. This gives clear insight in the amount of component hours at which overload takes place, the maximum overloading value and a general sense of the $time * severity$ factor of the overload which is present. Where to find these metrics in a CDF is shown in Figure C.7.

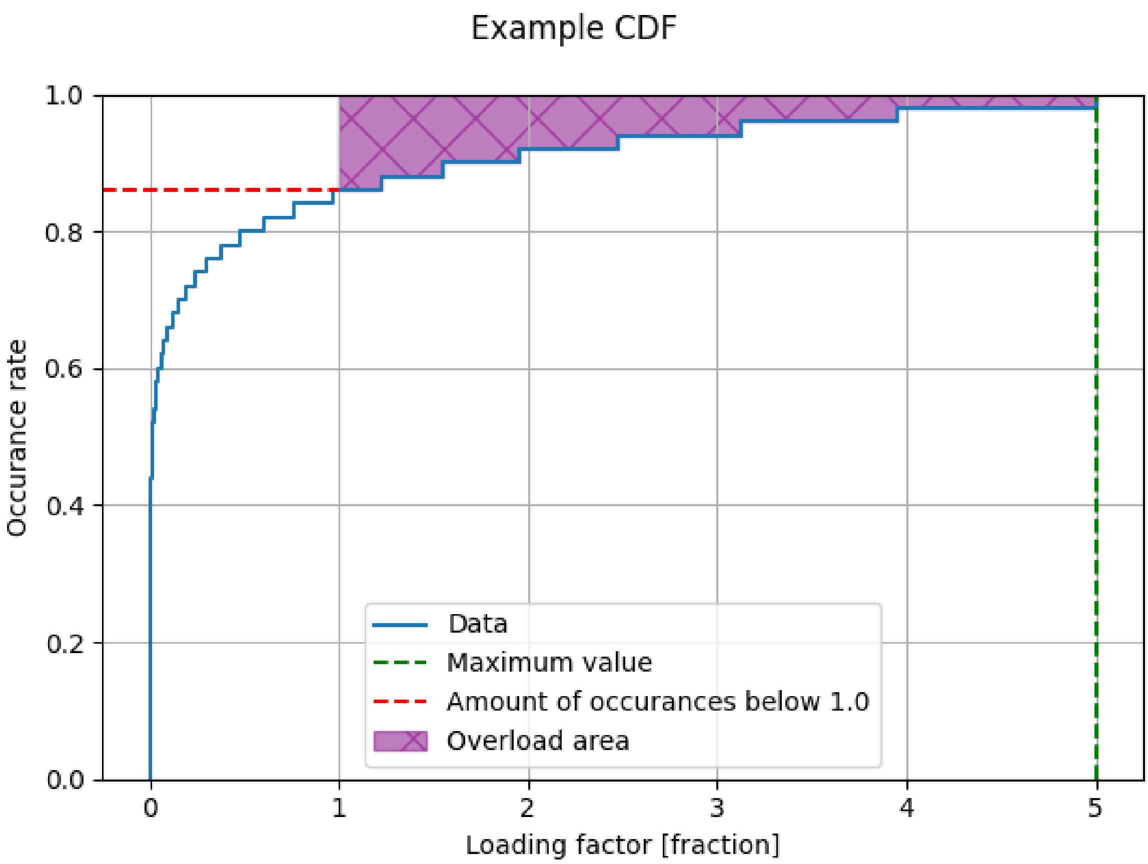

Figure C.7: An example of a CDF created by a logarithmic dataset between 0 and 5.

C.1.2. Colormesh

Another implemented visualisation method is a colormesh of the (over)loading values. Figure C.8 shows the region in which we can and want to reduce loading with PV curtailment, next to which the region is shown where curtailment has no impact as no significant PV generation is present. The downside to this visualisation method is the normalisation to the maximum (over)loading in the analysed year, thus absolute instead of relative numbers are more easily shown in a CDF plot.

Extensive colormesh figures are present in Appendix D. Some curtailment methods will be analysed by the maximum loading over multiple networks in Section 4. This is performed by taking the maximum loading of all analysed stations for that hour, year and curtailment method. By performing this operation the impact of different curtailment methods can be clearly visualised. It also provides a basis to see if overloading present in the CDF is due to generation or consumption at connections. In these colormesh figures a brighter color means a larger (over)loading value.

As well as showing a single station with a single curtailment method other options to evaluate the generalised effect of a curtailment method have been explored and implemented. An average of maximum station loading and the maximum of maximum station loading for the different hours can be shown. With effectiveness of curtailment the average of the maximum loading over multiple stations should go down, if however the maximum of the maximum loading does not go down the implementation does not have impact on all stations.

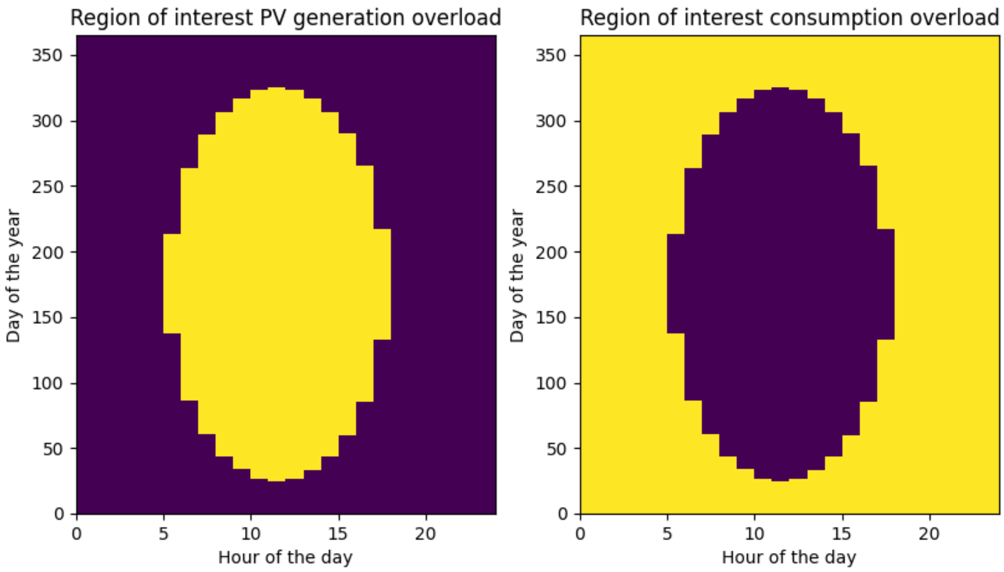

Figure C.8: The regions of interest (yellow) in the colormesh.

D

Curtailment methods appendix

In this appendix all different curtailment methods are explained. As to why these have been developed and to what extend they have been finished and used. Also presented below is a table showing earlier discussed curtailment metrics for relevant methods.

D.1. General curtailment figures and metrics

Below extended metrics and figures for analysis and comparison between curtailment methods are shown.

	Curt: 24				Curt: 25			
	2022	2025	2030	2035	2022	2025	2030	2035
TT080	0.01	0.06	0.11	0.14	0.01	0.04	0.05	0.07
TS085	0.19	0.27	0.27	0.23	0.12	0.23	0.31	0.25
TT096	0.00	0.10	0.17	0.16	0.00	0.06	0.07	0.07
TT024	0.00	0.10	0.25	0.19	-6.57	-9.76	-6.95	-7.50
TS047	0.27	0.10	0.20	0.34	0.07	0.07	0.17	0.27
TS041	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
TH007	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Avg.	0.094	0.126	0.200	0.212	-1.274	-9.360	-6.350	-6.840

Table D.1: Transformer overload energy (VAh) reduction per Wh curtailment, curtailment methods 24 and 25

	Curt: 98				Curt: 37			
	2022	2025	2030	2035	2022	2025	2030	2035
TT080	0.11	0.18	0.10	0.13	—	—	0.53	0.68
TS085	0.54	0.58	0.66	0.60	—	—	—	—
TT096	0.17	0.42	0.42	0.43	—	—	—	—
TT024	—	0.27	0.49	0.48	—	—	—	—
TS047	0.28	0.13	0.15	0.14	—	0.33	0.61	0.65
TS041	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
TH007	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Avg.	0.275	0.316	0.364	0.356	—	0.330	0.570	0.665

Table D.2: Transformer overload energy (VAh) reduction per Wh curtailment, curtailment methods 98 and 37. ”—” means no curtailment took place.

	Curt: 50			
	2022	2025	2030	2035
TT080	0.09	0.27	0.22	0.26
TS085	0.22	0.35	0.49	0.48
TT096	0.03	0.22	0.22	0.24
TT024	0.00	-0.00	0.00	-0.00
TS047	0.13	0.20	0.54	0.60
TS041	N.A.	N.A.	N.A.	N.A.
TH007	N.A.	N.A.	N.A.	N.A.
Avg.	0.094	0.208	0.294	0.316

Table D.3: Transformer overload energy (VAh) reduction per Wh curtailment, curtailment method 50

Curtailment energy summed over stations TT080, TS085, TT096, TT024 and TS047 For curtailment options 24, 25, 98, 37 and 50 throughout the years 2022, 2025, 2030 and 2035 is shown in Table D.5.

	2022	2025	2030	2035
Curtailment 24	$1.4GWh$	$17.7GWh$	$77.1GWh$	$56.6GWh$
Curtailment 25	$6.0GWh$	$21.8GWh$	$85.3GWh$	$65.8GWh$
Curtailment 98	$1.4GWh$	$2.0GWh$	$99.5GWh$	$130.1GWh$
Curtailment 37	$0.0GWh$	$3.2GWh$	$21.4GWh$	$24.9GWh$
Curtailment 50	$3.0GWh$	$6.3GWh$	$24.3GWh$	$27.3GWh$

Table D.4: Curtailed energy for station TS047 with different curtailment methods through the years.

	2022	2025	2030	2035
Curtailment 24	$43.2GWh$	$81.6GWh$	$145.5GWh$	$142.8GWh$
Curtailment 25	$79.5GWh$	$112.4GWh$	$193.6GWh$	$184.3GWh$
Curtailment 98	$6.2GWh$	$21.9GWh$	$135.7GWh$	$170.6GWh$
Curtailment 37	$0.0GWh$	$3.2GWh$	$21.7GWh$	$26.4GWh$
Curtailment 50	$13.3GWh$	$32.8GWh$	$59.7GWh$	$64.0GWh$

Table D.5: Curtailed energy for stations TT080, TS085, TT096, TT024 and TS047 with different curtailment methods through the years.

The cost of curtailed energy from Table D.5 combined with the average electricity cost in 2022 is shown in Table D.6 below.

	2022	2025	2030	2035
Curtailment 24	€$19.8milion$	€$37.4milion$	€$66.7milion$	€$65.4milion$
Curtailment 25	€$36.4milion$	€$51.5milion$	€$88.7milion$	€$84.4milion$
Curtailment 98	€$2.9milion$	€$10.1milion$	€$62.1milion$	€$78.2milion$
Curtailment 37	€$0.0milion$	€$1.5milion$	€$10.0milion$	€$12.1milion$
Curtailment 50	€$6.1milion$	€$15.0milion$	€$27.3milion$	€$29.3milion$

Table D.6: Cost of curtailed energy for stations TT080, TS085, TT096, TT024 and TS047 with different curtailment methods through the years.

Relative CDF's between multiple curtailment methods are shown in Figures D.1 and 4.9. In order to show the remaining overload and provide a basis for surface comparison. The y-axis is curtailment method 24 as this is the minimal amount of overloading, resulting in no PV overloading as shown in Figure 4.10. With in Blue the base scenario which is a reference case. In between the different curtailment methods are shown, the area between the curve and y-axis is compared to the are between the curt 0 curve and y-axis. This gives a sense of effectiveness, as curtailment method 24 is 100% effective in reducing PV overload.

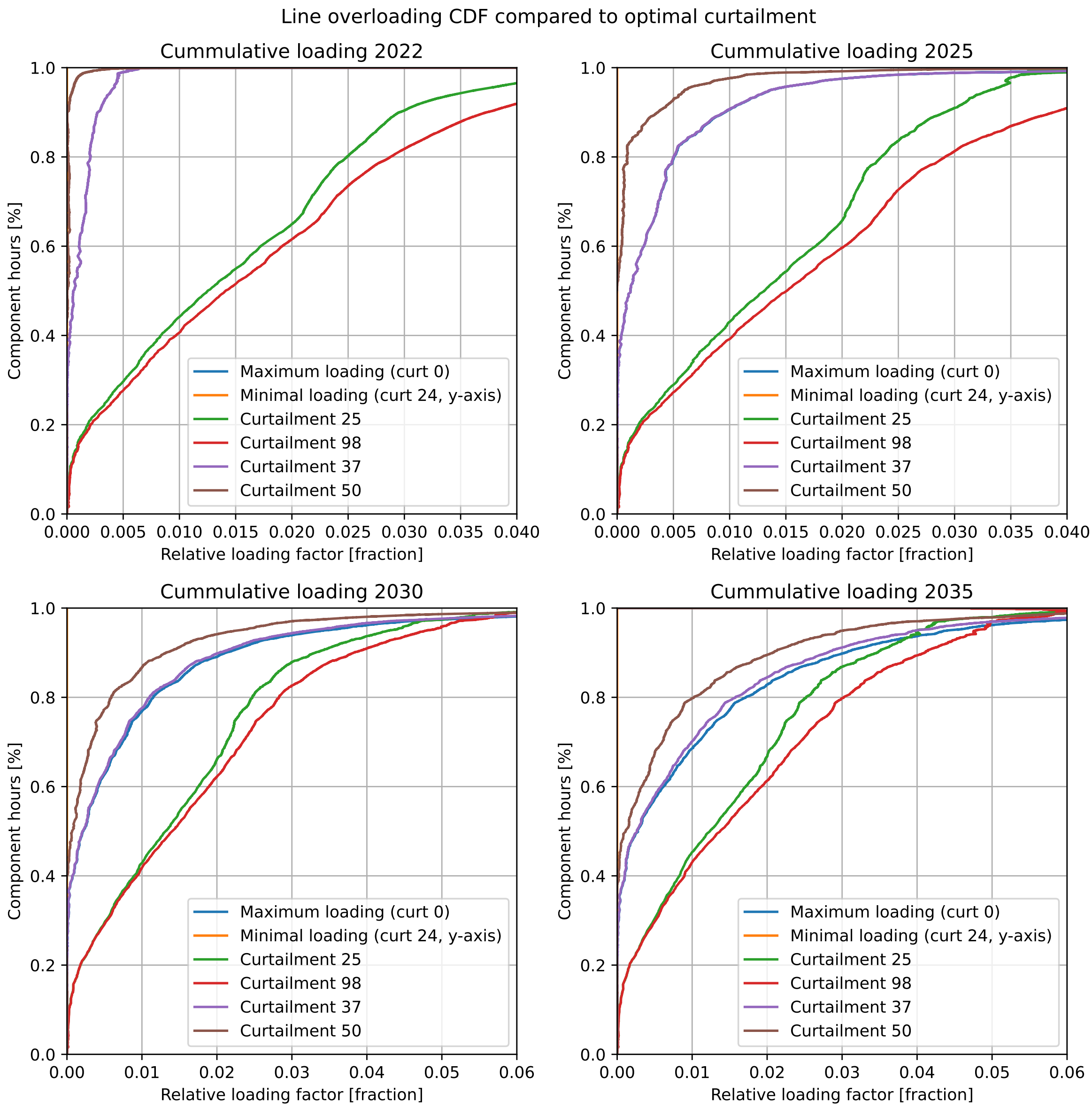

Figure D.1: Relative cable CDF's of curtailment 0, 24, 25, 98, 37 and 50 for stations TT080, TS085, TT096, TT024 and TS047 combined.

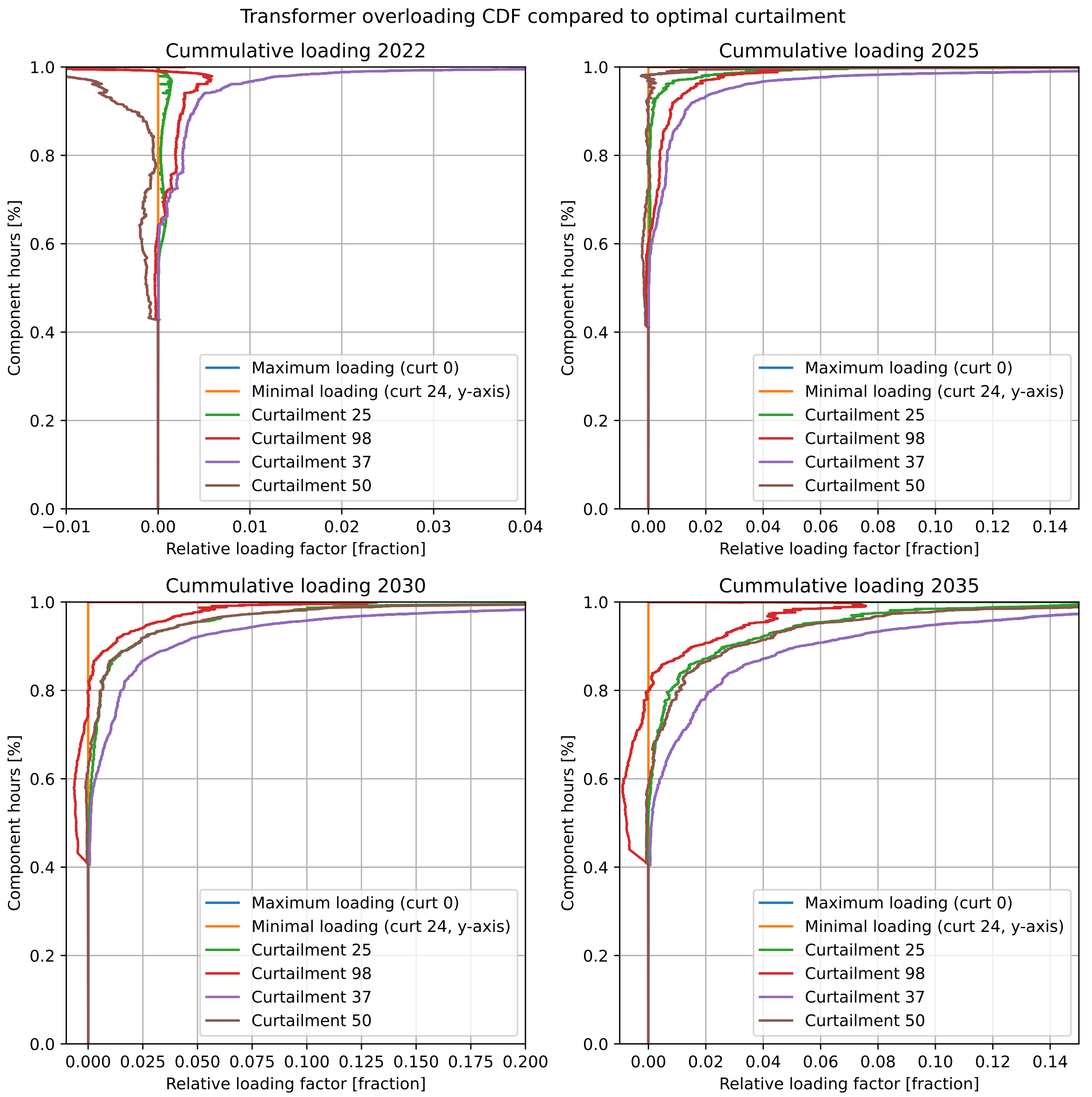

Figure D.2: Relative transformers CDF's of curtailment 0, 24, 25, 98, 37 and 50 for stations TT080, TS085, TT096, TT024 and TS047 combined.

D.2. Curtailment methods one-by-one

Below each curtailment method which was thoroughly analysed is explained. Other initially implemented methods are also shown and an explanation is provided why these methods were eventually not developed.

0: Base scenario

This scenario is self explanatory as it is used to develop the model and verify it to Stedin model data. Besides model development the results of this simulation are used as a comparison to other methods. Especially the metrics of overloading are significant. In Figure D.3 to D.16 the loading for every hour in the year is visualised, with clear high loading during the day due to sun (especially during the summer), in the evening high loading is observed as people begin cooking and charge their electric vehicles.

The figures show alternating all assets or only transport assets (excluding MV/LV transformers). The visualisation clearly shows large amounts of overload being present in most distribution networks, while only for stations TH007 (Figure D.16), TS047 (Figure D.12) and TT080 (Figure D.4) experience overloading in their transport networks due to PV. This is clear by the overload being present in the centre of the figure, which represents daytime hours during the summer.

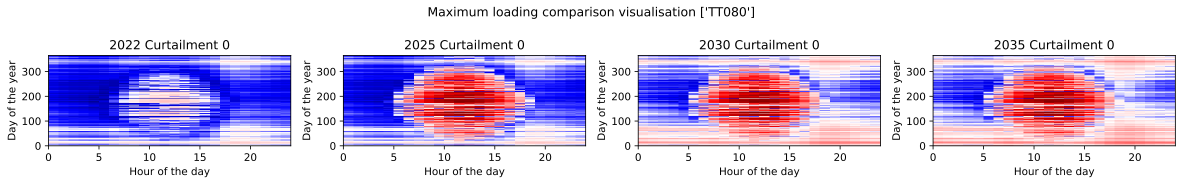

Figure D.3: Base simulation of TT080 visualised.

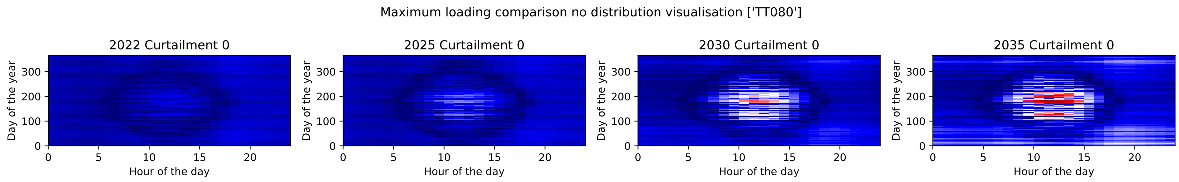

Figure D.4: Base simulation of TT080 transport assets visualised.

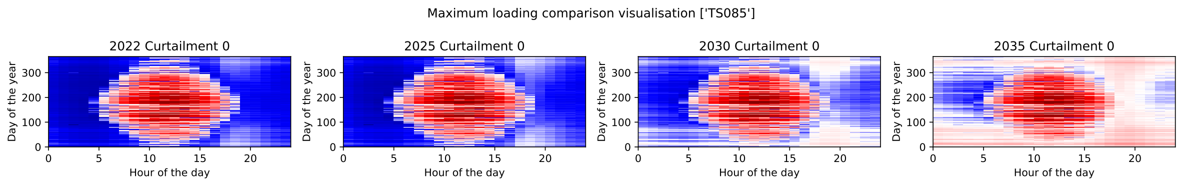

Figure D.5: Base simulation of TS085 visualised.

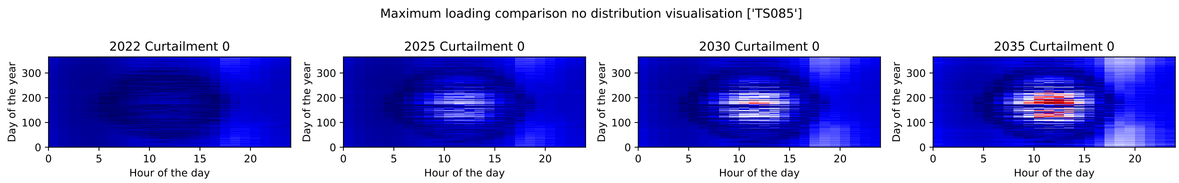

Figure D.6: Base simulation of TS085 transport assets visualised.

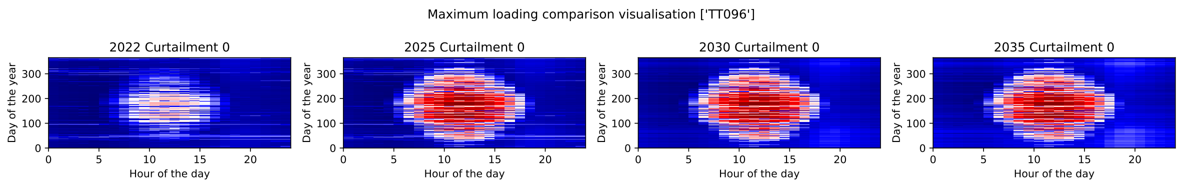

Figure D.7: Base simulation of TT096 visualised.

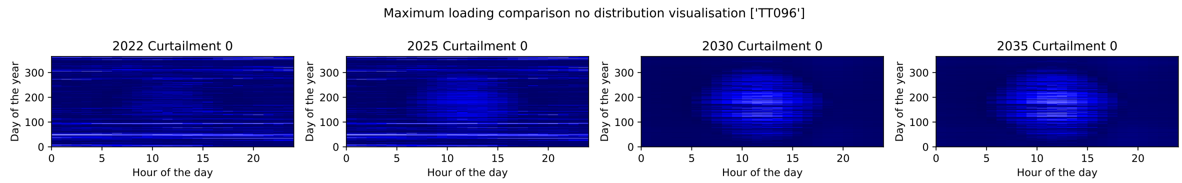

Figure D.8: Base simulation of TT096 transport assets visualised.

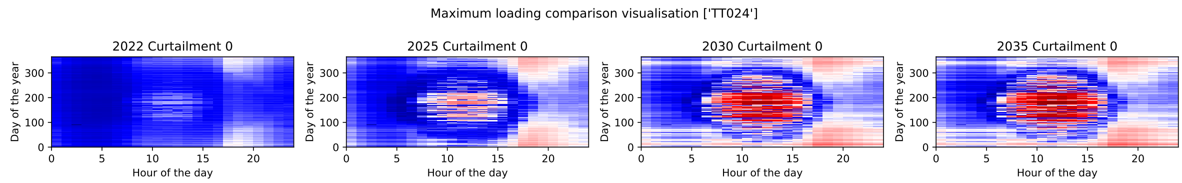

Figure D.9: Base simulation of TT024 visualised.

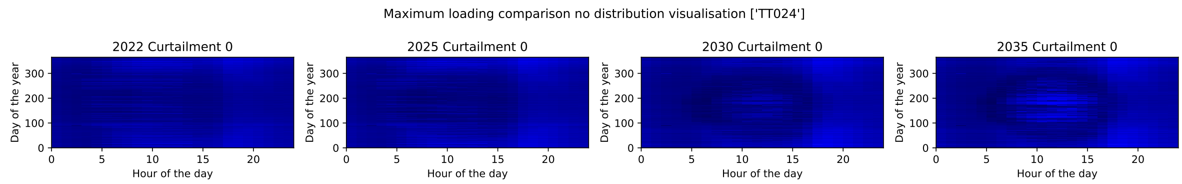

Figure D.10: Base simulation of TT024 transport assets visualised.

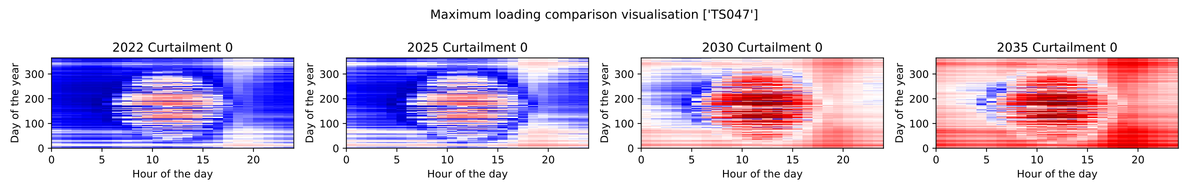

Figure D.11: Base simulation of TS047 visualised.

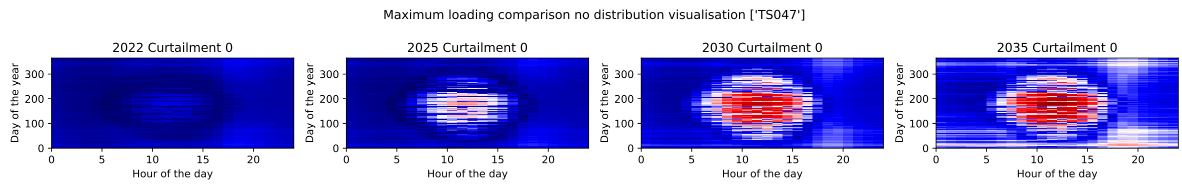

Figure D.12: Base simulation of TS047 transport assets visualised.

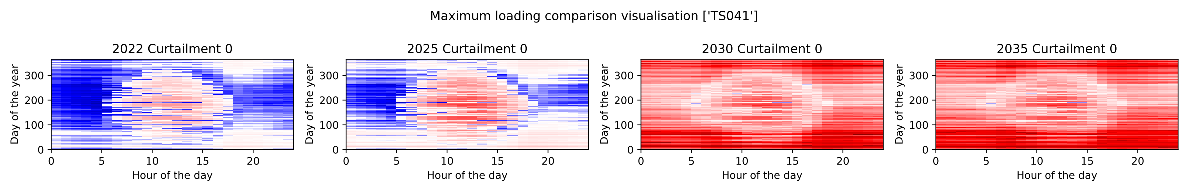

Figure D.13: Base simulation of TS041 visualised.

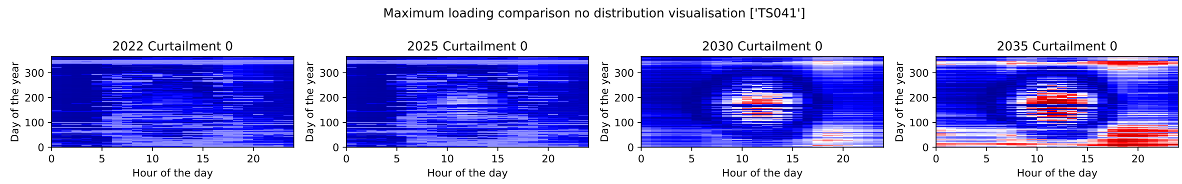

Figure D.14: Base simulation of TS041 transport assets visualised.

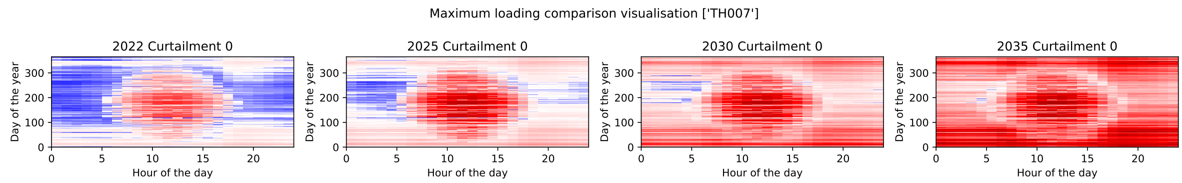

Figure D.15: Base simulation of TH007 visualised.

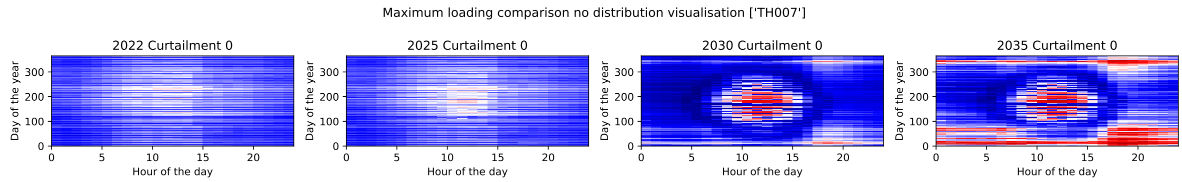

Figure D.16: Base simulation of TH007 transport assets visualised.

1-7,12: Test cases
These curtailment methods come down to 100% curtailment for different connections under different circumstances. For example when a certain level of irradiation is reached or overload is present in the system. Also different generation units were curtailed. For example all generating units over 1 MW (RfG class C [21]), all LV generation or all connected generating units.

8-10 and 13-15: Fixed back feeding limit
Multiple options with different levels of maximum back feeding have been explored. These shown to be effective to some extent, but not as efficient as a selective curtailment method explained later. Part of this code was implemented in curtailment method 50 for the LV curtailment. These options proved not as effective as other options, which are selective and are implemented in reality thus further research into those options is not beneficial.

11: Voltage based curtailment
This curtailment method is based on the node voltage level. If the voltage gets above $1.03p.u.$ the back feeding is set to 0%. However, this did not adequately reflect asset loading and in turn not significantly reducing them. Therefore simulations were not ran with this curtailment method after this revelation. Another contributing factor was the need for a specialised curve for each connected inverter [45].

16: Sensitivity analysis
A sensitivity analysis based curtailment method was also implemented in an experimental way. The sensitivity matrix was computed by setting each load to a certain value and watching asset loading change accordingly. This proved to be both computationally difficult and not very effective due to largely varying load powers in the network, due to which the linearisation was not applicable.

20-25 and 40-43: Heuristic local minimum search
A heuristic local minimal search was implemented on equal and different curtailment levels for HV, MV and LV connections. The resultant ”optimal” hourly curtailment was not significantly better than

other options, examples are shown in Figures D.17, D.18 and D.19 below. This curtailment method is effective, however it takes much more curtailment energy as shown in Table D.4.

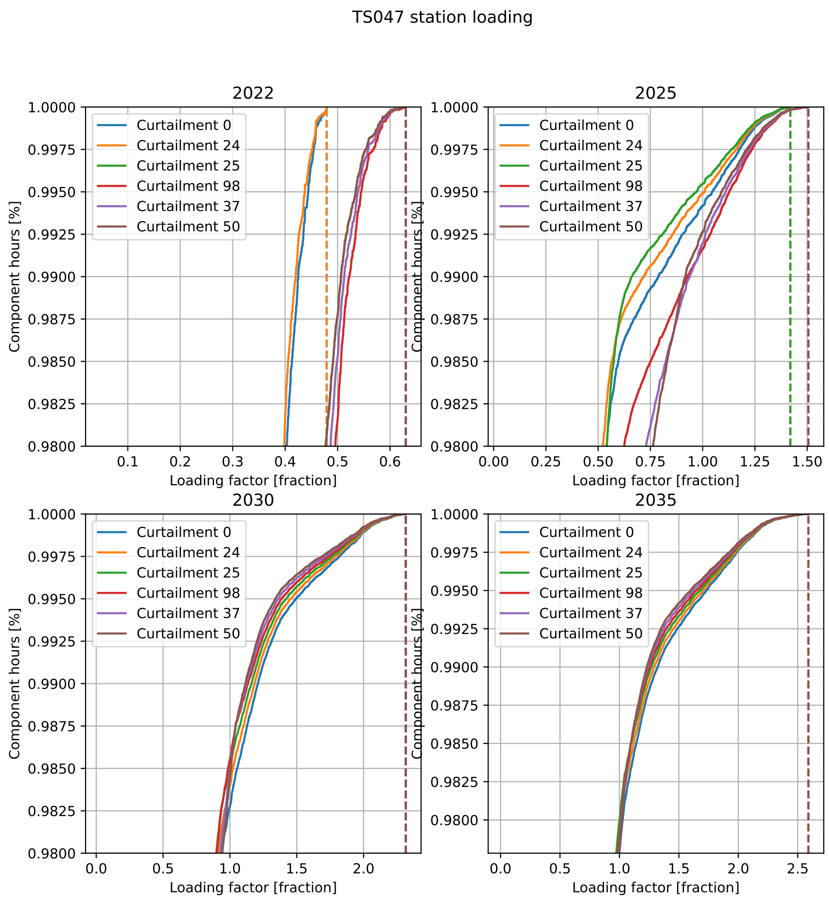

Figure D.17: TS047 connection CDF's with different curtailments.

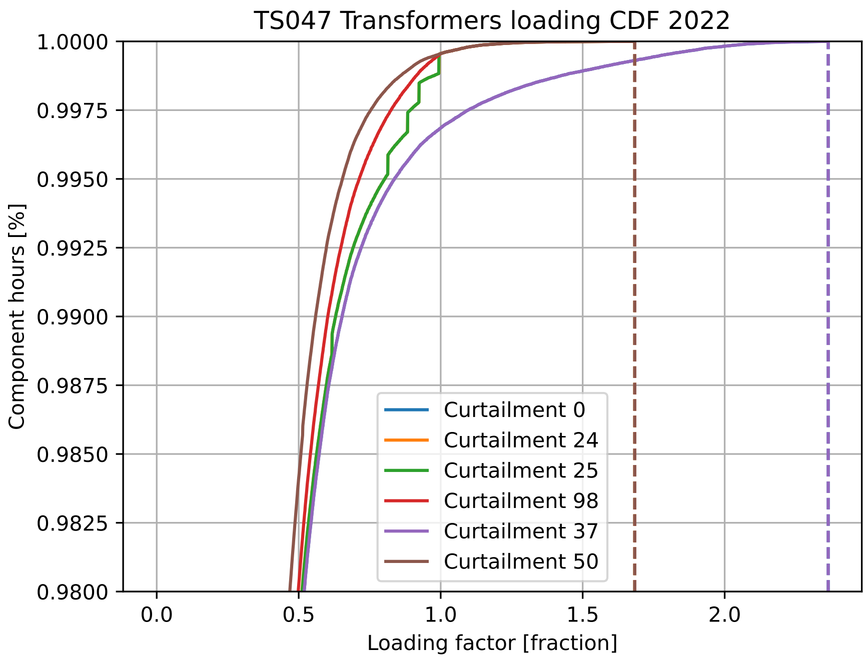

Figure D.18: TS047 transformers CDF with different curtailments from 2022.

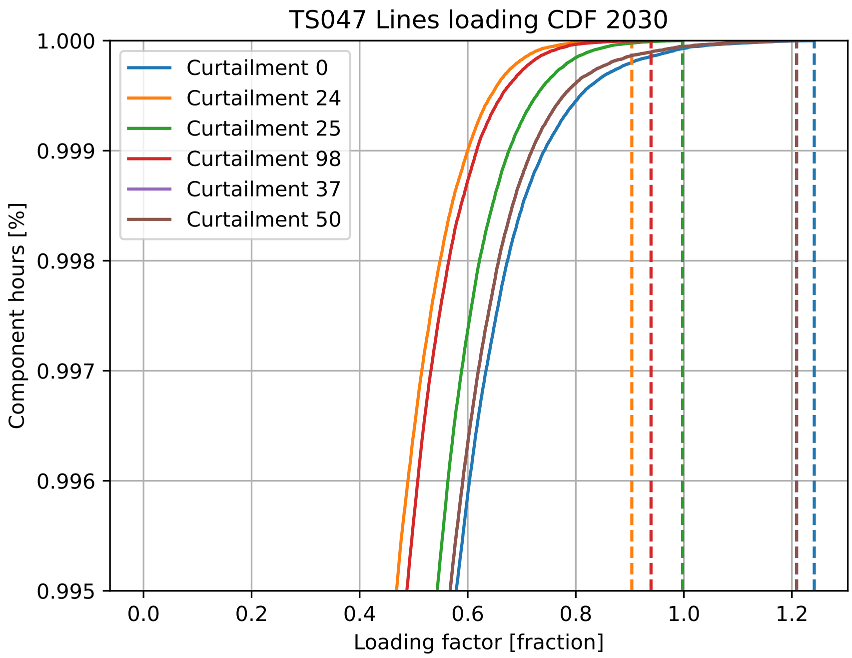

Figure D.19: TS047 cables CDF with different curtailments from 2030.

Curtailment methods 24 is similar to curtailment method 22, however this method does not aim for minimal loading but for loading close to nominal (loading of 1.0). An essential change in order to make a fair evaluation. Curtailment method 25 is the same but without impact LV PV generation.

30-38 and 98-97: Asset loading region selection

The curtailment methods explored in this part selects the maximally loaded asset. After which the power generating and power consuming side of the network are determined. Instead of applying a blanket rule with or without certain conditions, these methods of curtailment only curtail generation contributing to the overloading of a certain asset. As a result much less energy is curtailed while obtaining a similar or better reduction in asset loading.

Methods 30 has been improved upon which became method 98. This development was necessary as curtailment method 30 left more residual loading than expected. This improvement resulted in a very effective curtailment method as shown in Figures D.20 and D.21.

Option 98 was most effective and effected all connections with option 37 being the same as 98 but without taking LV connections into account. This combination was based in the analysis of LV curtailment necessity. From the figures below it is clear that as long as HV and MV assets are not overloaded curtailment method 37 does not effect system loading and generation.

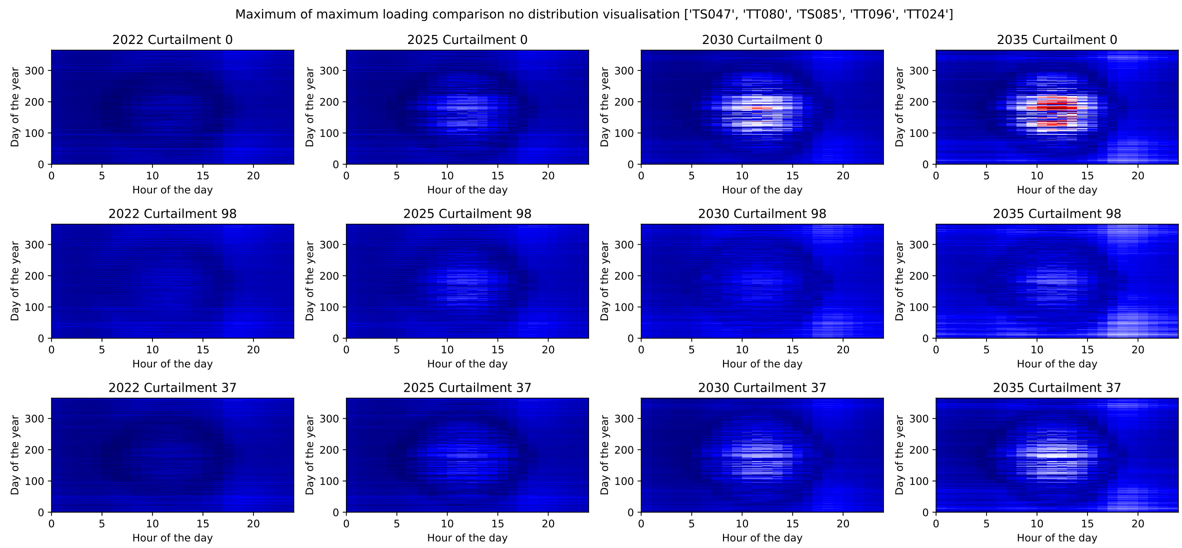

Figure D.20: Maximum loading of transport assets (MV/LV transformers excluded) over stations TT080, TS085, TT096, TT024 and TS047 for curtailment options 0, 98 and 37.

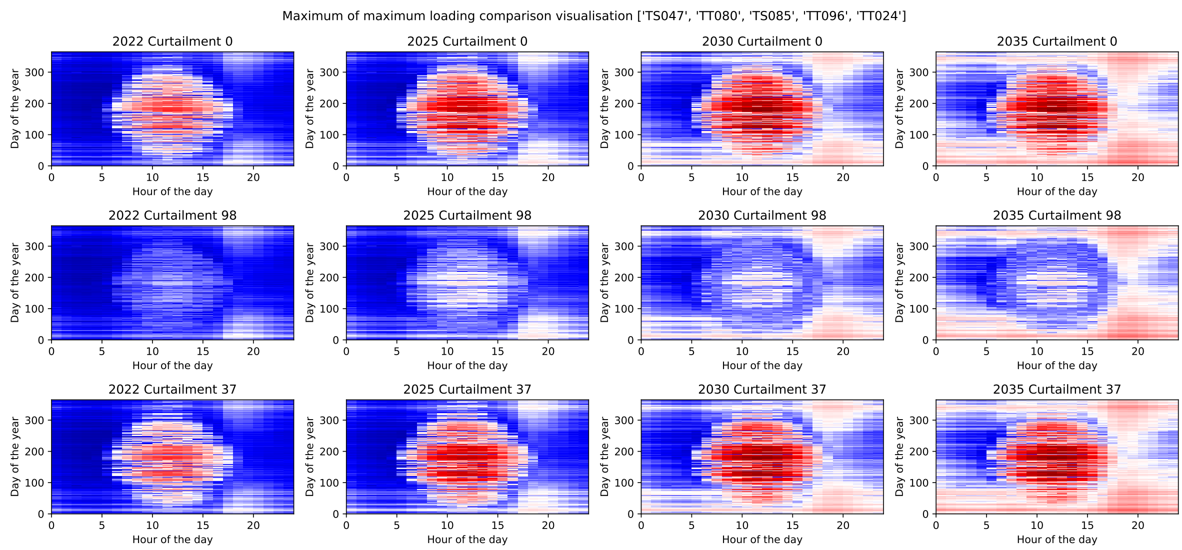

Figure D.21: Maximum loading over stations TT080, TS085, TT096, TT024 and TS047 for curtailment options 0, 98 and 37.

HV, MV and LV division In the curtailment options 30, 33 and 36 all loads were curtailed, options 31, 34 and 37 curtailed only the HV and MV connections. To determine LV impact 32, 35 and 38 were options with only LV curtailment. All these options were important for different assets to be analysed, which will be explained below.

Asset inclusion Different assets in the network were included or excluded in the curtailment calculation. In options 30-32 all assets were taken into account, while 33-35 only looked at cables and 36-38 excluded MV/LV distribution transformers. The options which only take cables into account has not been used as it does not significantly reduces loading in the network and as explained in Section 4.1.1 cable loading is not as significant with respect to congestion as transformer loading.

50: 70% LV limit, HV & MV asset loading based
The network requirements in Germany are reflected in this curtailment method. These prove to be even more effective than only looking at asset loading, which indicates that a fixed back feeding limit for LV connected systems may be a better option than a variable curtailment. For the HV and MV generation the same curtailment method is used as explained above in method 30 and 37.

99: Debug
This option was used in order to debug different options with print statements and other computation or output methods.