Mitigating high PV penetration-induced low-voltage grid overvoltage while stimulating the energy transition through a generalised approach

Master Thesis

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Abstract

This research describes a generic step-by-step approach that can be used to depict energy transition-enhancing overvoltage mitigation strategies that fit the local context of a neighbourhood. Although high PV induced low-voltage grid overvoltage mitigation has been studied extensively, this research adds onto existing literature in three ways. It is the first generic approach to develop neighbourhood overvoltage mitigation strategies. Moreover, it considers spatial and socio-economic aspects. Lastly, it regards system integration and wider energy transition ambitions.

The 6 steps of the transition-enhancing overvoltage mitigation framework (TENOMF) are described. Subsequently, the TENOMF is demonstrated on a case study in the Diamantbuurt in Amsterdam.

The results of the case study show that conventional mitigation strategies are very effective in overvoltage mitigation, however, they lack in wider energy transition ambitions. In consideration of local energy transition plans, hydrogen conversion shows to be very effective financially and energetically. In combination with high electrification, home batteries prove to be effective in system integration. The final decision-making should be done with the involvement of local stakeholders. For the social acceptance of a strategy, co-ownership, local benefits and involvement in the planning process are of great importance.

With the TENOMF, strategies mitigating PV induced overvoltage in the LV grid can be chosen that fit the local context of a neighbourhood. By using system integration, the TENOMF matches overvoltage mitigation strategies with energy transition ambitions. Therefore, using the TENOMF, overvoltage mitigation can be seen as an opportunity as it helps catalysing the energy transition as a whole.

Largest limitations were caused by the used PtX model for the energetic assessment. It is recommended to improve PtX's overvoltage modelling by using a higher time-granularity and by considering fundamental electrotechnical principles.

List of abbreviations

ATES – aquifer thermal energy storage

BF – benefit from postponing reinforcement by curtailing

Bh – overvoltage mitigation strategy of home batteries

CAPEX – capital expenditures

COP – coefficient of performance

DER – distributed energy resources

DSO – distribution system operators

ec – energy configurations

es – electrification scenario

EV – Electrical vehicle

EVmax – electrification scenario of all vehicles to be electric vehicles

GR – grid reinforcement

HEMS – home energy management systems

Hh – household

Hy – overvoltage mitigation strategy of hydrogen conversion

HyBh – overvoltage mitigation strategy of the combination of hydrogen conversion and home batteries

LV – low-voltage

KPI – key performance indicator

kW – kilowatt

kWh – kilowatt hour

MVS – mid-voltage substation

MVC – minimum value of conventional overvoltage mitigation strategies

MV – mid-voltage

MWh – megawatt hour

MJ – mega joule

TENOMF – transition-enhancing neighbourhood overvoltage mitigation framework

oms – overvoltage mitigation strategy

OPEX – operational expenditures

PV – photovoltaic

PtX – power-to-X

SUI – smart urban Isle

Inhoud

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1. Introduction

In the battle against climate change, the implementation of renewable energy production systems is growing rapidly. New decentralised photovoltaic (PV) systems are being installed at the fastest pace. Many of these PV systems are placed on rooftops within low voltage (LV) distribution networks. This is beneficial since it limits losses due to transmission and distribution. Moreover, low PV penetration provides ancillary services of improving grid voltage quality and decreasing power loss (Hashemi Toghroljerdi & Østergaard, 2016; Safayet, Fajri & Husain, 2017).

On the other hand, high PV penetration poses new challenges. Of these, overvoltage is one of the most challenging problems (Alqahtani, Ganesan, Zohdy, & Olawoyin, 2020; Hashemi Toghroljerdi & Østergaard, 2016). Most of the present electricity grids were implemented decades ago. They were not designed to handle the high amounts of electricity that the newly installed or planned distributed renewable energy systems are aiming to produce (Chaudhary & Rizwan, 2018). Moreover, the electricity grids were designed to have the electricity being supplied in one direction, in a unidirectional power flow. The implementation of distributed energy resources (DER) such as PV enhance a bidirectional power flow (Alqathani et al., 2020; Hao, Achanta, Rowland & Kivi, 2016). Since high PV penetration is stochastic and often not in pair with the local residential demand, reverse power flow and unacceptable voltage rise can occur. This causes overvoltage: the grid is overloaded (Hashemi Toghroljerdi & Østergaard, 2016). As a consequence of this overvoltage, excessive load, electrical equipment damages and power outages may happen (Hao et al., 2016).

The electricity grid of the Netherlands is divided into the high (>= 50kV), medium (>=400V, <50kV) and low voltage (<400V) network. These voltage networks are connected through transformer stations, which de- and increase the voltage level. Houses are connected to the low-voltage network with a small-usage electricity connection (Liander, 2021). The grid congestion due to PV induced overvoltage in the LV grid will happen at the distribution feeders connected to the low-to-medium transformer stations (Hao et al., 2016).

To prevent overvoltage from happening, overvoltage mitigation strategies are needed. Extensive research on overvoltage mitigation for low-voltage distribution systems with high PV production has been done. A wide range of overvoltage mitigation strategies is described. Some papers present multiple solutions, like Hashemi Toghroljerdi & Østergaard (2016), where strategies of grid reinforcement, active transformers, active power curtailment, demand response, reactive power absorption and electrical energy storage are considered. Others merely focus on one or a few mitigation strategies. For instance, Hao, Achanta, Rowland & Kivi (2016) and Supponen, Repo & Kulmala (2017) give overvoltage mitigation propositions with the focus on curtailment. Alqahtani, Ganesan, Zohdy & Olawoyin (2020) suggest reactive power absorption with the use of advanced, smart inverters. Such smart inverters use rapid response to measure the feeders' voltage profile to see if PV import into the grid is possible. In addition, energy storage systems are proposed for moments when no grid capacity is available (Alqahtani, Ganesan, Zohdy & Olawoyin, 2020). Energy can be stored using electrical energy storage systems (e.g. batteries) or by converting electricity into hydrogen or heat (Chaudhary & Rizwan, 2018; IRENA, 2019a).

A gap in scientific literature on overvoltage mitigation is the fact that financial, spatial and social implications of mitigation strategies on a local context are not considered. The strategies are assessed on their technical performance: they should be energetically optimal. Opposed to spatial and social implications, costs are often considered as an important factor to take into account for overvoltage mitigation. However, in overvoltage mitigation studies often no specifications of costs are given. For instance, Hashemi Toghroljerdi & Østergaard (2016) mention that costs highly depend on the local grid infrastructure and an area’s development plans. Such local specificities are not taken into account in literature on overvoltage mitigation. This research addresses the fact that other than energetical implications, also financial, spatial and social implications should be considered for overvoltage mitigation. An overvoltage mitigation strategy can be technically ideal, however, in the local context of a neighbourhood it can pose various spatial, financial and social implications. Therefore, it could impose resistance from residents. For this reason, it is needed to consider the local context of a neighbourhood. Within this local context, energetic, spatial, financial and social implications should be regarded. In that way, it is possible to transform a conceptually (and technically) ideal overvoltage mitigation strategy, to a successful strategy in reality: such that it can be implemented with the consent of local stakeholders.

Another gap in existing literature on overvoltage mitigation is that no discussion is being raised on the potential of system integration. System integration entails the coupling of energy demanding and generating sectors, such as the built environment and renewable energy sectors. By coupling them, more locally generated energy can be used for local demands. This can be done by directly using PV generated energy. However, often moments of demands and generations do not coincide. For system integration storage systems are thus needed. Overvoltage mitigation strategies that can enhance system integration are energy conversion and storage systems, and demand response. The study by Velik (2013) hint at system integration. Velik did a study on the integration of local PV production into a neighbourhoods energy system, by considering individual household energy storage systems. However, no comparison with other mitigation strategies is made and no evaluation of existing energetic potentials is done: wider system integration is not considered. Strategies using system integration pose opportunities to reduce a neighbourhood’s energy import and export demand. In that case, not only do these strategies mitigate overvoltage, they also reduce the neighbourhoods grid-dependency. Moreover, they can contribute to wider energy transitional ambitions. This is done by enlarging the share of renewable produced energy to be used locally, by reducing import demands and by increasing the capacity for PV generation. Thus, by using system integration, overvoltage mitigation is an opportunity to foster the energy transition.

A third identified gap in existing literature on overvoltage mitigation is identified: no generic approach to depict overvoltage mitigation strategies for a local context exists. In Hashemi Toghroljerdi & Ostergaard (2016), the potential as well as the need for combinations of overvoltage mitigation strategies is mentioned. Yet, they state that each grid requires a unique decision-making procedure as otherwise techno-economic solutions cannot be fitted for the local context. Furthermore, according to Hashemi Toghroljerdi & Ostergaard (2016) the result of mitigation strategies tailored for an individual LV grid cannot be generalized and implemented to other LV grids. This argues for the need of a generic approach. All overvoltage mitigation strategies have different benefits and disadvantages and their implications might change depending on the local area: each neighbourhood has specific potentials. A generic approach can provide the user with a guidelines that lead the user through the analysis and planning process. In that way, all relevant factors can be considered for the creation of a local fitting energy system that mitigates overvoltage. Such a framework can be used for each neighbourhood that faces overvoltage problems due to high PV penetration. Then, for each case study, local environments and energy system integration opportunities can be considered such that area-fitting solutions come forward. These will be based on energetic, spatial, financial and social implications.

To conclude, three gaps in literature have been identified:

1. Next to technical (energetical) implications, also financial, spatial and social implications of overvoltage mitigation strategies should be considered.

2. System integration, to foster the energy transition, should be considered for the development of overvoltage mitigation strategies.
3. There is a need for a generic approach to depict overvoltage mitigation strategies for the local context of a neighbourhood.

Based on these three gaps, this master thesis aims to develop a generic approach that can be used to depict overvoltage mitigation strategies that fit the local context of a neighbourhood and stimulate the local energy transition. This is done by creating a framework stating step-by-step guidelines. When assessing various potential overvoltage mitigation strategies, the generic framework should:

1. Consider local system integration opportunities: matching overvoltage mitigation strategies to the neighbourhood's existing energy supplies and demands.
2. Assess the potential overvoltage mitigation strategies based on their energetic, financial, spatial and social implications.

Accordingly, this study aims to answer the following research question:

How can a generic framework be developed to depict energy transition-enhancing overvoltage mitigation strategies, against PV-induced overvoltage in the low-voltage grid, that fit the local context of a neighbourhood?

To answer this research question, the following steps are necessary. The problems that occur in the electricity grid due to high levels of PV generation should be understood. Therefore, first an overview of the Dutch electricity is given as to have a general overview of the context in which the problems prevail. Subsequently, after zooming in onto the distribution grid, where overvoltage will occur, the problem is described in detail. Once the problems in the electricity grid are clear, existing solutions should be evaluated. Accordingly, their energetic, financial, spatial and social implications should be understood. Now that the problems are defined and bounded, and possible solutions and their implications are defined, a generic framework needs to be developed. In order to do this, state-of-the-art energy system design literature is evaluated. Using this, a generic framework – the TENOMF (transition-enhancing neighbourhood overvoltage mitigation framework) – can be created. This framework can be used to mitigate overvoltage in a neighbourhood energy system while enhancing wider energy transition ambitions. Subsequently, the developed framework is demonstrated on a case study. Here, the TENOMF will be applied to a neighbourhood in Amsterdam where grid congestion is expected to occur. Local governments, policy makers, DSO's and planners should be able to use the proposed framework as to plan for overvoltage mitigation and the realisation of the (local) energy transition.

The structure of this study is as follows. In the chapter 2, the Dutch electricity grid is elaborated and the problem of grid-overvoltage in the electricity grid is explained. Next, in chapter 3, existing overvoltage mitigation potentials are named and clarified by a literature review. Furthermore, all their energetic, financial, spatial and social implications are discussed. Chapter 4 states the literature review on energy system design. Subsequently, the TENOMF, a new framework for the development of local fitting overvoltage mitigation strategies, is proposed and described. In chapter 5 the TENOMF is tested on a case-study area in the Diamantbuurt in Amsterdam. Next, in chapter 6, limitations and recommendations of the study are discussed. Lastly, in chapter 7, conclusions are drawn.

2. Grid-overvoltage from high PV penetration

In this chapter, the consequences of implementing PV generation systems into the low voltage grid are explained. However, as to understand the wider context in which the problem of PV-induced overvoltage in the LV grid occurs, first a general overview of the Dutch electricity grid is given. Its lay-out, characteristics and components are described, with an emphasis on the lower voltage (distribution) grid. Subsequently, the changes to the power system due to decentralised energy generation, with the focus on PV, are described. Characteristics of PV generation that impact the power system are highlighted. Lastly, the various impacts that PV generation can cause to the low voltage grid are indicated.

2.1 Dutch electricity grid

The electricity grid transports electrical power from the location of generation to the location of consumption. Its three main requirements are (Kundur, 1994):

- The system has to be able to deal with the constantly changing loads put into the grid without overloading,
- The system should deliver power at costs as low as possible and minimal environmental impact,
- The quality of the deliverable has to meet the minimal system requirements of frequency, voltage and reliability.

Primary components of the grid last 20 to 40 years or longer. New grids are implemented with a long term vision. Investments are high, thus intermediary replacements are expensive and do not occur often.

The grid is divided in the transmission grid, transport grid and distribution grid. The transmission grid is the main transportation network, transporting electricity produced by large power plants (>500 MW). It is also connected internationally. Together with the transport grid, they make for the high voltage grid. The transport grid connects the transmission grid and distribution grid on the province level and connects power plants (10 – 500 MW), wind parks and large industrial customers (>10 MW). Regional and local distribution grids further transports electricity to customers. The regional distribution grid connects large decentral renewable energy production and medium-sized industrial customers (0.3 – 10 MW) with a capacity of 100 MVA. The local distribution grid has a capacity smaller than 1 MVA and connects smaller customers like households and small decentral energy production. In figure 1, an overview of the electricity grid, divided over its different parts and functions, can be seen. In the Netherlands, the transmission grid and transport grid are primarily situated above ground, while the distribution grid is almost completely implemented underground (van Oirsouw, & Cobben, 2011).

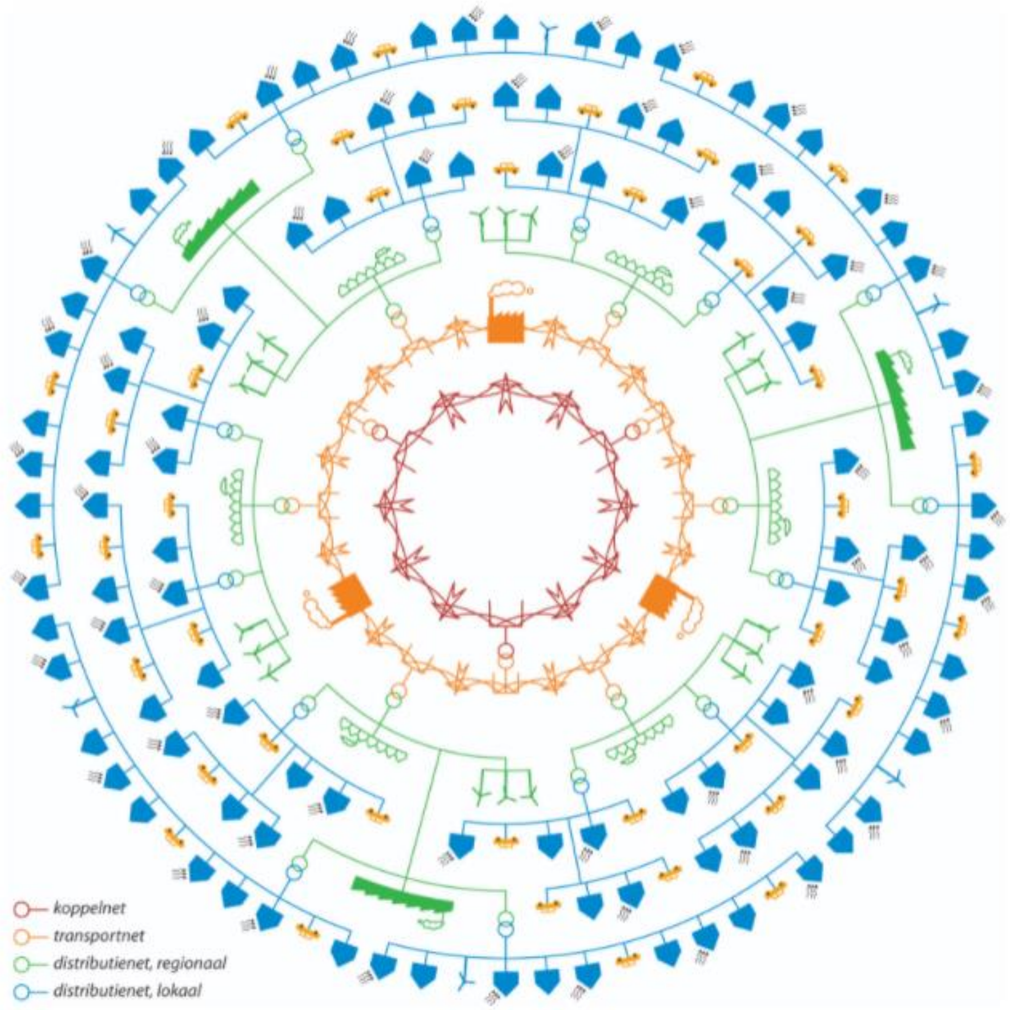


Figure 1: The electricity grid with its different functionalities, components and connections (van Oirsouw, & Cobben, 2011).

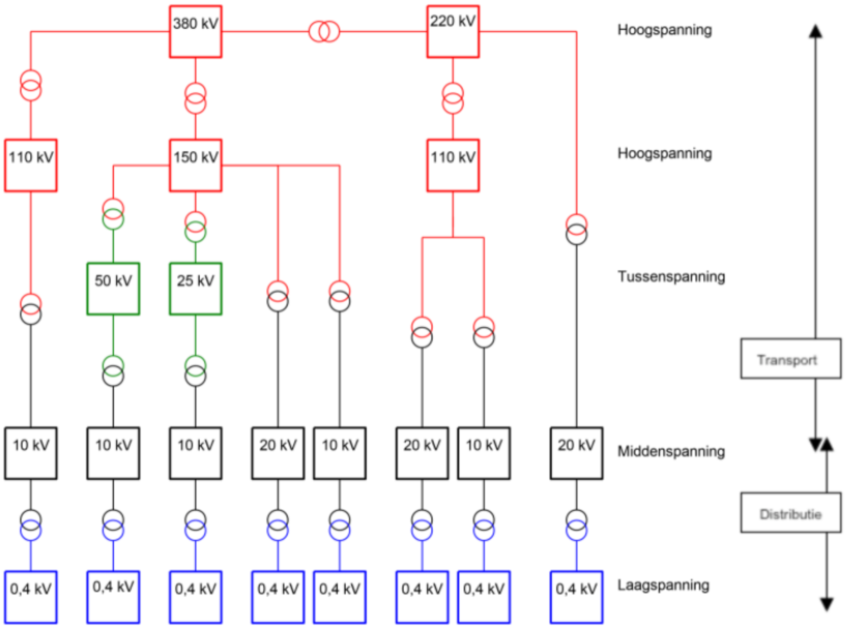


Figure 2: Voltage levels in the grid (van Oirsouw, & Cobben, 2011).

There are different voltage levels within the electricity grid. The voltage levels are divided as follows (also see figure 2) (van Oirsouw, & Cobben, 2011):

High voltage grid: 110 – 380 kV

Transmission grid: 220 – 380 kV

Transport grid: 110 – 150 kV

Intermediate voltage grid: 25 – 50 kV

Mid-voltage grid: 10 – 20 kV

Low-voltage grid: 400 V (230 phase-voltage)

At the connection points of two voltage levels, transformer stations are situated. The problem of PV-induced overvoltage occurs in the LV grid. Therefore, this study will focus on the LV grid.

Grid structures

Grids can be designed in different types of structures. Radial, ring and meshed are the most common forms (van Oirsouw, & Cobben, 2011).

Radial grid: there is a single connection between the point of consumption and transformer. In case of a defect, there will be a power outage as there is no alternative way of grid connection.

Ring grid: there are two ways of connection between the transformer and consumer. The ring is opened through a mains-disconnector, close to one of the further points of consumption. In case of a defect, the mains-disconnector is closed so that the connection can be restored through the alternative pathway. This can only be done under the condition that the capacity of the alternative grid string is large enough. Often there is also a connection to other service areas possible by closing a mains-disconnector.

Meshed grid: more than two connections from consumer to transformer are possible. Mains-disconnectors are present between the different connection paths. The advantage of a meshed structure is that the load of a heavily loaded part of the grid can be distributed over other parts of the grid.

Within the structures of ring and meshed grids, radial branches can be present (van Oirsouw, & Cobben, 2011).

Distribution grid

The distribution grid distributes power coming from the transmission and transport grids to the consumers. The voltage level has been scaled down step-wise through transformer substations. The last step, scaling down from mid-voltage to low-voltage level, is done through the mid-voltage substation (MVS). Originally, the grid was designed to have one power flow direction (unidirectional power flow) (Alqahtani, Ganesan, Zohdy & Olawoyin 2020; Stewart, Macpherson & Vasilic, 2013). However, due to decentral energy production, electricity is inserted into the distribution grid as well, creating a two-way flow direction (bidirectional power flow) (van Oirsouw, & Cobben, 2011).

The distribution grid is divided into two voltage levels: mid-voltage (10-20kV) and low-voltage (400V). The mid-voltage grid is out of scope for this study and therefore disregarded.

Low-voltage distribution grid

Low-voltage distribution grids, connecting customers with capacities up to 300 kVA to the grid, can have different structures depending on the local situation. The grid has 3 phases, 400 V (230 phase-voltage) and 435 A. Newly implemented low-voltage distribution grids are radially structured, while older ones can also be ring-structured or meshed. In older urban areas also meshed LV distribution grids without mains-disconnectors exist. This entails that no alternative reserve for defects is installed. An example of such a grid structure can be found in Amsterdam (M. Verkou, personal communication, March 25, 2021). A benefit of meshed grids is that the voltage distribution is more evenly spread and less losses occur. However, a defect will lead to larger short circuits and safeguarding the grid is complex. For that reason new LV distribution grids are implemented radially or with mains-disconnectors (van Oirsouw, & Cobben, 2011).

Mid-voltage substation (MVS)

As stated before, transformer stations are situated between the grids with different voltage levels. MVS's connect mid and low voltage grids. The stations do not have reserve components, or redundancy (a back-up connection), thus overvoltage in the MVS entails a power outage. In figure 3 a schematic representation of a mid-voltage substation is shown (van Oirsouw, & Cobben, 2011). In the Netherlands, currently 84009 MVS's are present (Netbeheer Nederland, 2021).

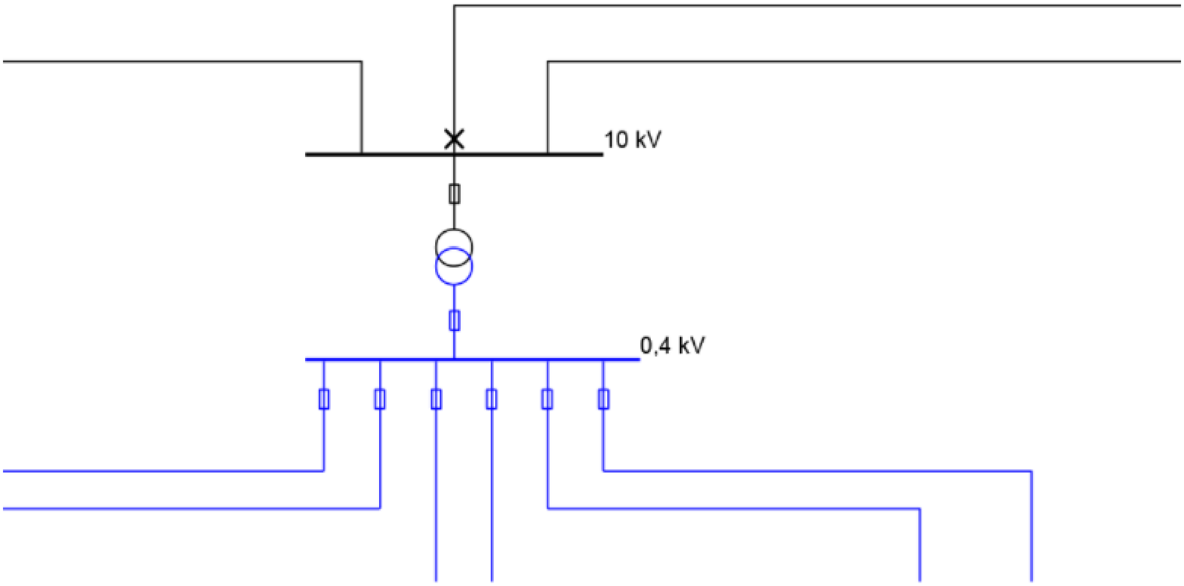


Figure 3: Schematic view of the mid-voltage substation connecting the mid-voltage grid and the low-voltage grid (van Oirsouw, & Cobben, 2011).

2.2 Decentral energy generation in the distribution the grid

Traditionally, the electricity grid was designed based on three stages: electricity is produced in large centralised power plants. From there, the electricity is transported over the transmission and transport grids. Lastly, the electricity is distributed over the distribution grid and delivered to the consumer (Alqahtani, Ganesan, Zohdy & Olawoyin, 2020). The grid was designed for unidirectional power flow (Alqahtani et al., 2020; Stewart, Macpherson & Vasilic, 2013).

Nowadays, due to the energy transition, this has changed. More and more decentralised energy generation systems are connected to the grid. In the LV-grid photovoltaic (PV) systems as decentral power generators are becoming increasingly popular (van Oirsouw & Cobben, 2011; Aziz & Ketjoy, 2017). The focus in this research is on PV systems as decentral energy generation. The power output at the point of interconnection (POI) (see figure 5) from the PV generation plant varies highly due to the intermittency of solar radiation. Where traditional power plants have inertia due to their rotating power generators, PV generation does not (Hao et al., 2016). It is very responsive to solar radiation: power is generated immediately with incoming solar rays and at the same time as the sun disappears, due to cloud coverage for instance, power generation shuts down. As a consequence, power output can rise or drop quickly causing voltage fluctuations exceeding the grid's allowed voltage limit (Hao et al., 2016). Therefore, installing intermittent power such as PV systems to the LV-grid can have consequences for the reliability, quality and stability of the electric power system as a whole (Hao, Achanta, Rowland & Kivi, 2016).

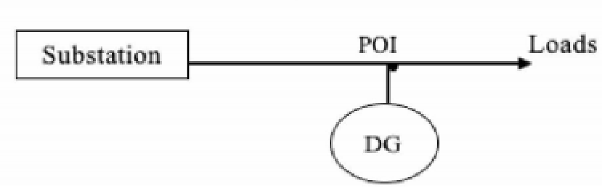


Figure 5: Schematic overview of a part of the distribution grid with PV generation (DG) and consumer loads (Alqahtani et al., 2020).

2.3 PV generation impacts on the power system

Due to the characteristics of PV systems, their integration into the LV distribution grids can have consequences for the power system. If many decentralised PV-systems are installed in a LV-grid, it can occur that on sunny days more electricity is produced than there are demands. Then, an electricity surplus is produced (van Oirsouw, & Cobben, 2011). This electricity is fed into the LV grid, causing voltage levels to rise. High PV penetration can thus threaten the system reliability, voltage stability and power quality. Power flow direction, voltage level, customers and utility protection can be impacted depending on the PV penetration (Hao et al., 2016). Five impacts due to high PV penetration into the LV distribution-grid are discussed in this section: voltage regulation, overvoltage, undervoltage, reverse power flow and islanding.

Voltage regulation in power system

Implementing PV generation into the LV-grid can affect voltage regulation in power systems. Losses in distribution lines need compensation to maintain voltage-levels along the grid. In order to do so, voltage regulators are installed onto feeders. Voltage regulation is based on the assumption that there is a unidirectional power flow. Depending on the location, the distribution system and the voltage regulation equipment, PV systems that inject power onto the LV-grid can change the voltage levels along a feeder (Hao et al., 2016). Moreover, as PV systems generate power intermittently and are out of operation at night, voltage regulation systems need to operate more frequently. This causes their lifespan to reduce (Stewart et al., 2013).

Overvoltage

High PV penetration into the LV-grid causes voltage levels to rise rapidly. Eventually this can cause overvoltage. The limit for overvoltage depends on the utilities and LV-grid, however, often 5% voltage-rise over nominal voltage levels is considered overvoltage (Stewart et al., 2013). It can also be up to 10% (Hao et al., 2016; Aziz & Ketjoy, 2017; Tan & Kirschen, 2007). This is a matter of regulatory limit. It could for instance be that 10% voltage variations would entail more PV systems to be implemented onto an LV-grid, however that local regulations limit voltage variations to 5%. In case of a limit of 10% voltage variations it is important that the PV systems are distributed properly along the feeder to ensure power quality (Aziz & Ketjoy, 2017). However, this is usually not the case (Westacott & Candelise, 2016). Overvoltage in the LV-grid causes electrical equipment damages, excessive loads and power outages (Alqahtani et al., 2020).

Undervoltage

Sudden drops in PV penetration, due to for instance cloud coverage, cause output power to decrease instantly enhancing a sudden increase in the feeders' load. This causes undervoltage (Hao et al., 2016). Reductions in PV penetration trigger the operation of under-voltage relays, causing PV inverters to trip (Tan & Kirschen, 2007). This protection, as well as the inverters ride-through capabilities prevent PV systems to operate in island mode. Inverters trip when voltage levels drop below specified limits (Hao et al., 2016).

Reverse power flow

In the case that PV production is higher than the consumption at the point of interconnection from the PV system to the feeder, the feeder will experience reverse power flow. The PV generated power exceeds the consumer demand and losses in the feeder, creating reversed flow of power to the substation. This is also known as back-feeding. Since most (tap changer) control systems in substations cannot register reversed power, they do not respond and continue to maintain the nominal voltage level. This induces overvoltage (Stewart et al., 2013; Aziz & Ketjoy, 2017). Reverse power flow thus causes power quality problems. It happens at solar irradiance peak moments, that often coincide with periods of low load in the LV-grid (Alqahtani et al., 2020). The PV generation has shifted the power system from a unidirectional to a bidirectional power flow.

Islanding

When a part of the power system, that has PV generation, is disconnected from the utility grid, islanding occurs when the PV systems keep generating and feeding power onto the separated grid. This can be dangerous for maintenance workers. Moreover, it deteriorates power quality as there is no connection to the system voltage and frequency anymore. In case of a fault in part of the grid where also PV generation is present, the mains-disconnector on the grid-side is opened, disconnecting the fault from the grid. As a consequence, voltage levels drop, and the PV inverters' ride-through mechanism is activated. Because of this, the PV system can continue feeding power to the fault for multiple cycles. Depending on the characteristics of the ride-through mechanism, this can be up to two seconds (Hao et al., 2016).

From all of the aforementioned problems coming from decentralised PV systems implemented in LV-distribution grids, overvoltage is reported most frequently (Cobben, Gaiddon, & Laukamp, 2008). Therefore, overvoltage is the most prominent challenge for implementing decentralised PV systems in

LV-distribution grids (Alqahtani et al., 2020; Aziz & Ketjoy, 2017; Hashemi Toghroljerdi & Østergaard, 2016). Bidirectional power flow also is one of the most challenging aspects (Alqahtani et al., 2020). However, the eventual consequence of bidirectional power flow is overvoltage. As overvoltage is thus the most prominent challenge, the focus in this research is on mitigating overvoltage. Therefore, overvoltage mitigation strategies are needed. As stated in the chapter 1, overvoltage mitigation strategies need to fit a local context as their accompanying implications can differ for each environment. Before regarding the local context, first the various overvoltage mitigation strategies that have been described in literature need to be considered and understood. Furthermore, their energetic, financial, spatial and social implications need to be evaluated. This is done in the following chapter, chapter 3.

3. Overvoltage mitigation strategies

In this chapter an overview of mitigation strategies against PV induced overvoltage is given. First, the conventional strategies of *grid reinforcement* (GR) and *curtailment* are discussed whereafter mitigation strategies providing flexibility services for local system integration are described. Subsequently, the implications that these mitigation strategies entail are characterised. The implications are divided into the four categories, as were previously named in chapter 1: energetic, financial, spatial and social.

3.1 Grid reinforcement

Reinforcing the grid can be done by replacing existing power lines or by implementing new, additional power lines parallel to the old ones. This decreases the resistance in the LV grid and thus mitigates voltages levels to rise in the points of intersection (between PV and LV grid) (Hashemi Toghroljerdi & Ostergaard, 2016). Because of this, grid reinforcement is one of the most effective ways to prevent overvoltage in the LV grid due to high PV generation (Pudjianto, Djapic, Aunedi, Gan, Strbac, Huang & Infield, 2013). In figure 7, the difference between a reinforced and a weak grid can be seen. The top figures show rise in power due to PV irradiance. The bottom figures show voltage levels coming forth of this power input. It is clear that the voltage levels in the weak grid rise rapidly (bottom left) as the generated power increases, until it is curtailed. Then the voltage levels can be seen to stagnate. In a reinforced grid, the voltage fluctuations are small (bottom right figure) and power does not have to be curtailed.

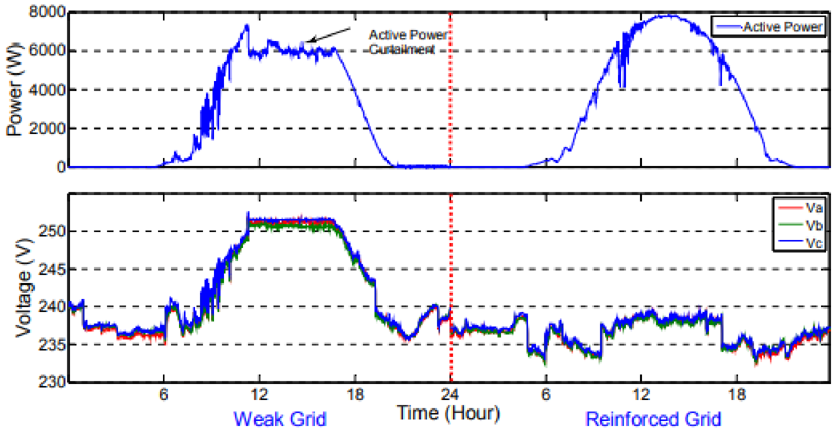


Figure 3: PV implementation into an LV grid: comparing a weak and a reinforced grid (Hashemi Toghroljerdi & Ostergaard, 2016).

In various studies, the biggest disadvantage of grid reinforcement is coined to be the high costs involved. Moreover, it is very time consuming (Hashemi Toghroljerdi & Ostergaard, 2016; Supponen, Repo, & Kulmala, 2017; Safayet, Fajri & Husain, 2017). The costs vary highly depending on the structure of the grid, the feeder length, the conductor types used in the grid and the grid's short circuit capacity. Therefore, it is difficult to make assumptions on the costs for reinforcing a specific grid as a whole (Hashemi Toghroljerdi & Ostergaard, 2016). Furthermore, solar irradiance is intermittent and highly varying throughout the year and over the day. The capacity factor of PV generation is small, in the Netherlands only 12% (Pfenninger & Staffell, 2016). Peaks of PV irradiance only occur limited times a year. Therefore, grid reinforcement is generally considered not to be a cost-efficient mitigation solution against PV overvoltage (Hashemi Toghroljerdi & Ostergaard, 2016).

Apart from reinforcing the electrical lines, changes can also be made to the grid structure or MVS (Hashemi Toghroljerdi & Ostergaard, 2016; Netbeheer Nederland, 2021). Sometimes it can be beneficial to change radial grids into ring-structured grids. This can increase the grids' capacity to host

PV generation. However, it is important to investigate the implications that this change will have on the power flow directions and protection system (Hashemi Toghroljerdi & Ostergaard, 2016).

3.2 Curtailment

Active power curtailment implies switching off the inverters of PV systems to disable them from feeding energy into the grid. This is done when an overvoltage event is bound to occur. Active power curtailment entails PV-system owners to lose revenue as they cannot make use of their solar panels at critical moments (Chaudhary & Rizwan, 2018). However, on the system as a whole it is an economically beneficial solution as it does not require substantial investments in infrastructure. Some studies state that, to a certain extent, curtailment is expected to be unavoidable as otherwise implementing a high share of PV energy generation within the energy system is economically ineffective (Hashemi Toghroljerdi & Ostergaard, 2016). By actively monitoring the output power of the inverters, they can be switched off at a specified level (Hashemi Toghroljerdi & Ostergaard, 2016). Because solar energy is strongly seasonally and hourly dependent, PV panels don't reach their nominal capacity often on a yearly basis. This can be seen in figure 8. For this reason peak PV events only cause relatively small amounts of energy to be curtailed (Wiest, Frey, Rudion, & Probst, 2016); Hashemi Toghroljerdi & Ostergaard, 2016).

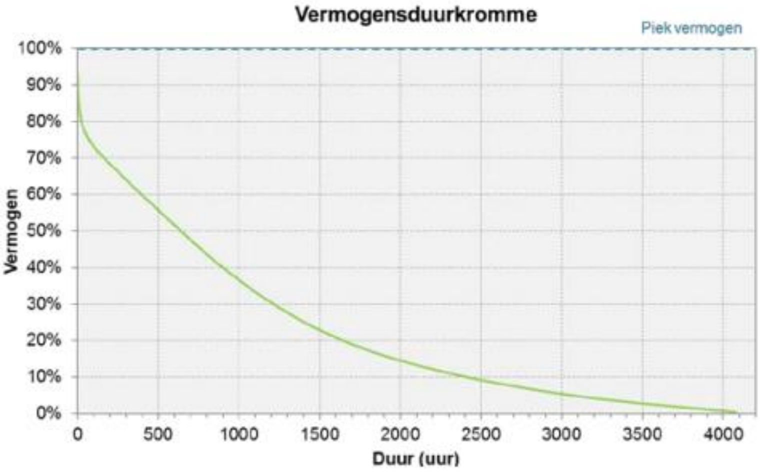


Figure 4: Percentage of nominal PV capacity used over time, as reached on a yearly basis. Moments of peak solar irradiance occur rarely. (Overlegtafel Energievoorziening, 2018).

Curtailment can be done in a static and dynamic way. Static curtailment implies curtailing the output power at a pre-set level. This strategy is for instance applied in Germany, where residential PV's are required to curtail power in case they reach 70 percent of their nominal capacity, regardless of the state of the grid at that time (Stetz, Marten, & Braun, 2012). Looking at figure 8, this would imply less than 2.5% of time annually. Dynamic curtailment limits power feed-in over a certain thermal or voltage limit (Wiest et al., 2016). It is based on a fixed or voltage dependent droop-based mechanism or by using a centralised controller. For dynamic curtailment the power flow has to be measured constantly, causing the need for extra ICT infrastructure. However, it reduces the annual amount of energy that is curtailed (Wiest et al., 2016). Curtailing in a dynamic way can increase the efficiency of a power system and entails less power loss (Hashemi Toghroljerdi & Ostergaard, 2016).

3.3 System integration overvoltage mitigation strategies

Besides the conventional mitigation strategies of grid reinforcement and power curtailment there are also mitigation strategies providing flexibility services for the energy system. Flexibility helps utilising as much renewable energy as possible by matching it to current demands or storing it for later purposes. By integrating flexibility services on a local scale in the energy system, the energy demand of a neighbourhood is optimally supplied by the renewable energy sources. In a recent report by Netbeheer NL (2021) on an integral infrastructure exploration of the Dutch energy system towards 2050, it was concluded that flexibility services can reduce bottlenecks coming forth of renewable generation load peaks enormously. Local system integration of flexibility services makes the distribution network more flexible and resilient towards highly fluctuating energy generation and uncertain demand profiles (Klyapoviskiy, 2019). As stated before in chapter 1, by regarding system integration for overvoltage mitigation strategies, not only overvoltage levels are reduced, also the wider energy transition is stimulated. Various overvoltage mitigation strategies can be used for local system integration: electrical energy storage, conversion into heat or hydrogen and demand response. These are described in the following sections.

3.3.1 Electrical energy storage

Electrical energy storage, or batteries, can be used to store part of the generated solar energy to limit power fed into the grid, preventing overvoltage. The stored energy can be used at a later moment of load consumption and/or at times when electricity prices are high (Hashemi, Yang, Østergaard, You, Cha, 2013, October). Batteries can be installed in front of the meter (FTM), for instance in case of a communal neighbourhood battery, or behind the meter (BTM). FTM batteries are implemented within the distribution grid, meaning that the renewable produced energy first has to be fed into the grid. BTM batteries are located within the internal electricity network where the PV-system is situated. This implies that the distribution grid is not loaded (IRENA, 2019b) and thus mitigates potential overvoltage even more. Although, these distances are short. Therefore, the difference between BTM and FTM can be neglected (T. Fens, personal communication, 29 July, 2021). Electrical energy systems can be controlled centralised or locally. In terms of flexibility, electrical energy storage is most suitable for short-term storage. Then they are most efficient and economically effective (IRENA, 2019a).

The large investment needed for electrical energy storage is the main obstacle for the implementation of this mitigation strategy (Hashemi Toghroljerdi & Ostergaard, 2016). When making a cost-benefit analysis other aspects should also be regarded: the space needed for storage, the energy storage lifetime for various modes of operation, the effect that storing energy in batteries has on the reduction of peak power generation costs and the potential of electrical energy storage to also mitigate undervoltage events in high load conditions (Hashemi Toghroljerdi & Ostergaard, 2016).

Electrical energy storage is an effective overvoltage mitigation strategy, however, advanced control methods are needed to control batteries in the most efficient way for overvoltage mitigation. If no advanced control methods are used, it can occur that batteries are charged up to their max capacity during moments when no overvoltage is bound to occur. Subsequently, in high PV irradiance peaks, the batteries could be full after which overvoltage will still occur. Advanced control methods can steer the moments of battery charge towards moments of high PV peaks to mitigate these effects. Just as with curtailment, this can be done statically or dynamically, where dynamical control methods (voltage-dependent dynamic charging) are the most effective (Hashemi Toghroljerdi & Ostergaard, 2016).

Electrical energy storage can also be combined well with other mitigation strategies. For instance, in combination with demand response and curtailment. This is elaborated in section 3.3.3. Such combinations increase the effectiveness of overvoltage prevention. Moreover, it reduces the need for expensive electrical energy storage systems (Hashemi Toghroljerdi & Ostergaard, 2016).

3.3.2 Conversion

Energy can also be stored using other energy carriers than electricity. As another overvoltage mitigation strategy PV generated electricity can be converted to heat or hydrogen. Subsequently, the thermal energy and hydrogen can be stored or directly used for varying use cases. Moreover, hydrogen can be converted back to electricity at a later moment. All conversion steps do imply losses due to the efficiencies of conversion devices such as electrolysers, heat pumps and fuel cells.

3.3.2.1 Heat

Excess PV generated electricity can be converted into heat using a heat pump. Heat pumps can be used to heat up buildings or to provide heat for storage, for instance in underground aquifer thermal energy storage (ATES). Heat pumps are powered by electricity. Different types of heat pumps are available, dependent on their source of heat and heated output. As input, heat pumps can use air or water. Subsequently, they can heat up air or water which is then distributed through a building. Heat pumps can thus be: air to air, air to water, water to water and soil to water. Their performance is not measured by their efficiency but by their Coefficient of Performance (COP). Heat pumps have a COP of 3 to 5, meaning that 1 kW of electricity is used to produce 3 to 5 kW of thermal energy (Accenture, Flexiblepower Alliance Network & TKI Urban Energy, 2021). The capacity of heat pumps that provide heating within a building is dependent on the level of isolation of the respective building (Overlegtafel Energievoorziening, 2018).

For ATES systems water sourced heat pumps are used. Here, two separate subsoil reservoirs are used for cold and hot water. Warm water is pumped up from the hot reservoir of the ATES by pumps within the system. Subsequently, its heat is transferred to another source of water via a heat exchanger. In most cases, heat pumps elevate the temperature of the heated water further. Then, the water is distributed within a building to provide heating. After the pumped-up water from the ATES has released its thermal energy via the heat exchanger, it is pumped into the cold storage. In summer, when cold water is needed, this process can be reversed (Accenture et al., 2021; E. van der Roest, personal communication, 19 November, 2019). ATES systems thus provide heating in winter and cooling in summer: they function as seasonal storage.

Neighbourhoods using ATES often have more heating than cooling demand (E. van der Roest, personal communication, 19 November, 2021). Therefore, in summer their heat reservoir needs to be replenished. This could be done with the help of an industrial scale heat pump. Here, overvoltage mitigation can be of aid: excess PV generated energy can be used for this purpose.

3.3.2.2 Hydrogen

To prevent overvoltage, electricity produced in peak moments of PV can also be converted into hydrogen using electrolysers. Subsequently, hydrogen can be used for different use-cases, depending on the needs of the local area. For instance, it can be used as an alternative for natural gas, thus for heating purposes. Although hydrogen is not yet used on a large scale for residential heating, pilot projects that retrofit the energy infrastructure of a neighbourhood in north-east Netherlands for hydrogen-use are about to start (Consortium Waterstofwijk Hoogeveen, 2020) Hydrogen can be used as a flexibility service for longer periods of time. It can be stored for months to bridge energetic gaps between seasons. For long-term energy storage, conversion to hydrogen is more beneficial than electrical energy storage (Eichman & Flores-Espino, 2016). It is possible to store hydrogen for months without losing much power, provided that the hydrogen is stored in a leak free system. Due to its relatively low energy/volume density, hydrogen needs to be pressurised for storage which entails energy losses. One of the options is to store hydrogen in underground salt caverns (Hydrogen Council, 2017). Otherwise, more small scale, hydrogen can be stored in high-pressure storage tanks, or it can be liquified at low temperatures. The latter faces relatively high energy losses due to liquefaction (40% as compared to 10% in high-pressure storage tanks) (Barthelemy, Weber, & Barbier, 2017). For this reason, liquefaction is mostly used for medium to large storage purposes like international shipment (Moradi & Groth, 2019). As energy available from excess PV generation due to overvoltage mitigation is small, hydrogen production from this surplus will be small as well. Therefore it is likely to expect hydrogen to be stored in high-pressure-tanks opposed to the other possibilities, unless these are already available within the region. After storage, hydrogen can also be converted back into electricity using fuel cells. This, again, comes with losses, therefore the full cycle electricity-hydrogen-electricity is not very efficient. However, the lost energy is thermal energy. If this is captured and put to use well, the overall efficiency can be lifted significantly: up to 86% (95% electrolyser, 90% fuel cell) (Buttler & Spliethof, 2018; Wang, Wang & Fan, 2018).

Different electrolysis technologies are available. Mostly used are proton exchange membrane (PEM) electrolysis and alkaline electrolysis (AEL) (PBL, 2020). Another technology is solid oxide electrolysis (SOE), however this is not yet commercially available. Benefits of PEM electrolysers over AEL and SOE are that PEM electrolysers have much faster ramp-up speeds (<10s warm start, 5-10min cold start) compared to AEL (1-5min warm, 1-2h cold) and SOE (15 min warm, multiple hours cold) (Buttler & Spliethof, 2018). The high ramp-up speed implies that they can be put to use most effectively for flexibility services, and thus for overvoltage mitigation. PEM fuel cells have a ramp up speed of less than 6 minutes (Dell, Moseley, & Rand 2014).

3.3.3 Demand response

Electrical applications connected to the grid can be controlled so that they are used during peak PV penetration periods. By this, electricity drawn from the grid is minimized and moments of consumption are matched to generation periods (Marra, Yang, Træholt, Østergaard, & Larsen, 2013). This is called demand response. Demand response reduces the electricity fed into the LV grid. Moreover, it decreases the peak load power and reverse power flow (Malík & Havel, 2014). As a result, overvoltage is mitigated and more PV systems can be integrated into the LV grid (Hashemi Toghroljerdi & Ostergaard, 2016). Demand response can be used for appliances like dishwashers, washing machines, fridges etc. Moreover, it can be used to charge electrical vehicles (EV's). By using electrical vehicles for demand response, they at the same time act as an electrical energy storage system. In that way, less static batteries are needed: EV's reduce the required capacity of electrical energy storage systems (Marra et al., 2013).

It is not likely that demand response can act as the only mitigation strategy preventing overvoltage as it highly depends on the behaviour of electricity consumers (Hashemi Toghroljerdi & Ostergaard, 2016). For instance, people tend to charge their EV after they come home, which often does not coincide with peaks of PV penetration (Hashemi, Ostergaard & Yang, 2014). Moreover, not all appliances (like washing machines) are used on a daily basis (Marra et al., 2013). However, just as electrical energy storage, it can be used as an addition to, for instance, power curtailment as to decrease the losses enhanced by curtailment (Hashemi et al., 2014). Furthermore, it could be combined with electrical energy storage (and curtailment) to decrease the storage capacity needed (Hashemi et al., 2013, October). In such a combination, electrical energy storage systems can be used more effectively for overvoltage prevention as (part of) their charging capacity is saved for moments of expected high PV irradiance peaks. Combinations like these enhance system integration. Although demand response asks consumers to change their behaviour which can be challenging to achieve, home energy management systems (HEMS) can help to achieve this. Such systems can automatically manage appliances and storage and conversion systems. For instance, when PV is overloading the grid, HEMS can turn on appliances like the dishwasher or washing machine, or if this is not needed at the time, it can charge batteries, turn on conversion devices or charge EV's.

3.3.3.1 Electrification

Electrification of energy demands can be seen as a form of demand response, although it does not specifically shift moments of energy-use to a better fitting period of energy generation. It does, on the other hand, cause more electric demand. The additional electricity demands potentially coincide with moments of PV generated electricity, thus during the middle of the day. In that case, electrification helps mitigating overvoltage as the added electricity demands match electricity generation peaks and therefore it provides peak shaving. Again, HEMS could be of aid to better match the moments of demand to PV generation. Examples of electrified energy demands are demands for EV's and induction cooking plates.

3.4 Implications

Previously, all conventional and system integration mitigation strategies have been discussed. Subsequently, it is necessary to understand what the implications of implementing each of the strategies in a local context could impose. Therefore, the implications are discussed in this section. This is done according to the four themes of the implications: energetic, financial, spatial and social.

3.4.1 Energetic aspects

There are large differences between the different mitigation strategies in terms of the amount of excess PV generated electricity that they are able to use. This has to do with the nature of the strategy, the use-case of the energy and the efficiencies of the devices used for the strategies. Storing and converting PV generated electricity implies losses. This has to do with the efficiencies of the used storage or conversion system. The energetic aspects of the overvoltage mitigation strategies are described in the following sections.

Curtailment

The overvoltage mitigation strategy of c*urtailment* entails the highest energy losses as all potential PV generated electricity is curtailed in case overvoltage is bound to occur. As stated before in section 3.2, the need for curtailment of PV generated electricity is less than 2.5% of time yearly, in case of static curtailment with a fixed curtailment rate at 70% nomical PV capacity (Stetz, Marten & Braun, 2012).

Grid reinforcement

Grid reinforcement implies maximum energy yield as it allows all PV generated electricity to be inserted onto the grid. Transporting electricity over the grid does entail losses, depending on multiple factors as the transport distance and the thickness and material of the cable (van Oirsouw, & Cobben, 2011). Within a distribution network, 1-2% of the electricity is lost (T. Fens, personal communication, July 13, 2021). These losses are caused by transmission over cables and through transformers and all other components in the grid. In a case study by Ding, Bell & Strachan (2010) on a distribution grid in the UK, losses were found to be 1.1%, of which 74% came forth of transformer losses and 26% of line losses. Thus, in case local energy demand is high enough at times of PV peak hours, meaning that PV generated electricity does not have to pass transformers, losses would be limited to 0.28%. Demand response could be of aid for this.

Demand response

Demand response is, energy-wise, an ideal mitigation strategy as it matches current energy supply with demand. In an optimal situation it could thus prevent peak PV generated energy to be lost. Then, just as is the case with grid reinforcement, only losses due to electricity transport occur.

Electrical energy storage

Electrical energy storage causes losses due to the efficiencies of the batteries used. An example of a home battery is the Tesla Powerwall (13,5 kWh). It's one-way efficiency is 95% (storing energy). A full cycle (storing and discharging) has an efficiency of 90%.

Hydrogen conversion

Conversion of electricity into hydrogen also causes losses due to the efficiencies of the electrolysers and fuel cells used. PEM electrolysers have efficiencies of 67.9% (PBL, 2020). Towards 2030, efficiencies of PEM electrolysers are expected to be 78.8% (IEA, 2019). It's efficiency degrades 0.5-2.5% per year. Electrolysers can reach higher efficiencies, thus implying lower losses, operating at part-load (Buttler & Spliethof, 2018). However, this makes them less cost-efficient. In case the waste heat is captured and used effectively, the efficiencies of electrolysers can be increased up to 95% (Buttler & Spliethof, 2018). Subsequently, if hydrogen is stored, the compression (from 10 to 450 bar, as an example) causes 3% additional losses (Buttler & Spliethof, 2018).

For the conversion of hydrogen back into electricity a fuel cell is used. This implies additional energy losses. Currently, PEM fuel cells have efficiencies ranging between 40-60% (Dell, Moseley, & Rand 2014; Wang, Wang & Fan, 2018). Towards 2030, efficiencies are expected to be 60% (van der Roest, Fens, Bloemendal, Beernink, Van der Hoek & Van Wijk, 2021). However, when waste heat is collected and used effectively, efficiencies can exceed 90% (Wang, Wang & Fan, 2018).

Heat conversion

Conversion of electricity into heat is done with heat pumps. Heat pumps can be very effective in their energy use. The performance of heat pumps is measured by the Coefficient of Performance (COP) and it ranges between 3 to 5. This implies 1 kW electricity to produce 3 to 5 kW of thermal energy (Accenture et al., 2021).

3.4.2 Financial aspects

Implementing a certain overvoltage mitigation strategy often implies costs to be made. This has consequences for the local municipality or the citizens depending on who will implement the infrastructure for a certain mitigation strategy. Furthermore, the overvoltage mitigation strategies have an impact on the neighbourhood's energy import demand. This entails residents and local stakeholders to have a higher or lower energy bill.

Their costs consist of two aspects: infrastructure investments and energy import demands. Energy import demands can only be considered for a local context. However, in general system integration will lower energy import demands as more locally generated PV electricity can be used. Curtailment will impose a high energy import demand as the least locally generated PV electricity can be used. Thus financially, curtailment impacts the energy bill of residents the most in a negative way. System integration strategies will generally have a positive effect on the energy bills.

The infrastructure investments for the overvoltage mitigation strategies vary greatly. Moreover, for the storage and conversion strategies, they depend on the capacities installed. Therefore, specific costs can only be evaluated for a local context. Curtailment and demand response are the only overvoltage mitigation strategies for which no new infrastructure needs to be implemented. An overview of the infrastructure investments needed for the various overvoltage mitigation strategies can be seen in table 1. Due to the lifespan of a certain infrastructure, investments have to be made more often. This impacts the financial situation of a certain strategy. Therefore, also the lifespan of the systems is stated. The costs and lifespans in table 1 were validated with P. Bonhof (Alliander), and T. Fens (TU Delft) E. van der Roest (TU Delft, KWR institute) (P. Bonhof, personal communication, July, 19, 2021; T. Fens, personal communication, July 30; E. van der Roest, personal communication, 27 October, 2021).

3.4.3 Spatial aspects

Most mitigation strategies have spatial consequences: for many strategies, the infrastructure has to be updated or newly installed. This means that they have to be implemented in the public space of a neighbourhood or in the houses of residents.

Grid reinforcement

Reinforcing the grid has temporary spatial consequences as the streets need to be opened up. This is done on a large scale as the whole LV grid around a mid-voltage substation has to be updated which implies that the neighbourhood will be bothered with maintenance for an extended period depending on the speed of the construction work. After the electricity grid is updated, the spatial impact is unnoticeable as the grid is situated underground. Furthermore, the MVS needs to be updated. This could entail that a new MVS is slightly larger. However this spatial difference is disregarded in this study. Grid reinforcement thus has no spatial impact.

Curtailment

Curtailment does not entail any spatial implications.

Electrical energy storage

The mitigation strategies of electrical energy storage and conversion to heat or hydrogen have permanent spatial implications. For electrical energy storage batteries are needed. These can be installed as a communal battery serving a neighbourhood around a mid-voltage substation, or as home batteries within residences. A Tesla Powerwall 2 home-battery (13.5 kWh) has the dimensions of 1,15m x 0,753m x 0,147m (LxWxD), or 0,13 m^3 (Tesla, 2021).

Hydrogen conversion

For hydrogen conversion electrolysers are needed, and depending on the use-case of the hydrogen, local fuels cells have to be installed. A larger communal fuel cell could be implemented or each residence can have their own. The latter would relieve the grid from electricity transport. Hydrogen

Grid reinforcement	CAPEX		OPEX	lifespan		source
MVS				40	yr	*, (Klyapovskiy et al., 2019)
new MVS	€ 39,600					
removing old MVS	€ 2,500					
implementation temporary MVS	€ 4,900					
(dis)connecting (temporary) MVS to grid	€ 47,700					
total (¬)	€ 94,700		1%			
cable reinforcement (adding cables) (¬)	€ 10,400	/100 m	1%	50-80	yr	*
cable replacement (¬)	€ 14,300	/100 m	1%	50-80	yr	*

Curtailment	CAPEX	OPEX	lifespan
infrastructure	€ 0	-	-

Electrical energy storage	CAPEX	OPEX	lifespan		source
home battery (13.5 kWh)	€ 8,240	1%	12	yr	(Tesla 2021; Engie, 2020)
installation	€1100-3300	-			(IRENA, 2017)

Demand response	CAPEX	OPEX	lifespan
demand response (manual/behavioural)	€ 0	-	-

Hydrogen conversion (¶)	CAPEX		OPEX	lifespan		source
electrolyzer	€ 500	/kW	2%	20	yr	(Farahni, Bleeker, van Wijk, Lukszo, 2020)
storage tank (+compression costs, 200 bar)	€ 450	/kWh	2%	20	yr	(EnergiNet, 2020)
retrofitting gas grid	€ 373	/house	0%	40	yr	(Hoogervorst, 2020)

Heat conversion	CAPEX		OPEX	lifespan		source
heat pump (residential)	€3000-4500	/kW	2%	15	yr	(Tennet, 2020)
storage tank (water)	€ 410	/kWh	2%	30	yr	(EnergiNet, 2020)

*(P. Bonhof, personal communication, July 19, 2021; T. Fens, personal communication, July 30)

¬ *These costs entail material costs, payments to third parties (contractors) and labour costs. Cost specifications are stated in Appendix A.*

¶ Targeted towards 2030

Table 1: Infrastructure investments needed (CAPEX & OPEX) for the various overvoltage mitigation strategies, excl. VAT.

transport infrastructure is also needed. Either new pipelines should be implemented underground, or the existing gas network has to be retrofitted. Furthermore, hydrogen storage tanks are necessary. Hydrogen can be stored on a large scale in salt caverns, however, as periods of PV induced overvoltage do not occur often, it can be argued that small scale storage is more beneficial. Except for areas where large-scale storage already exists. Although the active cell area of a PEM electrolyser is only 0.13 m^2 (Buttler & Spliethof, 2018), for the installation of an electrolyser with a capacity ranging from 50 to 250 kW, an area similar to a container is needed: 10 to 15 m^2 (height ≈ 2,5 m) (Elogen, 2021; Areva, 2016). Similar areas are needed for a communal fuel cell of 50-250 kW and a communal storage tank (8000 kWh) (Areva, 2016; US Department of Energy, 2017). Electrolysers with larger capacities (>2500 kW) require an area of <30 m^2/MW_{el} (Elogen, 2021). Residential electrolysers of 1000W have dimensions of 485 x 368 x 352 mm (L x W x H) (Fuel Cell Store, z.d.).

Heat conversion

Mitigating PV overvoltage with heat conversion requires heat pumps to be installed. For this, space has to be allocated within residences or in a neighbourhood. The size of a residential heat pump ranges from 1 m^2 to 3 m^2 depending on the type and the size of the heat storage vessels. The exact size depends on the type and capacity of the heat pump, which is amongst others dependent on the grade of isolation of the building. Communal heat pumps take up the size of a container (10 to 15m^2, 2,5m high) (T. Fens, personal communication, August 5, 2021).

Demand response

Demand response does not have any spatial impact.

3.4.4 Social aspects

All PV overvoltage mitigation strategies entail different social implications. Implications under this category entail aspects that are unquantifiable but still impact the daily life of residents or other local stakeholders. Social aspects are described in this section.

Grid reinforcement

Grid reinforcement causes a temporary large impact on residents due to constructional nuisance coming from opening up streets and maintenance of other grid infrastructure.

Curtailment

Curtailment, on the other hand, causes permanent impact. As curtailment is used at peak PV moments it implies that PV owners cannot produce energy at the most valuable hours of generation. Therefore, owners lose revenue (Chaudhary & Rizwan, 2018). This makes curtailment disadvantageous for PV owners, or the local community that would otherwise benefit from free, green energy. Hashemi Toghroljerdi & Ostergaard (2016) argue that because of the latter, curtailment alone will likely be an unacceptable solution for the public. Although it should also be named that curtailment only occurs for limited times a year: less than 2.5% yearly (see section 3.2). Moreover, using curtailment to some extent is likely to be economically unavoidable from the DSO's point of view. The way in which curtailment is set up can also cause social consequences. Organising curtailment dynamically (instead of statically) is detrimental for PV owners situated close to vulnerable electrical nodes in the grid. They will experience being curtailed more often than others (Von Appen, Stetz, Braun & Schmiegel, 2014).

Storage and conversion

If storage and conversion systems are installed within homes, it implies residents to cooperate in installing batteries in their home. This can be unwanted as available residential space might be limited. Similarly, if storage and conversion systems are installed in public space, they can take up potentially limited space available. Or residents might find them unappealing. Therefore, the implementation of such infrastructures can be impacting.

Demand response

Demand response has large social implications as it demands consumers to change their behaviour. For this reason, and for the fact that not all appliances are used every day, Hashemi Toghroljerdi & Ostergaard, (2016) argue that demand response is not to be considered a reliable mitigation strategy. One of the often named applications for demand response is charging electrical vehicles, however, electrical vehicles are often charged at home at the end of the day when PV penetration is limited (Hashemi, Østergaard, & Yang, 2014). Thus, for this application also behavioural changes are needed: users will need to charge their cars during the day e.g. at their office. Demand response can also be automated with ICT infrastructure, activating devices based on availability of energy. However for most appliances human interference is still needed: plugging in the EV, filling up the dishwasher or washing machine etc. Still it will likely be an improvement. Smart charging, or HEMS can be of aid for this.

4. Generic framework to depict neighbourhood-fitting overvoltage mitigation strategies

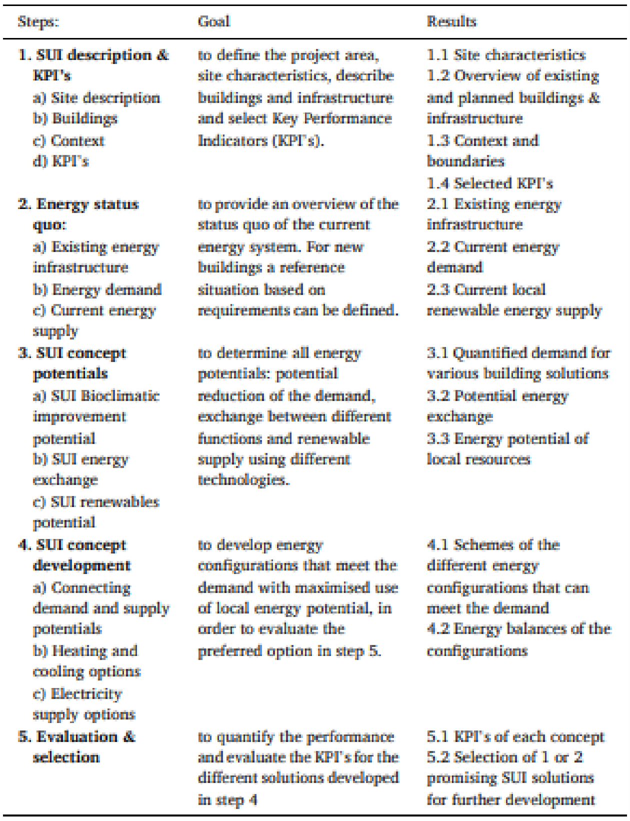
All overvoltage mitigation strategies and their local implications have been discussed in the previous chapter Now, it is necessary to identify how the strategies can be combined and how they fit a local context in order to depict optimal strategies. As all neighbourhoods have different characteristics and potentials, a neighbourhood fitting strategy cannot be replicated to fit different neighbourhood unconditionally. Therefore, a generic approach is needed to depict neighbourhood-fitting overvoltage mitigation strategies. In this chapter, first a literature review is done in order to explore existing approaches for designing neighbourhood energy systems. Using the information found through the literature review, together with the scientific gaps as where identified in chapter 1, a generic framework (TENOMF) is developed as to identify overvoltage mitigation strategies that fit the local context of a neighbourhood, while simultaneously stimulating the energy transition. In the framework, local energetic, financial, spatial and social implications should be considered.

4.1 Energy system design

To develop a generic framework for the design of energy systems that mitigate overvoltage while enhancing the wider energy transition, a review on state-of-the-art literature regarding energy system design is needed. In section 4.1.1, a literature review on generic approaches for energy system design is done. Furthermore, as the generic framework aims to consider socio-economic aspects, and as these are not quantifiable, it is evaluated how this can be assessed. Therefore, in section 4.1.2, a literature review on the assessment of social implications is done.

4.1.1 Generic approaches for energy system design

For the creation of a generic framework, literature search regarding the development of frameworks on energy system design is done. Hettinga, Nijkamp & Scholten (2018) propose a six step framework as a multi-stakeholder decision support system to plan local neighbourhood energy systems in collaboration with local stakeholders. Stakeholder involvement is important to gain support for the implementation of neighbourhood energy systems (Kelly & Pollit, 2011). However, this framework focusses mostly on the involvement of stakeholders for the decision making process and less so on how to systematically develop alternative neighbourhood energy system solutions, that preferably act autonomous. Nonetheless, as social acceptance is certainly an important factor for the implementation of mitigation strategies - they can have local implications such as nuisance due to construction work, financial consequences or spatial implications - stakeholder involvement is essential in the decision-making process for choosing mitigation strategies. The stakeholders' needs should thus be considered in the to-be-created overvoltage mitigation framework. In Mehleri, Sarimveis, Markatos & Papageorgiou (2012) an optimization approach to choose cost-optimal system components for a renewable distributed energy system on a neighbourhood scale is given. This model helps to depict financially beneficial options from a predefined list of possible system components. However, by having a predefined list it undermines the chance to look at area-specific potentials and system integration.



Steps:	Goal	Results
1. SUI description & KPI's a) Site description b) Buildings c) Context d) KPI's	to define the project area, site characteristics, describe buildings and infrastructure and select Key Performance Indicators (KPI's).	1.1 Site characteristics 1.2 Overview of existing and planned buildings & infrastructure 1.3 Context and boundaries 1.4 Selected KPI's
2. Energy status quo: a) Existing energy infrastructure b) Energy demand c) Current energy supply	to provide an overview of the status quo of the current energy system. For new buildings a reference situation based on requirements can be defined.	2.1 Existing energy infrastructure 2.2 Current energy demand 2.3 Current local renewable energy supply
3. SUI concept potentials a) SUI Bioclimatic improvement potential b) SUI energy exchange c) SUI renewables potential	to determine all energy potentials: potential reduction of the demand, exchange between different functions and renewable supply using different technologies.	3.1 Quantified demand for various building solutions 3.2 Potential energy exchange 3.3 Energy potential of local resources
4. SUI concept development a) Connecting demand and supply potentials b) Heating and cooling options c) Electricity supply options	to develop energy configurations that meet the demand with maximised use of local energy potential, in order to evaluate the preferred option in step 5.	4.1 Schemes of the different energy configurations that can meet the demand 4.2 Energy balances of the configurations
5. Evaluation & selection	to quantify the performance and evaluate the KPI's for the different solutions developed in step 4	5.1 KPI's of each concept 5.2 Selection of 1 or 2 promising SUI solutions for further development

Figure 9: The five steps of the SUI approach (Jansen et al., 2021).

The Smart Urban Isle (SUI) approach is a framework for developing local balanced energy systems for existing neighbourhoods (Jansen, Mohammadi & Bokel, 2021). Jansen et al. (2021) mention the five stages of designing energy systems as are described by Bejan, Tsatsaronis & Moran (1996): 1) Understanding the problem; 2) Concept Generation; 3) Detailed Design; 4) Project Engineering; 5) Service. According to Jansen et al. (2021) stage 2, concept generation, is key for developing energy systems for neighbourhoods. In this stage, alternative energy configurations are created. The SUI approach is created to specifically focus on the generation of alternative solutions, in the form of energy configurations, for neighbourhood energy systems. Former literature was not focussing on stage 2, but on understanding the problem (stage 1) by developing methods and approaches to identify local energy potentials and on detailed design (stage 3) by doing comparative analyses, trying to identify performance indicators or looking into optimization methods for energy systems (Jansen et al., 2021).

A smart urban isle is defined as an urban area that has minimal needs for external energy as caused by the presence of a smart local energy system. The SUI approach for developing locally balanced urban energy systems provides a framework consisting of five steps, as can be seen in figure 9. In the first step, the characteristics and context of the project area is described and the key performance indicators (KPI) are defined. In the second step, the area's energy status quo (energy infrastructure, demand and renewable supply) is described as the start of the analysis. Subsequently, in step 3, the area's energy potentials are investigated: the potentials for energy saving, energy exchange and local renewable energy production. In step 4, energy configurations as alternative solutions are developed. These are based on the previous analyses and defined upon the maximal use of local energy potential. Lastly, in step 5, the potential energy configurations are evaluated based on the KPI's, after which a best fit for the local environment is selected.

The SUI approach aims to create energy 'islands' by trying to fulfil a neighbourhood's energy demand with local potentials. By that, it enhances the energy transition. Most of the proposed grid-overload mitigation strategies can also help fulfilling part of a neighbourhoods' energy demand (energy storage, conversion, demand response, reinforcing the grid): they can contribute to the creation of new local renewable energy configurations and thus also stimulate the energy transition. Thus, the aim of SUI is comparable to the aim of this research. For this reason, the base of the SUI approach is used for the creation of the framework that this research aims to develop: the TENOMF, a generic framework to depict neighbourhood-fitting overvoltage mitigation strategies that aim to use local potentials and energy system integration as to foster the wider energy transition. The development of the TENOMF as well as how it differs from SUI, is described in section 4.2. In the following section, a literature review on the assessment of social implications is done.

4.1.2 Literature review on assessment of social implications

In this section a literature review on the assessment of social implications is done. This is needed as the assessment of social implications is not straightforward: they are not quantifiable. The concept of social acceptance is coined as a way of assessing the feasibility of mitigation strategies in terms of social aspects. For an energy system to be accepted two aspects are of importance: *co-ownership* and *local benefits and connectedness*. This is explained in the following section.

Social acceptance

Within the consideration of the implementation of energy technologies, only looking at technological and financial implications of energy technologies is not enough: social acceptance issues also determine the development considerably (Von Wirth, Gislason & Seidl, 2018). A literature review from Von Wirth et al. (2018) shows that multiple definitions for social acceptance towards energy technologies can be made: Social acceptance can be defined as having a positive attitude towards measures or technologies that are likely to cause supportive behaviour, if requested or necessary, to the technology. Social acceptance can also be seen as the opposite of a resistant attitude. Then, if the attitude is solely non-resistant, supportive behaviour can be seen as passive acceptance or ‘tolerance’.

Social acceptance can be distinguished into socio-political acceptance, market acceptance and community acceptance. Socio-political acceptance is acceptance on the most general level: it is the acceptance of a technology or policy by the public ‘as a whole’, key stakeholders and policy makers. Market acceptance is the acceptance of a technology by the market, or the adaptation of an innovation: consumers, investors and companies (are willing to) adapt. Community acceptance is acceptance by communities on a local level. As people can generally have an acceptant attitude towards a technology, they can be resistant against it within their local environment (‘Not in my backyard’). For community acceptance, the following factors are of importance: distributional justice (are costs and benefits shared fairly?), procedural justice (do all relevant stakeholders have the opportunity to participate?) and trust (in information and intentions of the outside-communal actors) (Wüstenhagen, Wolsink & Bürer, 2007). Community acceptance has a temporal factor, following a U-curve before, during and after the implementation of renewable energy technologies: Acceptance is high before the project (before people are confronted that a project will come to their neighbourhood), then during the location-selection and implementation it decreases, whereafter it increases again after the project is finished for some time (Wolsink, 2007). Within this research, when talking about social acceptance, community acceptance is meant.

For the implementation of renewable energy technologies, or mitigation strategies, within a neighbourhood, spatial proximity, the community’s place-related attitude and the spatial scale (to which extent the technology is implemented) should be considered (Von Wirth et al., 2018). Von Wirth et al., (2018) found three factors influencing social acceptance for the implementation of distributed energy systems: co-ownership, local benefits & connectedness and the technical and financial feasibility of the energy system. The first two are of importance for the social impacts for local communities and their acceptance towards the installation of local energy systems, or mitigation strategies.

Co-ownership

Co-ownership increases acceptance and local support for the implementation of local energy technologies. Moreover, it can help raise awareness of electricity consumption among users if continuous information is provided (Von Wirth et al., 2018; Stedmon, Winslow & Langley, 2013). Providing feedback on the energy gained locally makes acceptance grow (Boon & Dieperink, 2014). A study by Bosch & Peyke (2011) showed that even people with a sceptic attitude towards renewable energy generation could be interested in having co-ownership over the decentralised energy production.

Local benefits and connectedness

Another important aspect of enhancing acceptance for renewable energy technologies is the promotion of benefits for the local community as well as making the community feel connected, and letting them be involved in the decision-making or planning process (Von Wirth et al., 2018; Walker, 2008). Walker (2008) stressed that accompanied by the aforementioned importance of co-ownership, local income, control and permission for planning are important. Asides from private and communal benefits (Tofi, Schuitema & Thogersen, 2014; Wolsink, 2012), environmental benefits and personal norms were also coined as factors of importance (Tofi et al., 2014).

4.2 Transition-enhancing neighbourhood overvoltage mitigation framework: generic framework

In the previous subchapter, the literature review on energy system design was stated. From this review, an approach was found that can be used as a base for the development of the TENOMF. Furthermore, a way to assess the social implications of energy systems and overvoltage mitigation strategies was identified. Now, the TENOMF can be developed.

In this section, the alterations of the transition-enhancing neighbourhood overvoltage mitigation framework (TENOMF) as compared to the SUI approach are described after which the TENOMF's steps, aim and target audience are stated. In section 4.3, the method of the TENOMF is described in detail: all the steps of the TENOMF are elaborated on.

TENOMF: alterations compared to the SUI approach

The SUI approach is used as the base for the creation of the TENOMF. The SUI approach is a method to develop neighbourhood energy systems with the aim to be (grid-)independent. However, it does not consider overvoltage mitigation specifically. Therefore, for the purpose of this research, to create the TENOMF, the SUI approach needs to be altered. These alterations are described in this section.

The TENOMF entails 6 steps, as opposed to the 5 steps of SUI. In the SUI approach the first step consists of the characterisation of the neighbourhood and the KPI description. In the TENOMF this step is divided into two separate steps. This is done as the KPI's, which are called assessment criteria in the TENOMF to distinguish the two frameworks, are not case-study specific whereas the neighbourhood characterisation is. The TENOMF's assessment criteria state generic criteria, regardless of the context, that act as a method to compare different strategies such that optimal strategies can be identified. The area characterisation is highly case-study specific as it indicates the local context. Using this information, amongst other, in a later stage area-fitting strategies can be chosen using the assessment criteria. The other steps of the TENOMF are also altered compared to the SUI approach for a focus on PV generation and PV-induced overvoltage mitigation strategies, instead of SUI's focus on general neighbourhood energy reduction strategies and renewable energy generation.

Furthermore, the SUI approach merely looks into technical, or energetic, implications while the TENOMF takes up a more holistic approach: the TENOMF considers energetic, financial, spatial and social implications of overvoltage mitigation strategies. The stakeholders needs' are included by taking into account social implications coming forth of social acceptance for the measures. By doing this, instead of only regarding energetic implications, the TENOMF aims to ensure that technical solutions not only work conceptually, but are also feasible in reality, in the local context of a neighbourhood having a large variety of stakeholders with different needs and where space is scarce.

The overview of the TENOMF can be seen in table 2. The six steps of the TENOMF are as follows. In the first step, the assessment criteria are stated. Four of them are defined for choosing fitting mitigation strategies: i) energetic implications, ii) costs, iv) spatial impact of the mitigation strategies and v) their social acceptance. In step 2, neighbourhood description, the spatial boundaries of the neighbourhood are depicted and the area's characteristics and demographics as well as neighbourhoods' buildings and its functions are described. In step 3, energetic conditions neighbourhood, the infrastructure of the neighbourhoods' electricity grid and the heat network are described. Furthermore, the area's energy demand (electricity and heating) and PV supply are defined. This is slightly different as opposed to the SUI approach: only PV is considered as local renewable energy generation source as this study focusses on PV-induced overvoltage. The fourth step seeks to understand the neighbourhood's overvoltage mitigation potentials: what are possible overvoltage mitigation strategies fitting the local environment, what are energy exchange and system integration potentials in the neighbourhood. This step is also slightly altered for the purpose of the TENOMF, focussing on the implementation of overvoltage mitigation strategies instead of general energy reduction potentials as is done in the SUI approach. In the fifth step, concept development, various energy configurations as overvoltage mitigation strategies are proposed, based on the neighbourhoods energy potentials defined in step 4Lastly, in step 6, the evaluation of the proposed system integrated concepts is done. This is based on the assessment criteria giving the mitigation strategies' energetical, financial, spatial and social implications. The system integration overvoltage mitigation strategies are compared with the conventional mitigation strategies curtailment and reinforcing the grid. In the last step of the SUI approach apart from evaluation also one or two promising solutions are selected. This is not done TENOMF for the following reason: the TENOMF aims to evaluate all potential solutions as to be able to give recommendations for strategies fitting the local context. These recommendations are can be of use for local governments or policy makers in cooperation with DSO's and planners, after which the final selection of a fitting strategy for the neighbourhood should be done in a participative process with residents and other local stakeholders.

Aim & target audience

Although in essence the TENOMF is a generic framework to identify potential overvoltage mitigation strategies that fit a local context, it seeks to explore if system integration strategies can be used for this purpose. By doing this, it can, next to mitigating overvoltage, foster the (local) energy transition. In that way, overvoltage mitigation can be seen as an opportunity.

The TENOMF is a framework that can be used by local governments, policy makers, DSO's and planners as to plan for energy transition-enhancing neighbourhood energy systems that mitigate PV-induced overvoltage.

Step 1	Assessment criteria	
	a. Energetic implications	
		i. Curtailment
		ii. Energy import
	b. Costs	
		i. Infrastructure
		ii. Energy import
	c. Spatial impact	
	d. Social acceptance	
Step 2	Neighbourhood description	
	a. Spatial boundaries	
	b. Neighbourhood characteristics & demographics	
	c. Buildings & functions	
Step 3	Energetic conditions neighbourhood	
	a. Energy infrastructure	
		i. Electricity grid
		ii. Grid for heating: gas or heat
	b. Energy demand	
		i. Electricity
		ii. Heat
	c. Solar supply	
		i. Solar supply PtX
Step 4	Neighbourhood overvoltage mitigation potentials	
	a. Neighbourhood considerations & local policies and ambitions	
	b. Potential overvoltage mitigation strategies	
	c. Sizes of storage and conversion infrastructure & PtX simulation settings	
Step 5	Concept development	
Step 6	Evaluation	
	a. Assessment criteria evaluation per overvoltage mitigation strategy	
		i. Energetic implications
		ii. Costs
		iii. Spatial implications
		iv. Social acceptance
	b. Conclusions	
	c. Recommendations	

Table 2: The transition-enhancing neighbourhood overvoltage mitigation framework (TENOMF).

4.3 Method

In this section, the TENOMF is described step by step.

4.3.1 Step 1: Assessment criteria

In the first step, the assessment criteria are described. These include energetic implications, costs, spatial impact and social acceptance. Together, the assessment criteria define how suitable an overvoltage mitigation strategy is for the neighbourhood.

Energetic implications

The energetic implications of an overvoltage mitigation strategy are twofold. They concern *overvoltage* and *effectiveness of local energy use*. Overvoltage is measured by the yearly needed *level of curtailment* required to prevent overvoltage causing damage. Effectiveness of local energy use is measured by the yearly amount of external *energy import demand* that an overvoltage mitigation strategy has. The Power-to-X (PtX) model is used to calculate both implications for the overvoltage mitigation strategies.

Power-to-X

The model used for the calculation of the energetic implications in this study is the Power-to-X model. This is a model used to calculate energy and water flows for neighbourhoods in connection to renewable energy production, by taking as input hourly weather data (solar, wind and rainfall). Subsequently, PtX can do an economic evaluation of the used energy system. For this study, PtX's water system and economic evaluation are disregarded, therefore the models' functionality regarding these aspect will not be elaborated. A full conceptual description of PtX can be found in van der Roest, Snip, Fens & Van Wijk (2020). Furthermore, an extensive description of its modelling structure can be found in van der Roest et al. (2021). In figure 10, the concept of the PtX model is schematically displayed. As can be seen, the PtX model consists of a water system, a heat system with aquifer storage, a hydrogen system and a renewable electricity production and demand system. All parameters and inputs as weather data and energy profiles can be adjusted to the preferences of the user. In figure 11, the workflow of PtX is displayed schematically, showing inputs, calculations and outputs.

Calculating the neighbourhood's energy flows works as follows: the weather data is used to predict hourly renewable energy production. Subsequently, according to the hourly energy demand of the buildings in the neighbourhood, energy is distributed. The renewable generated energy can be directly used within the buildings, exported to the grid, stored in electric energy systems or converted into hydrogen or heat. Each hour, the model looks at demands and supply (from production and storage) and tries to allocate the energy as to match them optimally for that hour. For this distribution PtX does not account for future predictions on energy supply and demand. All outputs are given hourly in an excel file. For the purposes of this study, the needed outputs are summed over the period of a year. Although the outcomes for the energetic impacts are wanted for the period of one year, the simulations are conducted for a period of 16 months. This is done so that all storage facilities have a natural initial volume at the start of the year-to-simulate. However, it is also possible to manually set initial values in PtX.

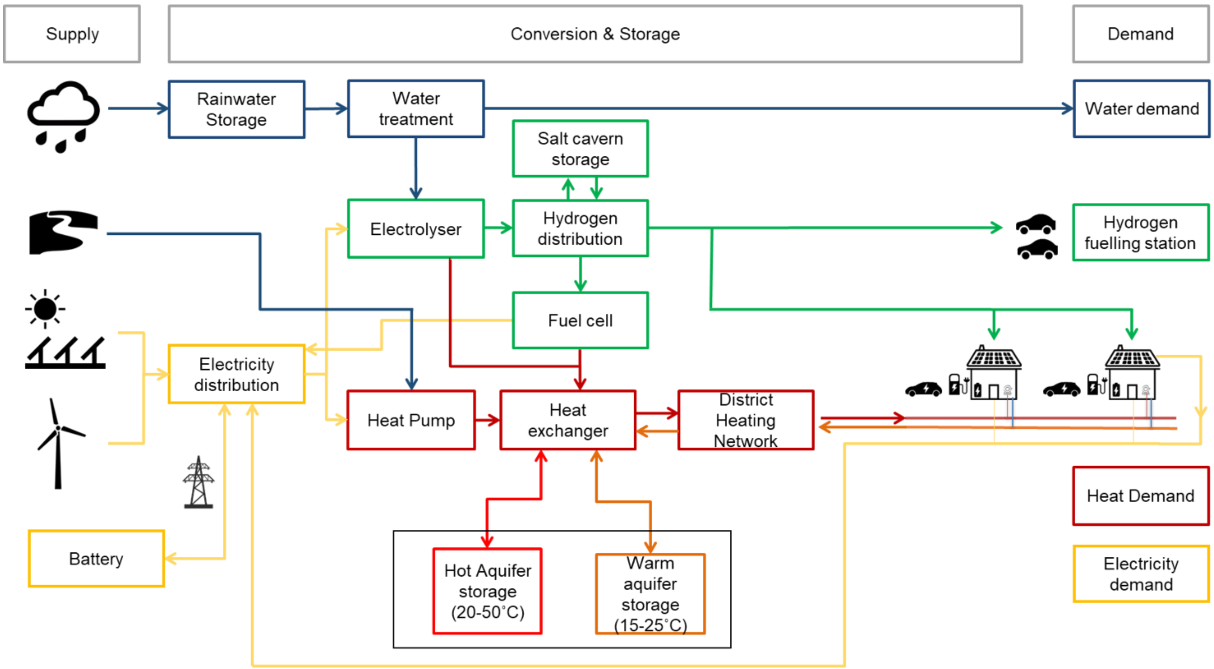


Figure 10: Schematic display of the concept of the Power to X model (van der Roest et al., 2021).

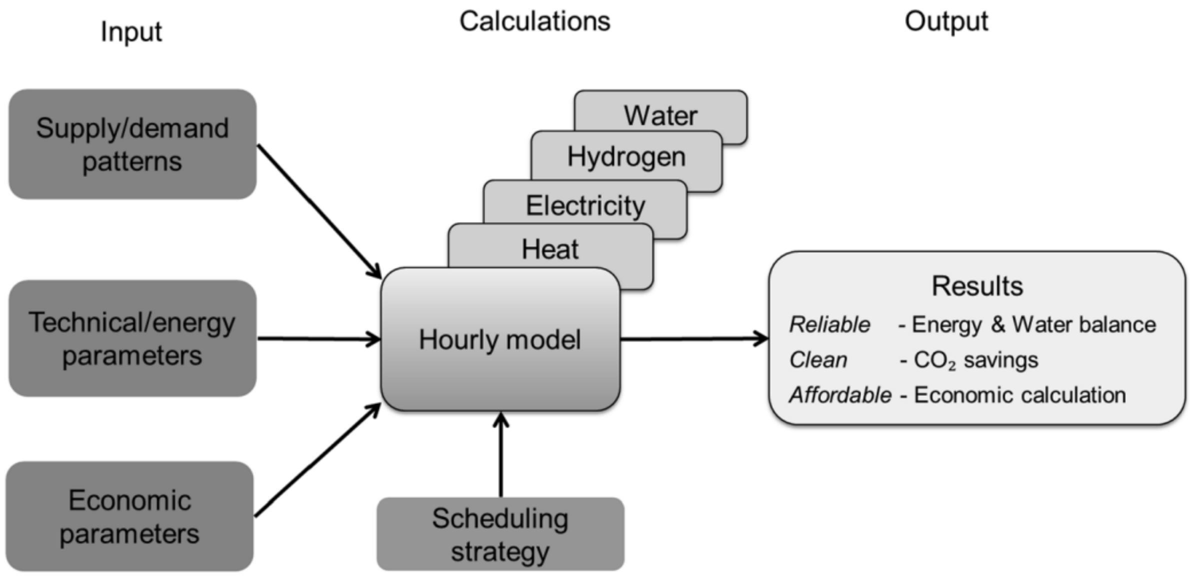


Figure 11: Schematic display of the workflow of the Power to X model, showcasing the model's inputs, calculations and outputs (van der Roest et al., 2020).

Additions to Power-to-X

For the purposes of this study, PtX's default neighbourhood is extended from three to four building typologies. Initially the neighbourhood included the categories new apartment, renovated apartment and terraced home. This was altered to one-floor apartment, two-floor apartment, shop and day-care/community centre. Furthermore, a residential hydrogen boiler is added in the neighbourhood system. This is done by adjusting the 'hybrid' residential heat pump. Per default in the original version of PtX, the hybrid heat pump uses hydrogen to heat tap water demand. Furthermore, hydrogen is used for heating when the heat pump efficiency is too low (outside temperature is below -5 °C). This definition is altered for the purpose of this study: in the PtX version used for this study, the definition of the hybrid heat pump is adjusted so that it functions as a hydrogen boiler using hydrogen for space and tap water heating demand, operating regardless of the outside temperatures. Thus, in the altered version of PtX (used in this study), by activating the defined hybrid heat pump PtX does not simulate a heat pump but it simulates a hydrogen boiler: the hydrogen boiler is actually activated. Then, hydrogen (instead of heat) is used for heating purposes. This rather unconventional way of defining in the model was done out of time-efficiency as otherwise the names throughout the whole code had to be adjusted: a time-consuming effort.

Curtailment

When overvoltage occurs, PV generation is curtailed in PtX. PtX determines the amount of curtailment that is needed per hour for each overvoltage mitigation strategy. The yearly amount of curtailment is obtained by summing the hourly curtailment output of PtX over the output of a year. As such, for each overvoltage mitigation strategy the yearly curtailment is obtained. In this way they can be compared. The conventional overvoltage mitigation strategy of *curtailment*, where no energy storage or conversion is possible, acts as a baseline.

Energy import

A strategy can be very good in diminishing the need for curtailment, however a second criterion is how effective the strategy uses the energy that would otherwise have been curtailed. To exemplify, think of a strategy with a very high electricity demand at times of solar generation, that at the same time has a very low efficiency due to which only a small fraction of the PV generated energy can be used at a later moment in time. Such a strategy would be very effective against curtailment, however it is not effectively using the solar energy: there is little system integration. Therefore, such strategy is not very advantageous. The effectiveness is measured by looking at the *yearly energy import demand* of the neighbourhood for each overvoltage mitigation strategy. The lower this is, the more effective the use of an overvoltage mitigation strategy is.

To compare different overvoltage mitigation strategies, different energy carriers are regarded in the total energy import: electricity, natural gas and hydrogen. The yearly electricity import demand (in kWh) and hydrogen import demand (in kg) for each of the strategies is obtained from the output of PtX. The natural gas import demand is manually calculated based on the total heating demand of the neighbourhood. This is obtained using the individual heating demands of the building typologies and their gas-boiler efficiencies, as will be defined in Step 2. The heating demand includes space heating, tap water heating and cooking demand.

The yearly import demand for all three energy carriers is converted to kWh, after which they are summed into the total energy import demand in kWh/year. In that way all overvoltage mitigation strategies can be compared on effective energy use.

For hydrogen this conversion is done using the higher heating value (HHV) of 39.4 kWh/kg. Natural gas demands are often indicated in m^3. For the conversion to kWh 31.65 MJ/m^3, or 8.79 kWh/m^3, is used (RVO, 2020).

Costs

As second criterion, the overvoltage mitigation strategies are assessed cost-wise. The total costs for an overvoltage mitigation strategy consist of infrastructure investment costs and energy import costs.

The latter are the yearly costs for the import demands of energy carriers that a neighbourhood energy system has. All costs are converted into a yearly amount as to be able to sum all costs for a better cost-comparison. VAT and interests are disregarded for all costs. A sensitivity analysis is performed to evaluate important factors for cost fluctuations of a strategy.

Infrastructure

For most overvoltage mitigation strategies new infrastructure has to be implemented. This implies costs. Infrastructure costs include CAPEX and OPEX. CAPEX for installing an overvoltage mitigation strategy consists of the investments needed for physical infrastructures and their installation. OPEX are the operation and maintenance costs of the used systems. These are usually given as a percentage and come as costs per year.

CAPEX are given as a total number. However, to obtain a full cost-comparison, all costs – CAPEX, OPEX and Energy import (elaborated in the following section, subsection *Energy import*) – need to be summed. OPEX and Energy import costs are yearly. Therefore, also CAPEX needs to be transformed into a yearly number. This is done linearly by dividing the total CAPEX over the lifespan of the infrastructure so that costs per year are obtained (€/year). Inflation or other potential future cost fluctuations are disregarded.

For an overvoltage mitigation strategy all investments needed the implementation of new infrastructures are considered. However, it may be that certain infrastructures will be used for multiple purposes, or that they are installed regardless of overvoltage mitigation: they are for instance installed out of wider energy transition purposes. Then it can be argued that the respective infrastructure costs can be subtracted from the total overvoltage mitigation costs. This can be decided in the evaluation (Step 6), also taking into account municipal and governmental ambitions and plans.

Energy import

The energy systems of diverse overvoltage mitigation strategies can use different energy carriers due to conversion. As different energy carriers have other prices per kWh, using one or the other can have an impact on the yearly energy bill. Also, one mitigation strategy can be more efficient in terms of energy use and therefore require less energy to be imported. This automatically lowers costs involved. Therefore, for the cost-comparison of overvoltage mitigation strategies also energy import costs are considered.

To compare all overvoltage mitigation strategies on their energy import costs, the hourly costs for the imported electricity, natural gas and hydrogen are summed over a year as to obtain yearly energy import costs per overvoltage mitigation strategy (€/year).

Choosing between conventional or system integration mitigation strategies

Klyapovskiy et al. (2019) argue that from a DSO's perspective, it is likely that the most cost efficient overvoltage mitigation strategy will be chosen. Therefore, system integration strategies need to be cost-efficient compared to conventional strategies. For this reason the *minimum value of conventional overvoltage mitigation strategies* (MVC) is coined. This value states what the cheapest conventional overvoltage mitigation strategy is: *curtailment or grid reinforcement*. System integration strategies need to be more economical than the MVC as to be the favourable strategy for DSO's. MVC is thus used to assess if conventional or non-conventional strategies are the most cost-efficient.

Sensitivity analysis

To evaluate cost fluctuations coming forth of the used differences in energy system variables, a sensitivity analysis is performed. This is done as follows. Costs are calculated by using various variables. All these variables are thus of influence for the total costs of an energy system. For the sensitivity analysis, one-by-one the variables are increased and decreased by a certain percentage, after which the total system costs are recalculated. Then, the fluctuations of the total system costs are obtained in relation to the percentual change of a certain variable. The difference that this fluctuation implies with respect to the original costs (without the in- or decrease of a variable) shows the sensitivity of certain variable to the system costs. Using the sensitivity, conclusions can be made on the importance of a variable to the total system costs. Moreover, it can be stated how important the uncertainty of a certain variable is.

Spatial impact

Asides energy and costs, energy configurations of the overvoltage mitigation strategies are also assessed spatially. This is done by regarding the space needed for the implementation of overvoltage mitigation infrastructures. A division is made between spatial impact in the public space (for collective infrastructures) and residential spatial impact (for infrastructures that are installed indoors).

The assessment is done using a rough classification on the space needed for the infrastructures of an individual overvoltage mitigation strategy. The classification ranges as follows:

-	no impact: no space needed
+	small impact: small infrastructures, comparable to a small fridge
++	middle impact: middle size infrastructures
+++	large impact: large infrastructures: comparable to 1-3 containers

For the energy configurations combining different individual overvoltage mitigation strategies, the scores of the individual strategies are summed. In that way, all overvoltage mitigation strategies are classified and can be compared.

As residential and public spatial impact have different consequences and the implementation calls for different approaches, both aspects, as well as the total impact, are considered in the evaluation phase (Step 6) of the mitigation strategies.

Social acceptance

Social acceptance is of major importance for the realisation of overvoltage mitigation strategies within a neighbourhood. However, it cannot be easily quantified. Therefore the impacts are assessed by argumentation using criteria for social acceptance as found by reviewing scientific literature (see section 4.1.2): co-ownership, local benefits and involvement in the planning process.

As quantification is difficult, no clear ranging classification of the mitigation strategies can be created. Therefore, social acceptance is used as a discussion starter in the evaluation phase (Step 6) which can help arguing why a certain strategy might be more fitting than another in case other aspects are fairly similar, or it can help identifying needs for better information provision and participation facilitation. It is thus used as a way of providing recommendations and opening up the discussion about the impacts on a local level for residents who will be confronted with various overvoltage mitigation strategies. This as to not only take into account quantifiable energetic, financial and spatial feasibility aspects. Social acceptance is needed to make theoretical, technologically feasible strategies actually succeed in reality.

4.3.2 Step 2: Neighbourhood description

The neighbourhood in need for a solution against overvoltage due to high levels of PV generation is described in the second step.

Spatial boundaries

First, the spatial boundaries are defined so that energy demands, generation, existing (energy) infrastructure and neighbourhood potentials can be identified. The neighbourhood consists of the service area of one MVS. This defines the spatial boundaries. For meshed grids there is no clearly bounded service area. However, for the simulation a defined service area is needed. In that case, a theoretical service area is estimated based on the distribution of the MVS's in the wider area.

Neighbourhood characteristics & demographics

After the area is bounded, the characteristics and socio-economical demographics of the neighbourhood are described. The level of urbanization and interesting characteristics within the neighbourhood as for instance canals or open public spaces are described. This is done by spatial analysis using geographic information services.

Socio-economical demographics of the neighbourhood are collected as to have a better understanding of the type of neighbourhood, its population and how involvement in the decision-making process can be done. Socio-economical demographics can give an insight in the potential (level of) social acceptance that measures will receive by for instance revealing financial status of the residents. Also social characteristics as migration-backgrounds and level of education can identify the need for extra focus on providing information (for instance in different languages) and involving citizens in the decision-making process. Furthermore an insight can be given on who is owning the houses (residents or housing corporations), how many people live in the neighbourhoods, how many cars are present etc. These types of characteristics help the decision-making process and provide valuable information for determining energy demands. Socio-economic demographics are gathered by data-search. In the Netherlands, much information can be found in the databases of CBS.

Buildings & functions

Subsequently, the type of buildings and its functions are described. This is used later on to have a clear understanding of the energy demands and potentialities of the buildings and the neighbourhood as a whole. General building typologies are defined for the energy simulation in the PtX model. This is done based on function and size, by doing a spatial analysis using geographic information services. As to not overcomplicate the energy simulation, these typologies are simplified and generalised. For each building typology the energy label, amount of buildings in this type, the area, electricity demands, heating demands and boiler efficiencies, construction years and roof types are defined.

4.3.3 Step 3: Energetic conditions neighbourhood

In the third step, the neighbourhood's energetic conditions are described: the existing energy infrastructure, both the electricity grid as well as the (type of) gas or heat network, the total energy demand (electricity and heat) and the (potential) solar supply. This information is all gathered as input for the assessment of energetic implications (and thus for the simulation in PtX) and costs.

Energy infrastructure

The energy infrastructure of a neighbourhood usually encompasses an electricity grid and a natural gas grid. However, in new-built or renovated areas the latter can also be replaced by an alternative heat network or retrofitted into an alternative gas grid. This is evaluated.

Electricity grid

The characteristics of the local LV grid are described: the grid structure (radial, ring, meshed) and the capacity of the existing MVS. This is done investigating open source data from local grid operators and further data-review.

Grid for heating: gas or heat

The existing (type of) network for heating (natural gas, bio gas, hydrogen gas or heating network) and the energy carrier used for heating the build environment is described. This is done investigating open source data from local grid operators and further data-review.

Energy demand

Next, an overview of the neighbourhood's energy demand is given for the different energy carriers. These numbers are used as input for the energy simulation in PtX and for assessing the energy import of an overvoltage mitigation strategy.

Electricity

Using the neighbourhood and building characteristics as gathered in step 1 and open source data, the total yearly electricity demand is obtained. This includes demand for households, electric cooking and EV's. Moreover, the electricity profiles used for each of the building typologies in the PtX energy simulation are stated.

Heat

Using the neighbourhood and building characteristics as gathered in step 1 and open source data, the total yearly heating demand is obtained. This includes demand for space heating, tap water and cooking. Heating demand can subsequently be converted into natural gas demand (or other energy carrier if needed) using its heating value.

Solar Supply

In this part, the total potential solar supply is stated. First, this potential is investigated by doing expert interviews. For this research Maarten Verkou, researcher at the PVMD group at TU Delft and expert in solar yield modelling in urban environments, was consulted. By consulting experts, a realistic number on the neighbourhoods maximum potential (in terms of physical space) for the implementation of PV panels, and on the overvoltage risk involved, is obtained.

Solar supply PtX

Subsequently, the obtained local PV potential is adjusted such that it fits the PtX simulation. PtX defines curtailment solely based on the hourly available capacity of the MVS and does not take into account other complex electro-technical parameters. Therefore, the prediction of overvoltage in PtX is less realistic. For this reason it is tested if PtX reaches similar curtailment levels as the models of M. Verkou. If not, the amount of solar panels in the case study area for the simulation in PtX are exaggerated to a number where similar curtailment levels are obtained. This exaggeration is done homogeneously over the case study area, meaning that the hosting capacity of each roof is multiplied by the same factor.

In this section also the characteristics of the used solar panels for the simulation in PtX are stated.

4.3.4 Step 4: Neighbourhood overvoltage mitigation potentials

In the fourth step, the neighbourhood's overvoltage mitigation potentials are investigated. First, considerations are made for the neighbourhood using information coming from Step 2. This is coupled to the known strategies for overvoltage mitigation (as are described in chapter 3). From these, potential mitigation strategies fitting for the local context are selected. Lastly, the specifications of the potential strategies are elaborated.

Neighbourhood considerations & local policies and energy transition ambitions

In this part, specific energy and overvoltage potentials are located based on the information that has been gathered in step 2. Moreover, local policies and ambitions by the municipality regarding the energy transition are evaluated (for the mobility, built environment and renewable energy sectors). These are used to help depicting overvoltage mitigation potentials as they can potentially strengthen each other. Ideally, the overvoltage mitigation strategies match wider plans and transitions within the neighbourhood.

Potential overvoltage mitigation strategies

Using the information described above, the feasibility of known overvoltage mitigation strategies (see chapter 3) for the local environment is stated. This results in a list of strategies that could potentially fit the neighbourhood and a list of strategies that are unsuitable for the local context. Here, the individual overvoltage mitigation strategies are elaborated.

Sizes of storage and conversion infrastructure & PtX simulation settings

Next, specific characteristics as sizes, capacities and initial simulation volumes for the overvoltage mitigation strategies are defined. This is done based on information gathered through literature review (see chapter 3). These characteristics are used for the energy simulation in PtX.

4.3.5 Step 5: Concept development

In step 5, different *energy configurations (ec)* for overvoltage mitigation are developed. These consist of the individual strategies and combinations of these. Subsequently, different *electrification scenarios (es)* are developed in which these overvoltage mitigation strategies could happen. These scenarios are based on electrification measures that are likely to happen in the local context, as identified from the information gathered in step 2, 3 and 4. The electrification measures influence energy demands and levels of curtailment, and thus change the overvoltage mitigation strategies' effectiveness. All energy configurations will be assessed for each of the electrification scenarios. This gives the following amount of overvoltage mitigation strategies to assess:

$$ec \times es = oms, \tag{1}$$

where ec = amount of energy configurations, es = amount of electrification scenarios and oms = amount of overvoltage mitigation strategies.

4.3.6 Step 6: Evaluation

Assessment criteria evaluation per overvoltage mitigation strategy

After all energy configurations are defined, the energy flows of the overvoltage mitigation strategies are simulated in PtX. Subsequently, they are assessed using the defined assessment criteria: energetic implications, costs, spatial impact and social acceptance.

Conclusions

From the assessment, conclusions are drawn on the best mitigation strategies for the different electrification scenarios.

Recommendations

Based on the conclusions, recommendations are stated that can be used by local governments, policy makers, planners and DSO’s.

5. Case study: overvoltage mitigation strategies for Diamantbuurt, de Pijp, Amsterdam

In the previous chapter, the TENOMF was developed and its method was stated. In this chapter the TENOMF is demonstrated on a case study in Amsterdam. First, in section 5.1, the wider context and the problems with overvoltage that the city of Amsterdam will have are described. Then, in section 5.2, the TENOMF is implemented on the case study.

5.1 Context & problem Amsterdam

In order to achieve the goals set by the 2015 Paris Agreement, the Netherlands has to transition its energy infrastructure towards a renewable one. The country is divided up in Regional Energy Strategy regions, among one of them is Noord-Holland Zuid. Amsterdam, the capital, which is situated in this region, is already planning for a renewable energy based future. Within the city, a large share of their electricity should come from solar energy. The city's total PV potential on roofs is 1100 MW. Under the motto "no roof unused", their ambition is to realise half of this in 2030: 550 MW. Amsterdam's current electricity demand is 3.8 TWh. This is expected to increase towards 2030 due to the electrification of heat, mobility, industry and data centres. Current heat demand is 6.9 TWh, and is expected to decrease to 6.1 TWh towards 2030 (Decisio, 2020).

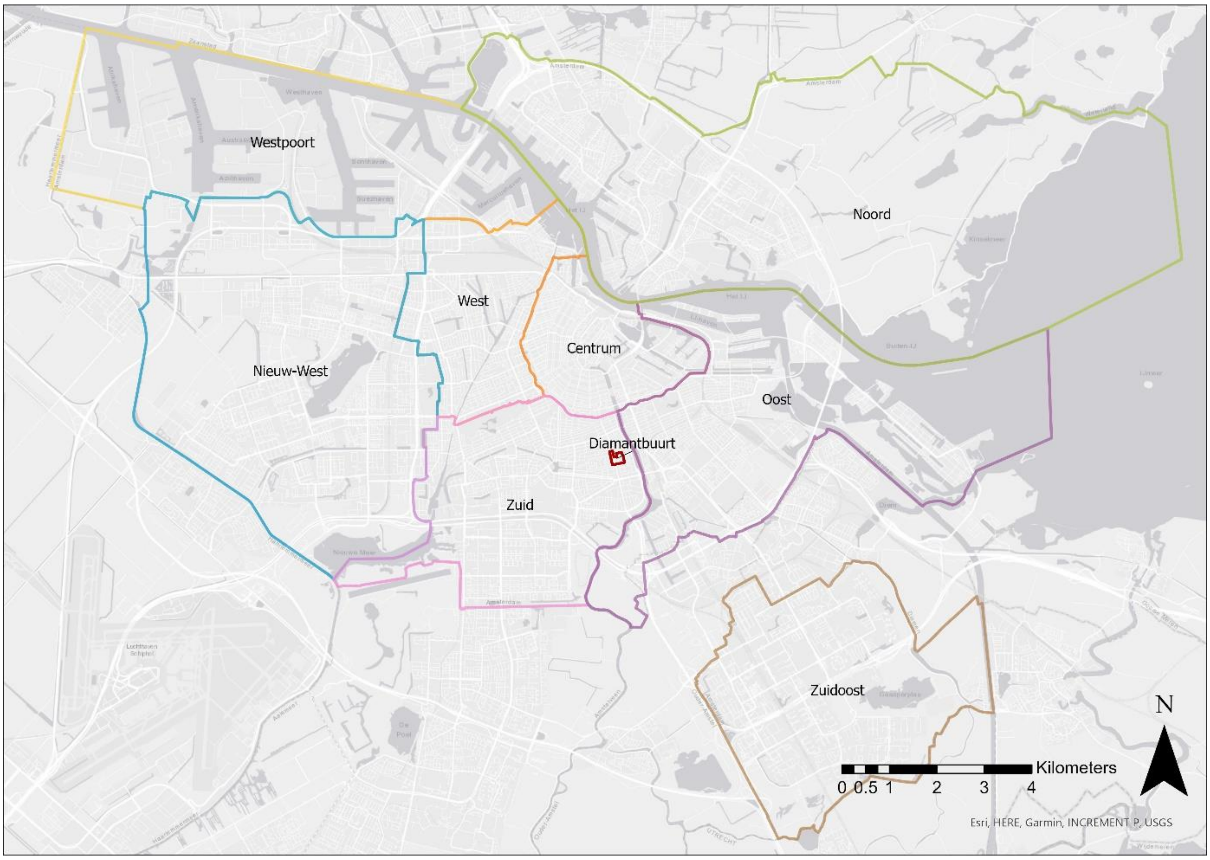


Figure 12: Amsterdam's districts and the case study area of Diamantbuurt.

5.1.1 Neighbourhood: Diamantbuurt, de Pijp, Amsterdam

In an (unpublished) study on the feasibility of these ambitions the solar energy potential of the Amsterdam south district has been modelled. According to Amsterdam's ambitions, if generation was distributed equally, the area would need to have 70 +- 20 MW of PV panels installed (M. Verkou, personal communication, March 25, 2021). It was shown that the capacity of solar energy for the south district would be 120 MW, a fair amount larger than the city's current ambitions. Although this should be taken lightly, since the distribution of renewable production might not be evenly spread over the city.

In the forementioned study, the PV generation capacity was coupled to the existing grid network in Amsterdam. It is shown that on peak hours of solar irradiance, on a sunny summers day, overvoltage of the grid occurs (M. Verkou, personal communication, March 25, 2021). Most of the existing electricity grids exist since decades and were not designed to handle the high amounts of electricity that our energy system is aiming to produce (Chaudhary & Rizwan, 2018). If the voltage is more than 10% over the nominal voltage level of the area, the inverters will switch off (M. Verkou, personal communication, March 25, 2021). Within the south district especially in the Diamantbuurt, an area in the south-east of de Pijp, overvoltage is expected to occur when PV panels will be widely implemented on its roofs (M. Verkou, personal communication, March 25, 2021). Therefore, the Diamantbuurt is chosen as case study to test the proposed framework for overvoltage mitigation, the TENOMF. In figure 12, the location of the case study area within Amsterdam can be seen. More specifically, the area itself with its buildings, the local electricity infrastructure, and the area's PV potential can be seen in figure 13.

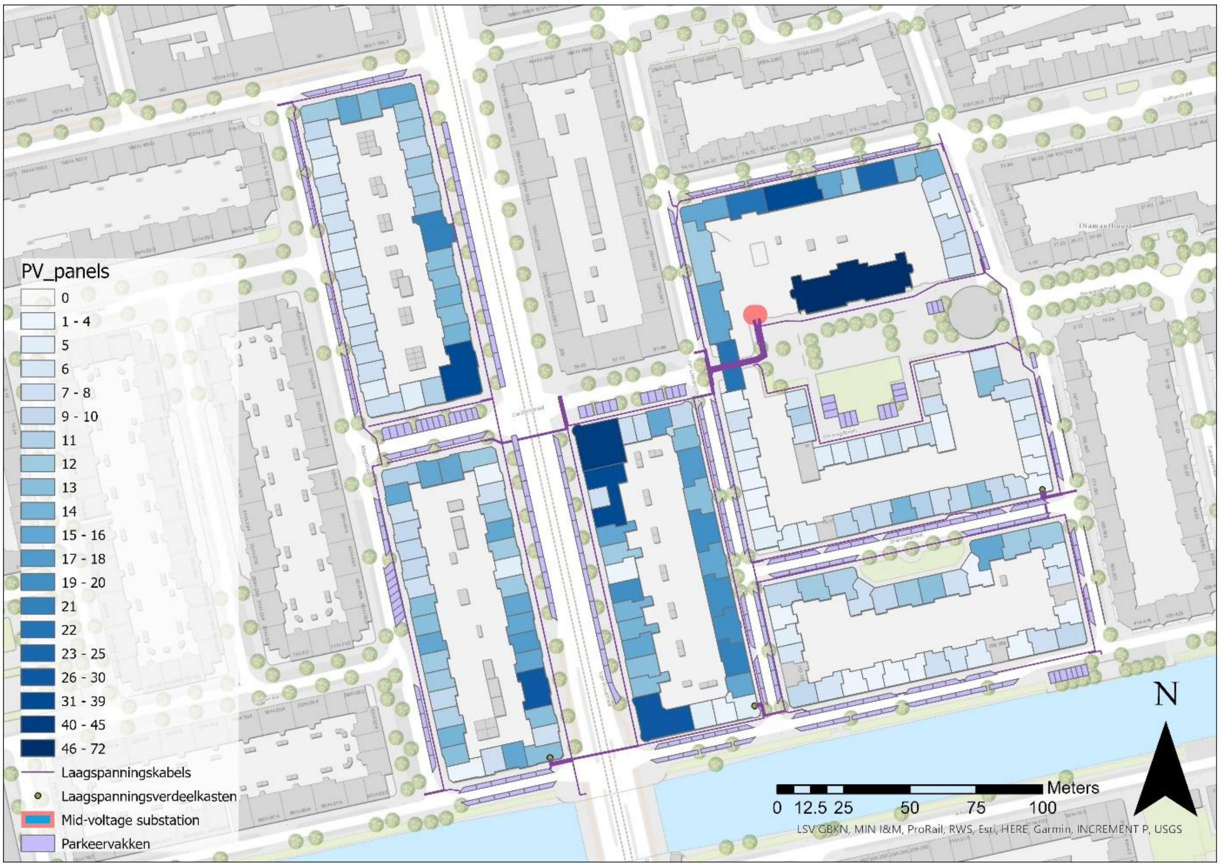


Figure 13: Case study, Diamantbuurt, de Pijp, Amsterdam. For the neighbourhood, the maximum potential of solar panels for each roof is visible (M. Verkou, personal communication, March 25, 2021). Furthermore, the grid-infrastructure and parking spaces can be seen.

5.2 Framework implementation

In this section, the TENOMF is implemented on a case study area that is likely to experience PV-induced overvoltage towards the future. Step-by-step it is described how the TENOMF should be used.

5.2.1 Step 1: Assessment criteria

The energetic, financial, spatial and social assessment criteria as described in section 4.3.1 are used in the case study.

5.2.1.1 Energetic implications

The assessment of energetic implications is done according to the method described in section 4.3.1.

PtX model

The parameters used in PtX for each of the overvoltage mitigation strategies, as well as default parameters, can be found in Appendix D.

5.2.1.2 Costs

Costs are calculated for 2030 as Amsterdam is not yet in a scenario where the whole city is full with solar panels. PV induced overvoltage mitigation is thus still a future task. For this reason, as well as the fact that some costs like hydrogen infrastructure and volumetric prices will change greatly, looking at a future scenario gives a more realistic comparison about the actual feasibility of the mitigation strategies and their involved technologies. This does cause extra uncertainties. The effect of these uncertainties is analysed in a sensitivity analysis.

An overview of costs for the different infrastructures (CAPEX & OPEX) and energy import prices can be seen in Appendix C. These costs were validated with E. van der Roest (personal communication, 19 October, 2021) The assessment of costs is done according to the method described in section 4.3.1.

5.2.1.3 Spatial use

The needed space for infrastructure of the mitigation strategies is based on the literature review stated in section 3.4.3. The assessment of spatial use is done according to the method described in section 4.3.1.

5.2.1.4 Social acceptance

The social acceptance criteria of the different mitigation strategies are based on the literature review stated in section 4.1.2. The assessment of social acceptance is done according to the method described in section 4.3.1.

5.2.2 Step 2: Neighbourhood description

The case study area of Diamantbuurt is defined in this subchapter. First the spatial boundaries are described, then the neighbourhoods characteristics and demographics are stated. Lastly, the type of buildings and its functions are described.

5.2.2.1 Spatial boundaries

As the grid in Amsterdam is meshed, it is not straightforward to depict the service area of a mid-voltage substation: there is no clear service area as all mid-voltage substations are interconnected by the low-voltage grid. However, to simulate overvoltage potential for a specific mid-voltage substation with the PtX model, boundaries are needed. The PtX model calculates overvoltage based on the capacity of a mid-voltage substation, not taking into account losses due to transportation and detailed electro-technical characteristics. Therefore it is not possible to simulate meshed grids. Moreover, the overvoltage simulation is less realistic. However, for the purpose of showing mitigation strategies, it suffices. The spatial boundaries of the service area of the mid-voltage substation in the case study are estimated by looking at the placement of all mid-voltage substations within the surrounding region, and then distributing equal service areas over all substations, while assuming that all buildings within one housing block are connected to the same mid-voltage substation. As the purpose of the case study is to test the effectiveness of the TENOMF, not the exact simulation of the electrical grid and the overvoltage potential, it suffices to estimate the boundaries of the service area. If the overvoltage modelling is needed in detail, technical modelling is required as can be carried out by DSO's. This will be discussed further in the discussion in chapter 6.

The spatial boundaries of the service area of the mid-voltage substation within the Diamantbuurt used for the case study can be seen in figure 13. The area consists of six housing blocks, in connection to one mid-voltage substation through the low-voltage network.

5.2.2.2 Neighbourhood characteristics & demographics

The Diamantbuurt is a protected township area with historical buildings in the 'Amsterdamse school'-style. It is a very urbanised neighbourhood in the south district of Amsterdam. On a scale of 1 (very strongly urbanised, >= 2500 addresses/km^2) to 5 (not urbanised), it scores 1 (CBS, 2019b). Furthermore, it is a residential area. This entails the area to have little free space for the implementation of new-built (overvoltage mitigation) infrastructures. The case study area is split up by a busy road with shops and restaurants on both sides. For the simulation, it is assumed that there are only shops, no restaurants or other consumption-type businesses. This is done because otherwise the demand-profiles and housing typologies within PtX would become too complex. On this road, the van Woustraat, there are tram and bus lines with a stop. The case study area is close to the Amstel and borders on a canal, the Amstelkanaal. In the middle of one of the houseblocks, on Smaragdplein, there is a square with a sporting pitch.

It table 2, the socio-economical demographics of the neighbourhood are stated. The age distribution within the Diamantbuurt is fairly similar to the average distribution in the Netherlands. Slightly more than half the inhabitants has a migration-background, of which 65% is non-western. The majority of residences are rental: 84%. Almost two-third of the houses is owned by a housing corporation: 64% (CBS, 2019b). This should be noted when making policy: not inhabitants but corporations and property owners should be addressed for the installation of residential overvoltage mitigation infrastructure. On average, a household in the Diamantbuurt contains 1.7 people (CBS, 2019b). As the apartments are not inhabited by large families, it means more residential space might be available for implementing overvoltage mitigation infrastructure as batteries or heat pumps. Furthermore, on average 0.3 cars are owned by a household. 80% percent of these cars runs on gasoline, 20% is powered in another way: diesel, LPG, electrical or other (CBS, 2019b). For the case study it is assumed that all non-gasoline cars are powered electrical: 0.06 EV's are owned per household in the neighbourhood. There are 695 households. Thus, the neighbourhood currently hosts 42 EV's. Currently, only 4 EV charging stations are present within the case study area. However, for the simulation it is assumed there is charging infrastructure available to charge all of them at the same time. In the case study area, as can be seen in figure 13, there are 303 parking spaces. If these were all occupied by residents, it would mean that a household would own 0.436 cars, or that 43.6% of the households would own a car. Thus, currently with the household car-own rate of 0.3, not all parking spaces are used (by residents). The municipality of Amsterdam ambitions to have only emission-free modes of transportation within its city towards 2030. This would mean that all cars would have to be EV's (Gemeente Amsterdam, z.d.-c). This also accounts for boats. Currently, there are two electric boat charging stations close by (<50m) the case study area, on the Amstelkanaal (Gemeente Amsterdam, z.d.-b).

Most residents have a degree in higher education (38%), 35% is mid-educated and 26% followed lower-education. Compared to the Dutch average, as can be seen in table 2, there is a slightly higher education-rate in this neighbourhood. At the same time, the employment rate is lower than average, as well as the average income of Diamantbuurt's residents (CBS, 2019b). This needs to be considered when making decisions on overvoltage mitigation strategies in terms of financial implications.

age (%)	<14 yr	15-24 yr	25-44 yr	45-64 yr	>65 yr
Diamantbuurt	12%	12%	33%	27%	15%
Netherlands	16%	12%	25%	28%	19%

migration background	yes	no
	55%	45%
non-western	65%	
western	35%	

houses	rental	owner-occupied	owned by housing corporation	
	84%	16%	64%	
households				
people per household	1.7			
cars per household	0.3			
	80%	gasoline		
	20%	non-gasoline (diesel, lpg, electric, other)		

level of education	low	mid	high
Diamantbuurt	26%	35%	38%
Netherlands	28%	41%	30%

employment	Diamantbuurt	NL
employment rate (%)	62%	69%
average income (€/yr)	€ 25,100.00	€ 27,000.00

Table 2: Socio-economical demographics of the Diamantbuurt (CBS, 2019b).

building type	**energy label** (average)**	**number**	**area [m2]**	**electricity demand*¶ [kWh]**	**space heating: nat. gas demand*¶ [GJ]**	**space heating: heat demand [GJ]**	**tap water: heating dem. [GJ]**	**Tap water: nat. gas dem. [GJ]**	**Efficien-cy gas boiler¤**
Appartement, 1 floor	D	594	80	1620	23.91	21.52	4.95	5.5	0.9
Appartement, 2 floors	D	101	145	1910	29.0	26.10	5.6	6.2	0.9
Shop, 1 floor	C	37	80	1630	21.84	19.66	1.5	1.7	0.9
Day-care/community centre	G	2	750	3410	67.22	65.88	15	16.7	0.98
Total addresses	**D**	734	66625	1 222 320	18 074.06	16 278.16	3591.4	3989.5	0.9
Total buildings/roofs		204							

Table 3: Diamantbuurt case study area: building typologies and their characteristics. *(CBS, 2019b), **(Esri Nederland, 2020), ¤(CE Delft, 2019), ¶(CBS, 2019a)

5.2.2.3 Buildings & functions

As stated before, Diamantbuurt is a neighbourhood with mainly a residential function. Other than residential, also shops, a day-care and a community centre is present. In the case study area, four types of buildings have been characterised: apartment with 1 floor, apartment with 2 floors, shop (1 floor) and children's day-care/community centre. In table 3 their characteristics are shown. In total there are 734 addresses within 204 buildings. This number, as well as the area for each of the typologies, is an estimation coming forth of a sight visit to the area while looking at the type and functionality of the buildings, looking at the amount of doorbells within each building and exploring geographical information services on the neighbourhood.

In reality there are more different types of apartments, shops and other categories. However, these four categories are chosen as the simulation in PtX quickly gets very complex when extra, specific categories are added. Moreover, the goal is to approximate reality in a simulation as to test the TENOMF.

The energy labels are averaged for each building type coming forth of an Esri geographical information service dataset (Esri Nederland, 2020). Energy labels define the isolation rate of a building. This influences space heating demand and capacity needed for a heat-pump operate efficiently. In figure 14, the energy labels for the buildings in the neighbourhood can be seen.

All buildings in the case study area, except one small block in the mid-west (on the Smaragdplein), are built between 1921 and 1929. See Figure 15. The forementioned row is built in 1930-1932. Heating demand is depended on the construction year. Therefore, again, for the reason of not overcomplicating the PtX simulation, it is assumed that all buildings were constructed before 1929.

Furthermore, all roofs within the case study area are flat except the roofs on the same block (with the 1930-1932 construction year) in the mid-west. For the simulation all roofs are assumed to be flat. Therefore, the solar panels can be placed in the same angle (25 degrees), and oriented towards the same, optimal, direction: south.

5.2.3 Step 3: Energetic conditions

In step 3, the energetic conditions of the case study area are described. First the energy infrastructure present in the neighbourhood is stated, then the area's energy demand is evaluated. Lastly, the potential solar supply of the case study area is defined, as well as corrections and assumptions necessary for the PtX simulations.

5.2.3.1 Energy infrastructure

The energy infrastructure of the case study area Diamantbuurt encompasses an electricity grid and a natural gas network. These are described here.

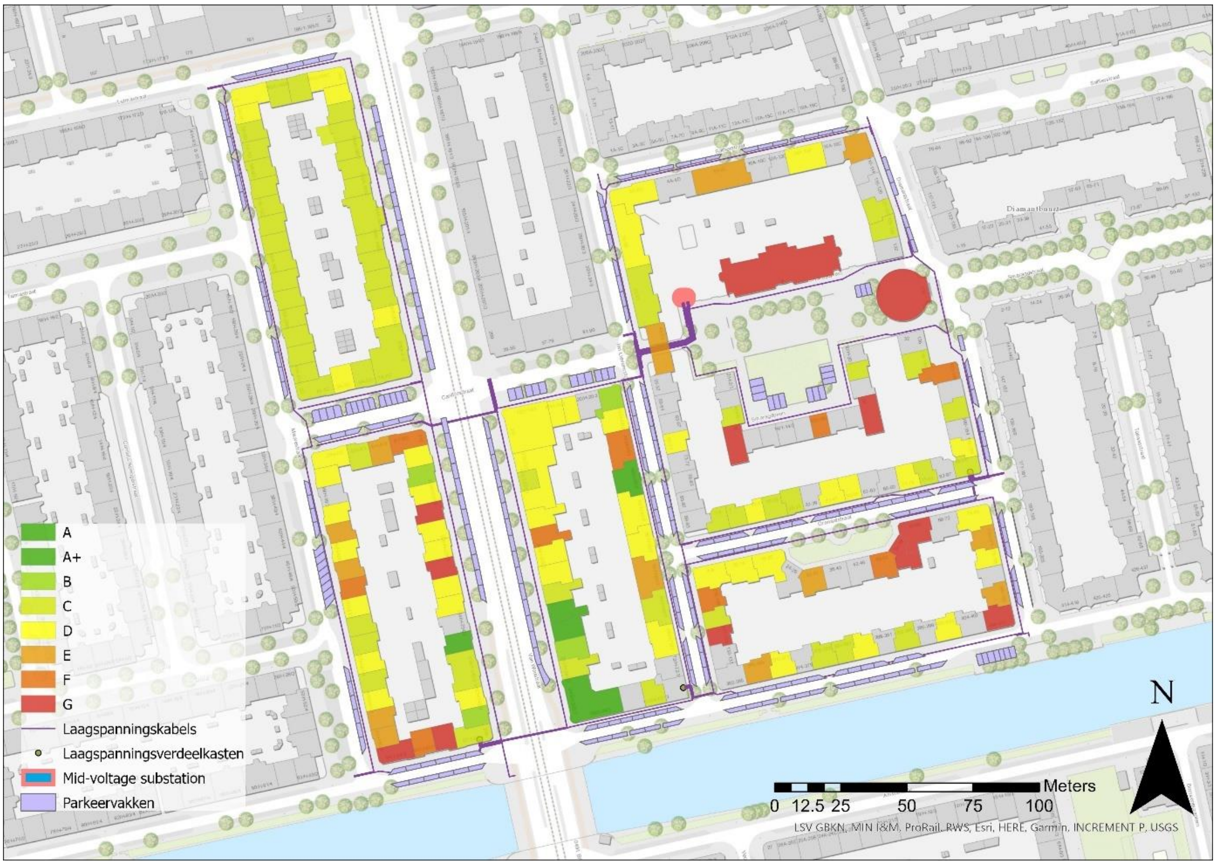


Figure 14: Case study area Diamantbuurt: energy labels.

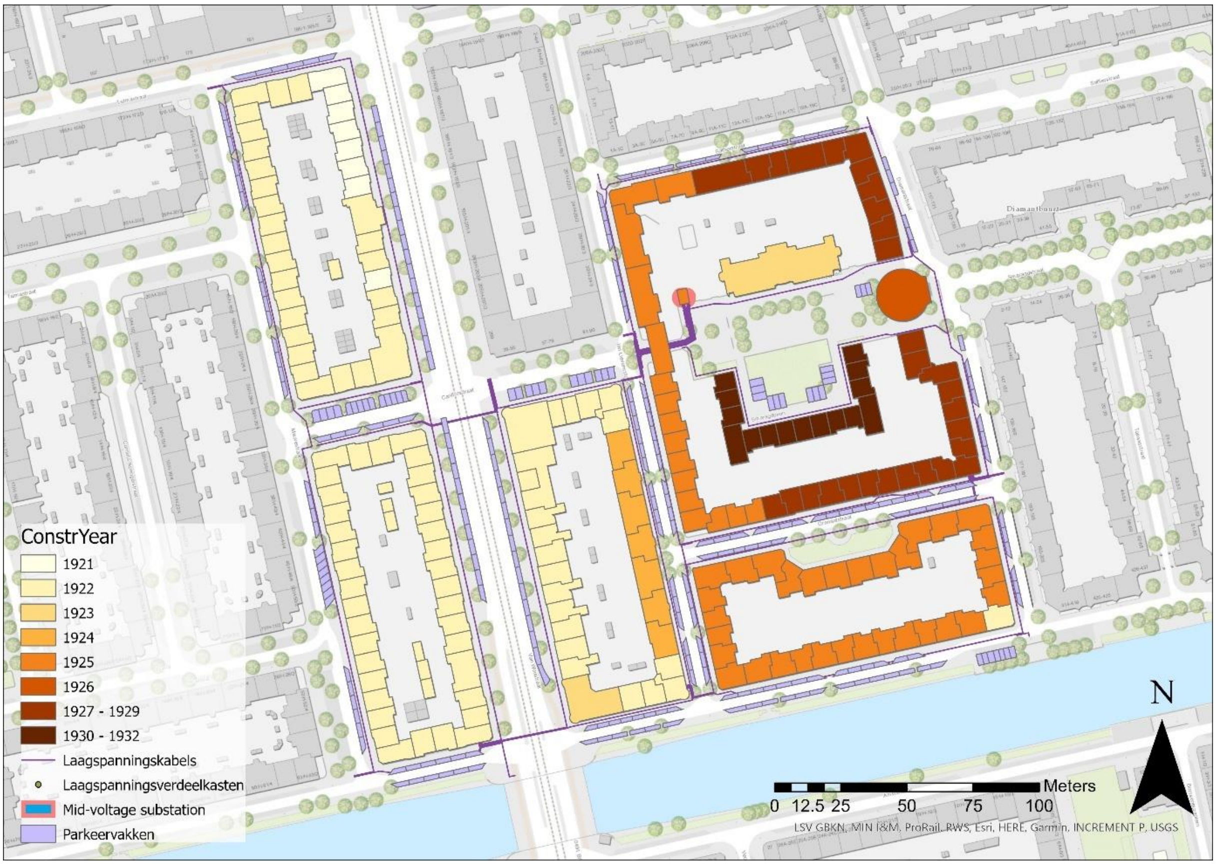


Figure 15: Case study area Diamantbuurt: building construction year.

Electricity grid

In Amsterdam, and thus also in case study area Diamantbuurt, the electricity grid is meshed (P. Bonhof, personal communication, July 19, 2021). This is visible in the overview of the mid- and low-voltage grid of de Pijp in figure 16. Multiple mid-voltage substations exist within each neighbourhood. The mid-voltage substation in the case study area Diamantbuurt, of which the grid overview can be seen in figure 17, has a capacity of 630 kVA (P. Bonhof, personal communication, July 19, 2021). As stated before in 5.2.2.1, the service area of the mid-voltage substation within the case study area is estimated. A meshed grid does not have a bounded service area, however this is necessary for the simulation. The area was depicted based on the spatial division of the mid-voltage substations in the neighbourhood, as well as on the estimated overvoltage potential of the housing blocks as discussed and validated with M. Verkou (PVMD group, TU Delft) (personal communication, March 25, 2021).

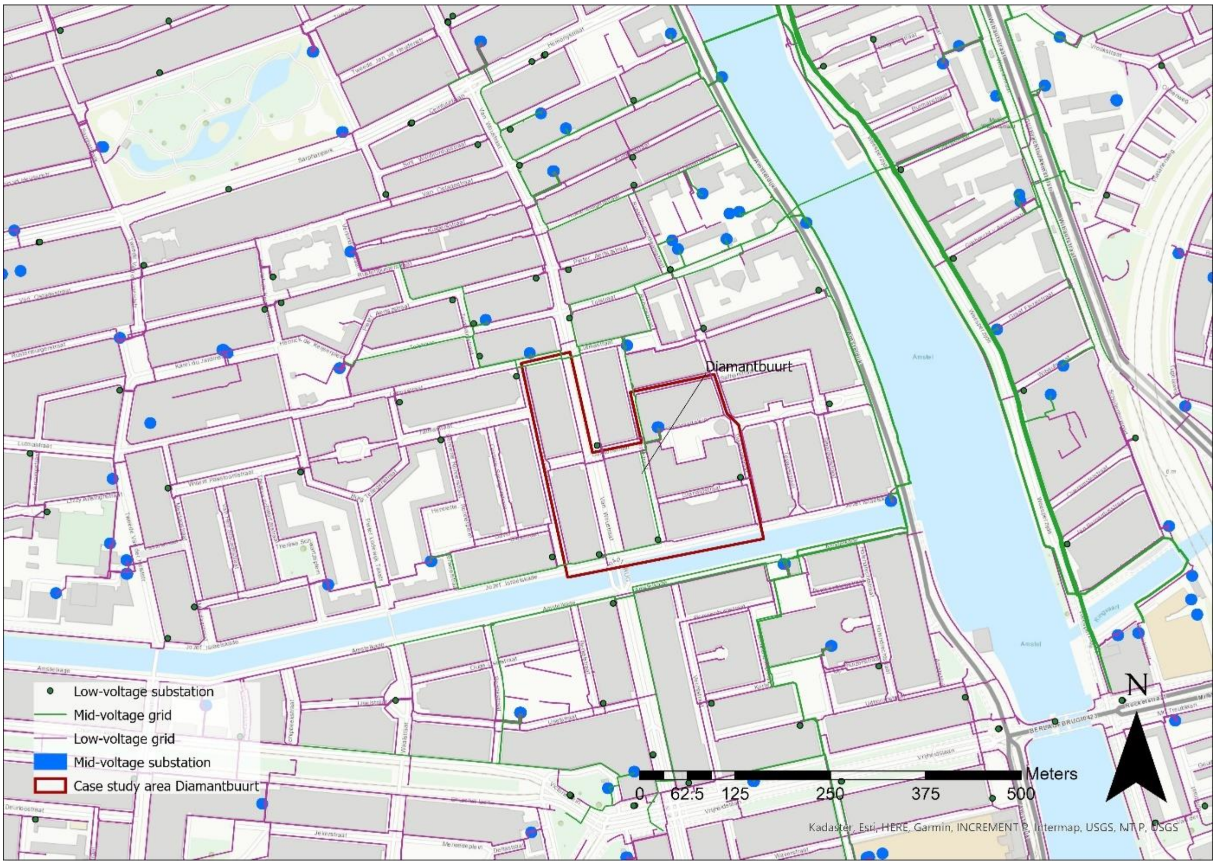


Figure 16: Grid infrastructure, De Pijp Amsterdam.

Grid for heating: gas or heat

In the case study area Diamantbuurt currently no (alternative) heat network exists (CBS, 2019b). All buildings are connected to the natural gas grid. Space heating demand is fulfilled with natural gas. For the simulation it is assumed that per default for all households natural gas is used for cooking. As the buildings in the case study area currently on average have energy label D, it is not feasible to implement a heating network. Heat pumps would need very large capacities to fulfil space heating demands. In order to make use of such heating technologies, the isolation of the buildings would need to be upgraded to at least energy label B (CE Delft, 2019).

Figure 17: Grid infrastructure, case study area Diamantbuurt.

5.2.3.2 Energy demand

The neighbourhoods electricity and heating demand is described in this section.

Electricity

The average yearly electricity demand of an apartment in the Diamantbuurt is 1620 kWh (CBS, 2019b). The electricity demands of each of the building typologies can be seen in table 3. The total electricity demand for the households (without electric cooking) is 1222 MWh.

For the different building typologies, different standard electricity profiles are taken from NEDU (2018). For apartment 1 floor and apartment 2 floors, the profile E1A (=< 3 x 25 A) is used. For shops profile E3B (> 3 x 80 A, 2000-3000 hours). Profile E3C (> 3 x 80 A, 3000-5000 hours) is used for the community centre and day-care.

Electrical vehicles consume 20 kWh/100 km and drive an average distance of 13000 km per year (in the Netherlands), therefore they have a yearly electricity demand of 2600 kWh (CBS, 2012; Canals Casals, Martinez-Laserna, Amante Garcia & Nieto, 2016). As described in section 5.2.2.2, there are currently 42 EV's in the case study area. 60 percent of their energy use is assumed to be charged at home: 1560 kWh/year. The total electricity demand for EV's in the case study area currently is 66 MWh.

Summed up, a household living in a 1 floor apartment with an electrical vehicle has an average yearly electricity demand of 4220 kWh. The yearly electricity demand of the case study area Diamantbuurt is: 1222 MWh (household) + 66 MWh (EV) = 1288 MWh (see table 4).

For a simulation with an energy configuration where cooking demand is taken electric, demand is as follows: yearly electric cooking demand is 175 kWh/year/hh (Milieu Centraal, z.d.). This is assumed to be similar for the apartments as well as the community centre and day-care (see Appendix B). The shops have no cooking demand. Thus, if all cooking is done electrical, the total yearly electric cooking demand is 122 MWh. In that case, a household in a 1 floor apartment with an EV and electric cooking facilities has an average yearly electricity demand of 4395 kWh. The total yearly electricity demand of the case study area Diamantbuurt is then 1222 MWh (household) + 122 MWh (cooking) + 66 MWh (EV) = 1410 MWh (see table 4).

Heat

The average yearly natural gas demand of an apartment in the Diamantbuurt is 940 m^3 (CBS, 2019b). This includes tap water demand, space heating and cooking. For heating the apartment, after conversion to gigajoules, 23.91 GJ of natural gas is needed. Taken that the efficiency of a gas boiler in an average apartment is 0.9, an apartment has an average yearly heating demand of 21.52 GJ (CE Delft, 2019). The heating demands and gas boiler efficiencies of the other building typologies can be seen in table 3. The base temperature is the air temperature outside of a building below which the building needs heating or above which a building needs cooling. For the simulation in PtX, the base temperature for heating is taken 15.5 °C and for cooling 22.0 °C, similar to the base temperature as is mostly used in the UK (Spinoni, Vogt, Barbosa, 2014). The total space heating demand of the case study area Diamantbuurt is 16.3 TJ, or 4522 MWh. In natural gas, this demand is 18 TJ, or 5021 MWh.

The tap water demand of a 1 floor apartment is 4.95 GJ (CE Delft, 2019). The tap water demands of the other building typologies can be seen in table 3. The total tap water heating demand of the case study area Diamantbuurt is 3.6 TJ, or 998 MWh. In natural gas demand this is 4.0 TJ, or 1108 MWh.

Currently, no houses in the Diamantbuurt are connected to alternative heat sources: all heating demand is fulfilled with natural gas (CBS, 2019b).

Cooking in the case study area Diamantbuurt is currently done using natural gas. Yearly cooking demand is 37 m3/year/hh, or 325 kWh/year/hh (natural gas: 8.79 m3/kWh) (Milieu Centraal, z.d.; RVO, 2020). Then the total yearly cooking demand for the case study area is 221 MWh.

In total, the yearly heating demand of the case study area is 5741 MWh (see table 4). Heating demand fulfilled with natural gas is 6350 MWh.

		Demand per category [MWh]	**Demand per energy source [MWh]**	**total energy demand [MWh]**
electricity	household	1222	1288	7029
	EV	66		
heat	space heating	4522	5741	
	tap water	998		
	cooking	221		

Table 4: Energy demands of the case study area Diamantbuurt.

5.2.3.3 Solar supply

Currently, within the case study area of Diamantbuurt only one building has solar panels installed on its roof. This roof holds 5 solar panels of which the characteristics are unknown.

The maximum potential of PV implementation (in terms of physical space) of the case study area is obtained by using data as obtained from M. Verkou (PVMD group, TU Delft). The numbers were validated with Verkou. Based on the physical space available for each roof, the maximum potential of each roof for Amsterdam has been calculated by M. Verkou (personal communication, March 25, 2021). This was done taking the following assumptions: 1) On flat roofs all panels are south oriented with an angle of 15 degrees and a row distance of 70 cm. 2) Solar panels with a performance of less than 650 kWh/kWp are disregarded because they will not be financially viable. 3) Buildings with a hosting capacity of less than 3 panels are disregarded because they will not be financially interesting. As validated with M. Verkou, for the case study area of the Diamantbuurt the PV capacity and (yearly) energy yield can be seen in figure 18 and figure 19. In figure 13 it is visible how this translates to a number of PV panels per roof. The maximum hosting capacity and energy yield of the case study area as a whole is: 2059 panels, 679 kW and 618 MWh/year (see table 5). For these calculations, a solar panel with the following characteristics is used (M. Verkou, personal communication, March 25, 2021; JA Solar, 2019):

- Solar panel: JA Solar JAM60S17 330/MR
- Rated capacity: 0.330 kWp
- Measurements: 1689±2mm × 996±2mm × 35±1mm

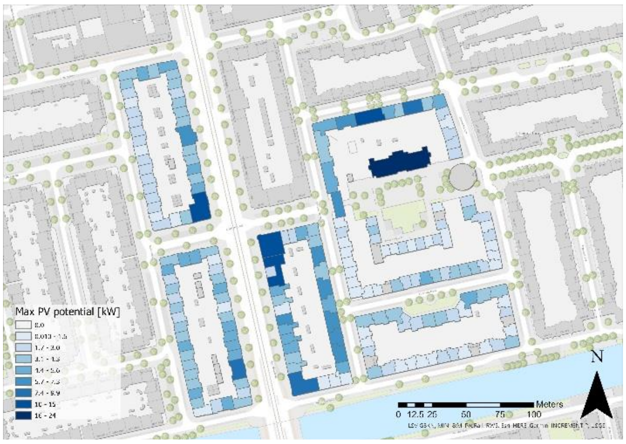


Figure 18: Maximum PV capacity case study area Diamantbuurt [kW].

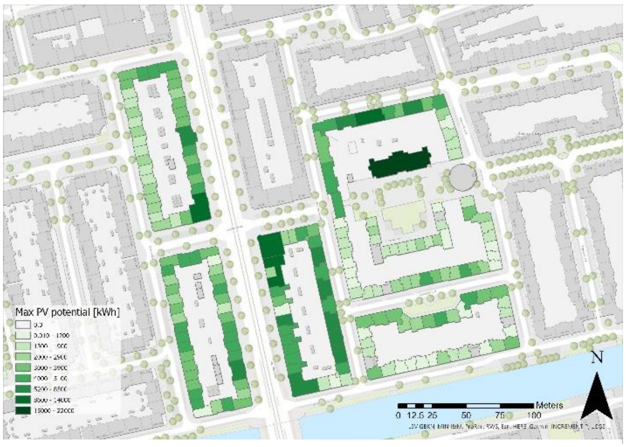


Figure 19: Maximum yearly PV energy yield case study area Diamantbuurt [kWh].

PV panels #	rated capacity [kWp]	energy yield [MWh]
2059	679	618

Table 5: Maximum PV potential of the case study area Diamantbuurt (M. Verkou, personal communication, March 25, 2021).

Solar supply PtX

As the aforementioned calculations were done based on physical space available, solar potential will grow with improved solar panel performance. Therefore, for the case study simulation with PtX, state-of-the art solar panels are used with a higher rated capacity: 405 Wp. The characteristics of the solar panel used for the simulation with PtX can be seen in table 6.

PV panel	**REC Alpha Pure Black 405 Wp***
nominal cell temperature [°C]	44.0
surrounding temperature of defined NOCT [°C]	20.0
radiation of defined NOCT [kW/m2]	800.0/1000
efficiency panel at maximum temperature [%]	21.9
temperature coefficient of power [%/°C]	-0.26
STC temperature [°C]	25.0
transmission of panel	0.9
rated capacity (1 panel) [kWp]	0.405
rated capacity (m2) [kWp/m2]	0.2189
performance in year 1 [%]	98
yearly derating factor [%]	0.25
STC radiation [kW/m2]	1.0
length [mm]	1821±2.5
width [mm]	1016±2.5
thickness [mm]	30
Surface panel [m2]	1.85

extra losses (cables, temperatures, dust etc.)	0.9
latitude (case study area)	52.351
orientation (south) [°]	180.0
angle panel [°]	25.0

simulation period	01/09/2018 - 31/12/2019
assessment period	01/01/2019 - 31/12/2019

Table 6: Solar panel and PV generation characteristics for the PtX simulation of the case study area Diamantbuurt. *(REC, 2021)

Using the capacity of solar panels as stated in table 5, the calculations of Verkou showed overvoltage larger than 10 percent for case study area of Diamantbuurt (personal communication, March 25, 2021). However, when simulating the same amount of panels (2059 panels) in PtX, with the characteristics of table 6 (405 Wp), no overvoltage is found. The total rated capacity is 834 kWp, the yearly energy yield 927 MWh (simulated over the year 2019). The fact that there is no overvoltage could have various causes arising from the way the PtX model simulates:

1. The solar irradiation and output data of PtX is hourly. For this reason, the level of detail is lower. The simulation potentially misses high solar irradiance peaks due to the fact that solar irradiance is highly fluctuating.
2. The service area of the MVS within the case study area of Diamantbuurt is estimated (see section 5.2.2.1). In reality the LV grid in Amsterdam is meshed, making it difficult to bound the

service area. This has consequences for the precision of the overvoltage calculation of the case study area in the PtX model.

3. The criterium for overvoltage in the PtX model is that it occurs when the capacity of the MVS is exceeded. In reality, this has a more complex electrotechnical base and could happen in an earlier stage: overvoltage has to do with rapid and/or significant rising voltage-levels. This enhances changes in power quality and bi-directional power flow (Hao, et al., 2016).

4. PtX does not take into account electricity transport distances from generation to MVS. Transportation can influence power quality and is thus of importance for the calculation of overvoltage (Aziz & Ketjoy, 2017; M. Verkou, personal communication, March 25, 2021).

As the goal of this case study is not to calculate the exact overvoltage of the neighbourhood, but to test the proposed framework for the mitigation of overvoltage, it suffices to use the PtX model and its less realistic grid calculations for the simulation. However, to test the framework a case study area is needed that shows overvoltage so it can be tested how different mitigation strategies have an effect on the overvoltage. Therefore, the capacity of PV panels in the case study area is increased up to 3089 panels (1.5x the areas maximum physical hosting capacity). The rated capacity of these panels is 1251 kWp, almost twice the rated capacity with which M. Verkou simulated (personal communication, March 25, 2021). The aforementioned limitations to the overvoltage simulation were validated with M. Verkou (PVMD group, TU Delft) and P. Bonhof (Alliander).

PV panels #	rated capacity [kWp]	energy yield [MWh]
3089	1251	1393

Table 7: Amount and rated capacity of PV panels for the PtX simulation of the case study area Diamantbuurt.

As there are 204 buildings in the case study area, 3089 panels in the case study area entails each roof to host around 15 panels (in case they would be distributed homogenously and differences between roof surfaces are disregarded); around 4.2 panels per address. As stated before, for the simulated case study, these panels are all placed on flat roofs with a south direction, in an angle of 25°. In figure 13 it can be seen that the building in which the day care and community centre are located can host 72 panels: 36 on the community centre and 36 on the day care. If this is multiplied by 1.5 both roofs can host 54 panels. As this is such a large difference with the rest of the buildings, the amount of panels per address is adjusted to allocate for this: community centre and day care both host 54 panels, all the other addresses host (the theoretical amount of) 4.1 panels.

In the theoretical, ideal case, if all solar generated energy supply could directly be used for the demand (without conversion or storage), local PV generation would account for 20% (1393 / 6930 * 100% = 20%, see table 4 and 7) of the case study areas' demand.

5.2.4 Step 4: Neighbourhood overvoltage mitigation potentials

In step 4, the neighbourhood overvoltage mitigation potentials are described. In order to do this, first local considerations, policies and ambitions are evaluated. Subsequently, the potential overvoltage mitigation strategies fitting the local environment of the case study area Diamantbuurt are defined. Likewise, the unsuitable strategies are stated. Lastly, the sizes of the depicted overvoltage mitigation strategies as well as PtX simulation settings are characterised.

Neighbourhood considerations & local policies and energy transition ambitions

In the case study area, on Smaragdplein, there is spatial potential for the implementation of collective mitigation strategies. Either on the square or for instance underneath the sporting pitch infrastructure (e.g. batteries, electrolysers and fuel cells and types of energy storage etc) can be implemented.

As the buildings in the case study area are poorly isolated (label D on average), heat pumps currently are not considered economically viable. Moreover, no aquifer storage is available in the region. The neighbourhood is protected township, therefore it is also unclear to what extend isolation is possible. In case the isolation grade would be upgraded and heat pumps would be feasible, then the canal (Amstelkanaal) bordering the case study area could be used as a source of heat (although storing heat is not possible in the canal).

Another potential coming from this canal is the fact that it hosts many recreational and tour boats. Currently most of these boats are sailing on fossil fuels, however, from 2030 onwards all boats within the city of Amsterdam are obliged to be electrical (Gemeente Amsterdam, z.d.-b). Close (<50m) to the case study area, on the canal, an electric charging station for boats is located. The city is planning to implement more of these stations in the near future (Gemeente Amsterdam, z.d.-b). Recreational boats often sail in summer when the sun is out, meaning that they are being used in the period when curtailment mitigation is most needed. Thus, if such charging stations would be paired with a battery, boats could be charged at the end of the sunny day using excess solar energy, mitigating curtailment. The charging station close to the case study area could be fed in with solar energy from the case study area and new charging stations could be implemented in the case study area. This is not simulated with PtX as the charging patterns cannot be found.

Similarly, the municipality ambitions all vehicles to be emission free towards 2030 (Gemeente Amsterdam, z.d.-c). Therefore, the share of EV's should grow rapidly in the coming years and more charging infrastructure is likely to be installed. This can be used as extra energy storage infrastructure, and is a potential overvoltage mitigation strategy.

As the Netherlands has a very extended natural gas grid, there is potential to retrofit the network and use it as a hydrogen transport system. Therefore hydrogen is an interesting energy carrier for this case study area. Especially as it helps reducing the pressure on the electricity grid that rises due to the electrification of energy demands.

The municipality of Amsterdam ambitions to dismiss all natural gas use in the city by 2040 (Gemeente Amsterdam, z.d.-a). This aim matches with electrifying heat purposes or with using hydrogen as heating gas. In figure 20 the plans for heating the Diamantbuurt emission free can be seen: although the surrounding neighbourhoods will be connected to a heat network, the Diamantbuurt is planned to be heated by 'sustainable gas'. Motivations for using 'sustainable gas' instead of a heat network are that in such areas the buildings are in such a state (too old) that renovation towards a degree of isolation, where a heat pump can become financially feasible, is too expensive. The aim is therefore to upgrade the isolation grade to such a level that the heating demand (gas usage) is reduced by 70% (AT5, 2021). To stimulate citizens to transition into a sustainable way of heating, the city hands out subsidies: a maximum of €5000 if citizens choose to go along with the proposed sustainable heating plans for their neighbourhood (e.g. 'sustainable gas' in the Diamantbuurt), and €3000 if they choose to go for an alternative (Gemeente Amsterdam, z.d.-d). This to promote collective solutions. Reviewing these ambitions, it is clear that using hydrogen as an alternative for natural gas suits the case study area of Diamantbuurt. Therefore hydrogen conversion, and using hydrogen boilers for heating purposes, has potential to be a fitting overvoltage mitigation strategy for this neighbourhood. Especially since subsidies can help financing the costs.

Figuur 20: Amsterdam's natural gas-free plans for the Diamantbuurt and its surrounding neighbourhoods (Gemeente Amsterdam, z.d.-a).

Potential overvoltage mitigation strategies Diamantbuurt

Below, the potential overvoltage mitigation strategies for the Diamantbuurt are described.

Home battery (Bh): Home batteries can be installed in the buildings in the case study area Diamantbuurt. They take up little space.

Collective battery (Bc): Also a collective battery could be implemented in the neighbourhood. This relatively cheaper than home batteries, however, compared to implementing home batteries in all buildings, less capacity can be implemented for collective batteries.

Hydrogen (Hy) (electrolyser, fuel cell, storage, hydrogen boiler): Hydrogen has potential in the neighbourhood as it can be stored in tanks and the natural gas infrastructure can be retrofitted to host hydrogen, or in the transitional phase (when still little hydrogen is available), even to host a mixture of natural gas and hydrogen. When hydrogen is used, it makes sense to also install a fuel cell as to be able to convert the hydrogen back into electricity when needed. Furthermore, storage infrastructure is needed to make use of the potential of hydrogen to store energy over an extended period of time without big losses (if storage is sealed well). Therefore, when the mitigation strategy of hydrogen conversion is chosen, an electrolyser, fuel cell and storage tank will be used. In this strategy also hydrogen boilers will be used for heating the built environment: tap water and space heating.

An advantage of using hydrogen for heating is that it reduces the need for further electrification of the current natural gas demand, which would be the case if heat pumps and electrical cooking would be used. For the implementation of hydrogen boilers, the natural gas infrastructure has to be retrofitted. This will only be done if there is enough market potential: the business case has to make sense. Therefore, retrofitting the natural gas network will not be realised solely for the purpose of mitigating

PV overvoltage. Then too little hydrogen would be produced. This means that either hydrogen infrastructure needs to be available: then hydrogen can be imported and exported. Or hydrogen has to be used in a mixture with natural gas: hydrogen can be transported through the natural gas grid in a mixture with natural gas. Such a mixture is also a possibility for the transitional phase towards a widely implemented hydrogen economy (IRENA, 2020). As the municipality ambitions to use 'sustainable gas' as alternative heating source for natural gas, retrofitting the gas network for hydrogen purposes is an interesting alternative. With that ambition in mind, hydrogen import would be necessary. Therefore, in the case study simulation in PtX hydrogen import is allowed with the hydrogen configurations.

Electrical Vehicles current (EVcurrent): Currently the neighbourhood hosts 42 EV's, 6 percent of households owns an EV. This is extra electrical storage capacity that is easy to realise with the implementation of 42 charging connections, or 21 charging stations (each containing two sockets). These still need to be installed. Currently, 2 charging stations, with each 2 charging connections (thus 4 cars can be charged in total), are located in the case study area (Gemeente Amsterdam, z.d.-c)), however, for the simulation it is assumed that this infrastructure is already there and the 42 EV's can be charged in the case study area (42 charging connections are present). Therefore, a minimum storage capacity coming from EV's is available in every simulated energy configuration.

Electrical Vehicles upscaled (EVmax): If all cars in the neighbourhood are electrical vehicles, 43.6% of the households would own an electrical vehicle: 303 EV's. In case all parking spaces would have charging infrastructure, this storage potential could be used as extra solar energy storage and thus mitigation. This mitigation strategy in the form of extra storage potential is relatively easy to realise, only having to implement charging infrastructure: 261 new charging points are needed. This comes down to 131 charging stations, as each station has 2 sockets. The share of EV's is projected to grow towards the future, making the implementation of EV charging infrastructure inevitable at a certain point: compared to 2020, 5x the amount of EV's is expected to be present in the Netherlands. In 2040 this is even 6.5x as much (Agentschap NL, 2019). Following this, the case study area would host respectively 210 and 272 EV's by 2030 and 2040.

Electrical Cooking [Cook]: Cooking infrastructure can be retrofitted into electrical infrastructure (induction cooking plates). This is relatively easy to implement. It will give rise to an extra electricity demand for which PV can be used, either directly or in combination with energy storage strategies (in this case batteries or hydrogen conversion). Electrical cooking infrastructure has to be installed within the homes of residents. This will help the city of Amsterdam in realising their goals of getting the city off the gas in 2040 (Gemeente Amsterdam, z.d.-a). It should be noted that by electrifying more appliances, also more pressure is potentially added onto the electricity grid.

Demand response (DR): Demand response can aid matching demands to moments of generation and therefore reducing overvoltage levels. This can be done by using HEMS or by behavioural change of citizens. Due to the functionalities of PtX, DR cannot be considered in the simulations and therefore it cannot not be assessed in this case study.

Unsuitable overvoltage mitigation strategies Diamantbuurt

Collective heat pump (HPc): The case study area of Diamantbuurt has no heat storage potential: aquifer storage is not possible due to the dense urban nature and the geographic characteristics of the neighbourhood. Furthermore, air sourced heat pumps are not logical on a neighbourhood scale. Therefore, collective heat pumps do not fit the case study area as an overvoltage mitigation strategy.

Home heat pump (HPh): The buildings in the case study area are not isolated well enough to be suitable for air sourced residential heat pumps, see table 3. On average, the apartments have energy label D. Some buildings even have with label G. In such poorly isolated buildings, for an air sourced heat pump to heat a building properly a very large capacity is needed (CE Delft, 2019). This is not viable to make a business case. No aquifer storage is possible in the region around the case study area, therefore other types of heat pumps (ground sourced) are not possible. If buildings would be isolated well towards a minimum of energy label B, air sourced heat pumps could potentially be a suiting overvoltage mitigation strategy, although without heat storage enough heat demand should be available during PV peaks. Or it should be combined with other types of energy storage so the heat pump can be powered at later moments of demand.

Heat recovery (HR): Efficiencies of electrolysers and fuel cells can be improved from respectively 78.8% to 95% and 60% to 90% by recovering the heat which is released during the conversion process, and using it efficiently (Buttler & Spliethof, 2018; Wang, Wang & Fan, 2018). This is makes hydrogen conversion a lot more cost effective. However, for heat recovery to be used effectively heat pumps and heat storage are needed, otherwise the heat cannot be used. As heat pumps are found to be unsuitable for the case study area Diamantbuurt, and no aquifer storage is available, heat recovery thus is also not possible. Therefore efficiencies of electrolysers and fuel cells will remain at 78.8% and 60%.

Sizes of storage and conversion infrastructure & PtX simulation settings

The mitigation strategies all have different capacities and sizes. Batteries, electrolysers, fuel cells and storage tanks are completely scalable to all sizes possible within a neighbourhood or building. In table 8 the capacities and efficiencies that are used for the simulation of the case study area Diamantbuurt can be seen.

For configurations with home batteries (Bh), all apartments and shops are assumed to have 1 home battery. The day care and community centre both have 5 home batteries as their energy demand is much larger and they have more space. All configurations have a minimum of 42 EV's (the current amount of EV's that is present in the neighbourhood, see section 5.2.2.2). Configurations with the maximum EV potential (EVmax) have 303 EV's (all of the case study area's parking spots are occupied by an EV). As stated in table 8 and section 5.2.3.2, it is assumed that 60 percent of the EV's energy demand is charged at home (in the case study area).

At the start of the simulation, the initial volume of the hydrogen storage tank and the batteries is 0, unless they have a minimum hosting capacity or depth of discharge: in that case their initial volume is the minimum amount of energy necessary. However, as to have more realistic starting volumes, the simulation is conducted over a slightly longer period (4 months) than is needed. The period over which overvoltage is calculated for this study is 01/01/2019 – 01/01/2020. However, the simulation is conducted from 01/09/2018 – 01/01/2020 so that batteries and storage tanks have a natural initial volume on 01/01/2019 (from then the overvoltage is being tracked).

For the simulated hydrogen configurations, hydrogen is used for heating purposes causing its demand to be bigger than can be made by solely overvoltage mitigating hydrogen production. Therefore, external hydrogen import is allowed. Within the PtX model this is simulated by allowing the connection to a theoretical salt cavern storage with an 'infinite' hydrogen volume (1000000 kg). The hydrogen target in PtX is set to 0 (PtX, parameters: h2_target = 0), meaning that there is no cap on production and electrolysers can operate at all times.

An overview of the PtX parameter files and settings of all simulated energy configurations can be seen in Appendix D.

	#	unit	efficiency	source
electrolyser	150	kW	78.8%	(IEA, 2019)
fuel cell	150	kW	60%	(van der Roest et al., 2021)
hydrogen storage tank	8000	kWh		
hydrogen boiler			98%	(van der Roest et al., 2021)
home battery	13.5	kWh	95% (one-way)	(IRENA, 2017)
energy demand EV	2600	kWh/year	90.7%	(Farahani et al., 2020)
percentage battery EV charged at home	60	%		
AC/DC conversion electricity grid	98	%		(van der Roest et al., 2021)

Table 8: Characteristics of the conversion and storage mitigation strategies for the simulation of the case study. Targeted towards 2030.

5.2.5 Step 5: Concept development

From the potential overvoltage mitigation strategies described in section 5.2.4 energy configurations are formed, see table 9. The energy configurations are divided in conventional strategies (*Curtailment & Grid Reinforcement* (*GR*)), and in system integration strategies (*Bh, Hy & HyBh*). The configurations are elaborated below.

Conventional strategies

Curtailment: No storage or conversion infrastructure is present in the neighbourhood. PV generation is curtailed to mitigate overvoltage in the LV grid.

Grid reinforcement: The grid is reinforced to prevent overvoltage from happening. The MVS is upgraded to 1 MW and the electricity grid is upgraded.

System integration strategies

Bh: Home batteries are implemented in all apartments, shops and other building typologies. The batteries have a capacity of 13.5 kWh.

Hy: An electrolyser (150 kW), a fuel cell (150 kW) and a hydrogen storage tank (8000 kWh) are implemented in the neighbourhood. Furthermore, the gas grid is retrofitted for hydrogen transport, and hydrogen is used for heating the built environment. Therefore, hydrogen boilers are installed in all buildings. A wider hydrogen economy is assumed, making it possible for the local energy system to import and export hydrogen. The stored hydrogen can be used for electricity demands (using the fuel cell) and hydrogen demands (using the hydrogen boiler). Hydrogen is not purely produced as overvoltage mitigation, it is also produced in a base load and imported for heating demands.

HyBh: This energy configuration is a combination of *Hy* and *Bh*. Home batteries (13.5 kWh) are installed in all buildings. Furthermore a wider hydrogen economy is assumed with import and export possibilities. Hydrogen is used for heating the built environment, thus hydrogen boilers are installed in all buildings. An electrolyser (150 kW), a fuel cell (150 kW) and hydrogen storage (8000 kWh) are implemented in the neighbourhood.

Different electrification scenarios are simulated:

1. *No electrification:* no extra electric demands are added compared to current demands.
2. *Electric cooking (Cook):* All cooking is electrified, using induction cooking plates and electric ovens.
3. *Maximum EV (EVmax):* All vehicles in the case study area are EV's. They are assumed to be charged at home for 60%, and there is charging infrastructure to charge all (302) vehicles similarly.
4. *Electric cooking & maximum EV (Cook + EVmax):* All cooking and all vehicles are electrified.

No electrification	**Electric cooking**	**Maximum EV**	**Electric cooking & maximum EV**
Conventional			
Curtailment	Curtailment + Cook	Curtailment + EVmax	Curtailment + Cook + EVmax
GR	GR + Cook	GR + EVmax	GR + Cook + EVmax
System integration			
Bh	Bh + Cook	Bh + EVmax	Bh + Cook + EVmax
Hy	Hy + Cook	Hy + EVmax	Hy + Cook + EVmax
HyBh	HyBh + Cook	HyBh + EVmax	HyBh + Cook + EVmax

Table 9: Energy configurations for overvoltage mitigation in the case study area Diamantbuurt.

5.2.6 Step 6: Evaluation

In the evaluation, all defined overvoltage mitigation strategies are assessed using the four assessment criteria. Subsequently, results and recommendations are stated.

5.2.6.1 Energetic implications

The configurations, as defined in section 5.2.5, are simulated in PtX for the case study area Diamantbuurt. An overview of the needed levels of curtailment (kWh/year) of all energy configurations for the different scenarios can be seen in figure 24.

Electrification scenario 1: No electrification

In figure 20, the needed levels of curtailment per strategy without extra (cooking and EV) electrification (*no electrification*) can be seen as a percentage of the needed curtailment for the conventional strategy of *curtailment*. Using home batteries halves the amount of curtailment in comparison to the conventional strategy of *curtailment*. Using hydrogen (either with a boiler and replacing natural gas, or only as hydrogen storage using it for electricity conversion) reduces curtailment levels to almost a fifth. Strategies combining hydrogen conversion with home batteries bring levels of curtailment down to 7% compared to the strategy of curtailment. Grid reinforcement causes no overvoltage.

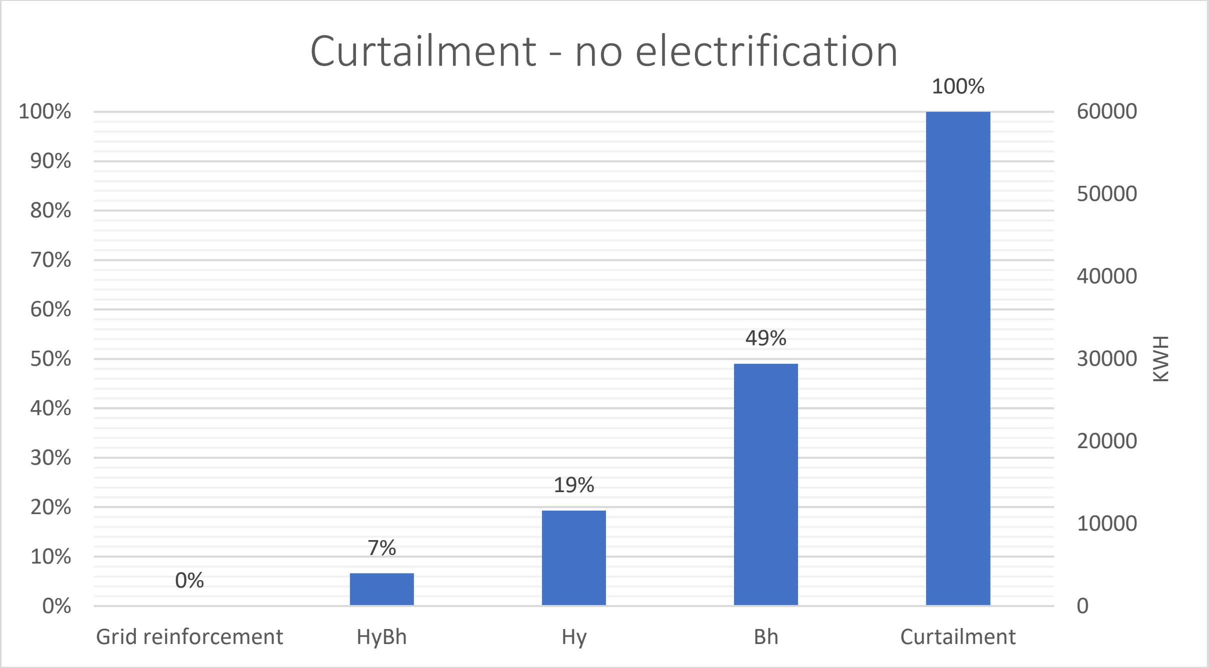


Figure 20: Percentage of curtailment needed per energy configuration, as compared to the conventional overvoltage mitigation strategy Curtailment (most right bar). For the scenario with no extra cooking and EV electrification (No electrification). The y-axis on the right shows levels of curtailment in kWh.

Electrification scenario 2: electric cooking

In figure 21, the needed levels of curtailment per strategy with electrified cooking (*electric cooking*) can be seen as a percentage of the needed curtailment for the conventional strategy of *curtailment*. In these energy configurations cooking is electrified (instead of using natural gas), posing an extra electric demand for the households. The most right bar, *Curtailment*, is the conventional curtailment strategy with additional electrified cooking demand. Using home batteries bring curtailment levels down to around 40%. Hydrogen conversion (*Hy*) reduces curtailment need to slightly less than a fifth. The combinations of hydrogen conversion and home batteries with electrified cooking (*HyBh*) have curtailment levels of 5% compared to the conventional curtailment strategy. *Grid reinforcement* causes no overvoltage.

Electrification scenario 3: maximum EV

In figure 22, the needed levels of curtailment per strategy for a scenario where all cars in the case study area are EV's (*maximum EV*) can be seen as a percentage of the needed levels of curtailment for the conventional strategy of *curtailment.* In figure 22, *curtailment* is the conventional curtailment strategy with additional EV electricity demand. Home batteries in the *maximum EV* scenario require only 20% of the needed levels of curtailment as compared to the conventional strategy of *curtailment* (*Curtailment*). In comparison to the other two scenario's (*no electrification* & *electric cooking*) home batteries (*Bh*) are a lot more effective in mitigating overvoltage, and reducing needed levels of curtailment, with the addition of EV's. In this electrification scenario, hydrogen conversion (*Hy*) is only slightly more effective in mitigating overvoltage than home batteries: its curtailment levels lie around

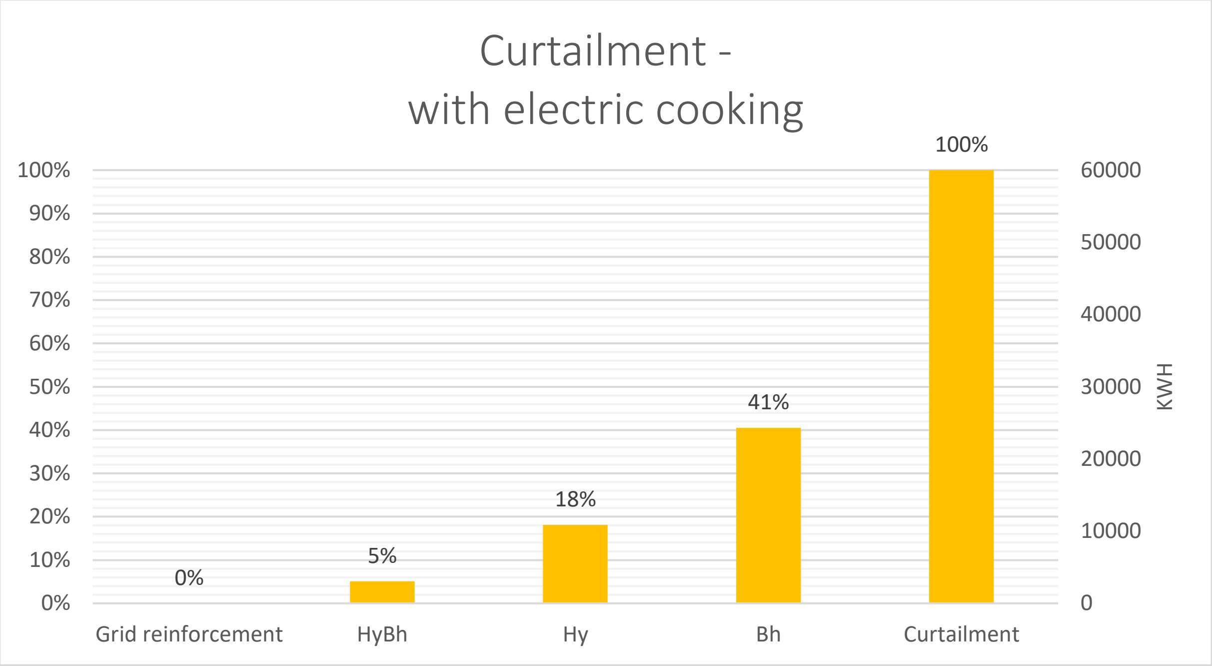


Figure 21: Percentage of curtailment needed per energy configuration, as compared to the conventional overvoltage mitigation strategy Curtailment (most right bar). For the scenario where cooking demand is electrified. The y-axis on the right shows levels of curtailment in kWh.

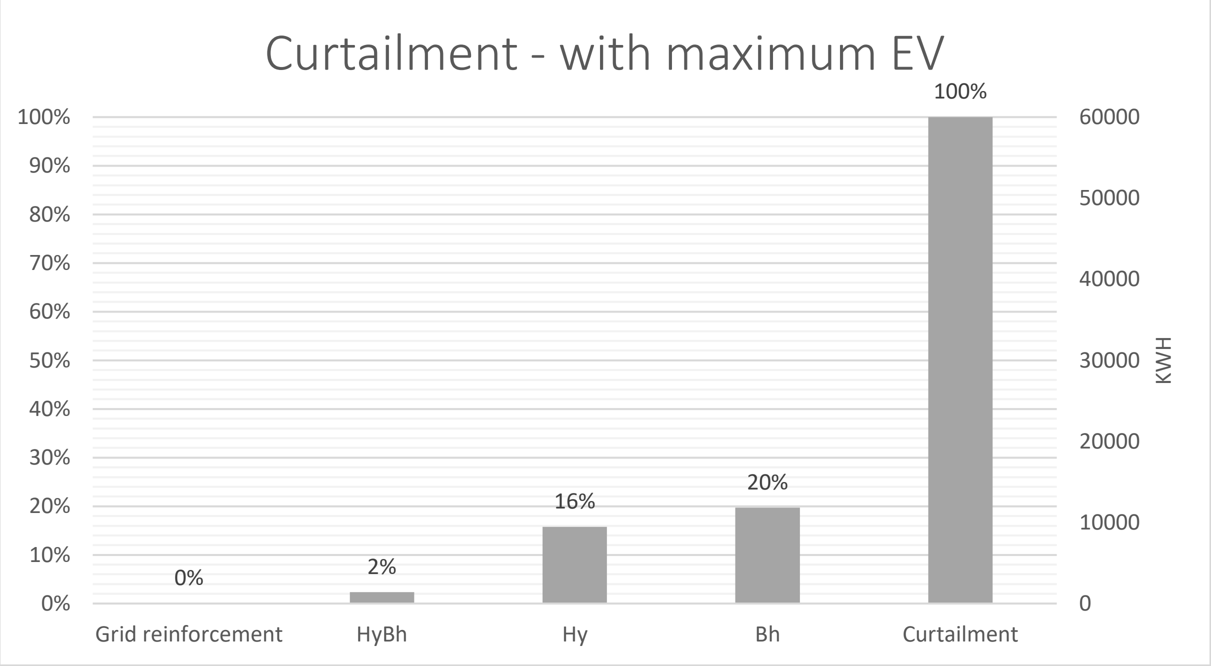


Figure 22: Percentage of curtailment needed per energy configuration, as compared to the conventional overvoltage mitigation strategy Curtailment (most right bar). For the scenario where all cars in the case study area are EV's. The y-axis on the right shows levels of curtailment in kWh.

16%. The fact that home batteries in combination with maximum EV is so much more effective than in the other scenarios can be explained by the effect seen in figure 23. Here the (dis)charging pattern of a home battery in the *no electrification* scenario is compared with that of one in the *maximum EV* scenario. In the graph, a fully charged battery states ‘0’, meaning that it cannot be further charged. At the end of the afternoon, both batteries have reached full capacity. From 17:00, as the PV generation reduces and is not capable of fulfilling all electricity demands, they both start to discharge. The battery in the *maximum EV* scenario encounters a higher electricity demand in the evening and overnight due to the charging demand of the EV’s, as compared to the *no electrification* scenario. Therefore, this battery discharges more and faster. For that reason, the next day, the *maximum EV* battery has almost twice the charging capacity of the *no electrification* battery available when the sun starts to shine, causing the batteries to recharge. Subsequently, the *no electrification* reaches full capacity 2 hours before the *maximum EV* battery. As the battery is full relatively early, while the sun is continuing to generate electricity for the coming hours, PV generated electricity is fed onto the grid. This eventually causes overvoltage. This can be seen in figure 24. As the batteries reach full capacity, the grid’s available capacity starts to reduce until curtailment is needed to mitigate the effects of overvoltage. EV’s cause this to happen for a shorter period of time. Moreover, the levels of curtailment needed (the red line in the graph) for *maximum EV* are smaller than for the *no electrification* scenario. This exemplifies how system integration and sector coupling (the mobility, built environment and renewable energy generation sectors) can strengthen overvoltage mitigation strategies. This effect could be strengthened even further by using smart charging. Then the batteries could be instructed not to start charging as soon as the sun is up, but to spare its capacity for later moments of high PV irradiation as to more effectively mitigate overvoltage. This could not be simulated with the current version of the PtX model.

For *Hy*, the aforementioned effect is not seen as the hydrogen storage tank is never completely full: there is a constant heating demand for hydrogen. For that reason, the added EV electricity demand does not ‘spare’ the hydrogen storage tank in the way it does for the batteries in *Bh*. This can be seen in figure 25. Overvoltage for the hydrogen conversion strategies is imposed by the fact that the production capacity of the electrolysers is maxed before PV generation peaks. The electrolysers cannot produce extra hydrogen during the highest PV peak as to mitigate overvoltage. At the same time, the hydrogen storage tank is rather empty during the day. It is only filled after the curtailment is over. Figure 26 clarifies how the levels of overvoltage for the *maximum EV* scenario are still smaller than those in *no electrification*. Here, the relation between overvoltage, energy demands and electrolyser capacity using PV (PV induced hydrogen production) are shown. It is seen that as the capacity of the electrolysers in both scenarios are maxed (150 kW), the energy demands due to the added electrification of EV are larger. Therefore, more PV generated electricity can be used directly (to charge the EV’s). This reduces overvoltage, and thus levels of curtailment needed.

All in all, the effect of the extra electricity demand imposed by the *maximum EV* scenario on the needed levels of curtailment is smaller hydrogen conversion (*Hy*). Therefore, the levels of curtailment needed in *maximum EV* for *Bh* reduced to 34% of the curtailment levels in the *no electrification* scenario while for *Hy* they only reduced to 68%. In both cases adding EV helps reducing needed levels of curtailment greatly, however the effect is a lot greater for home batteries.

Lastly, as can be seen from figure 22, the combination of hydrogen conversion and home batteries for the scenario of *Maximum EV’s* (*HyBh*) reduces curtailment to 2%. *Grid reinforcement* causes no overvoltage.

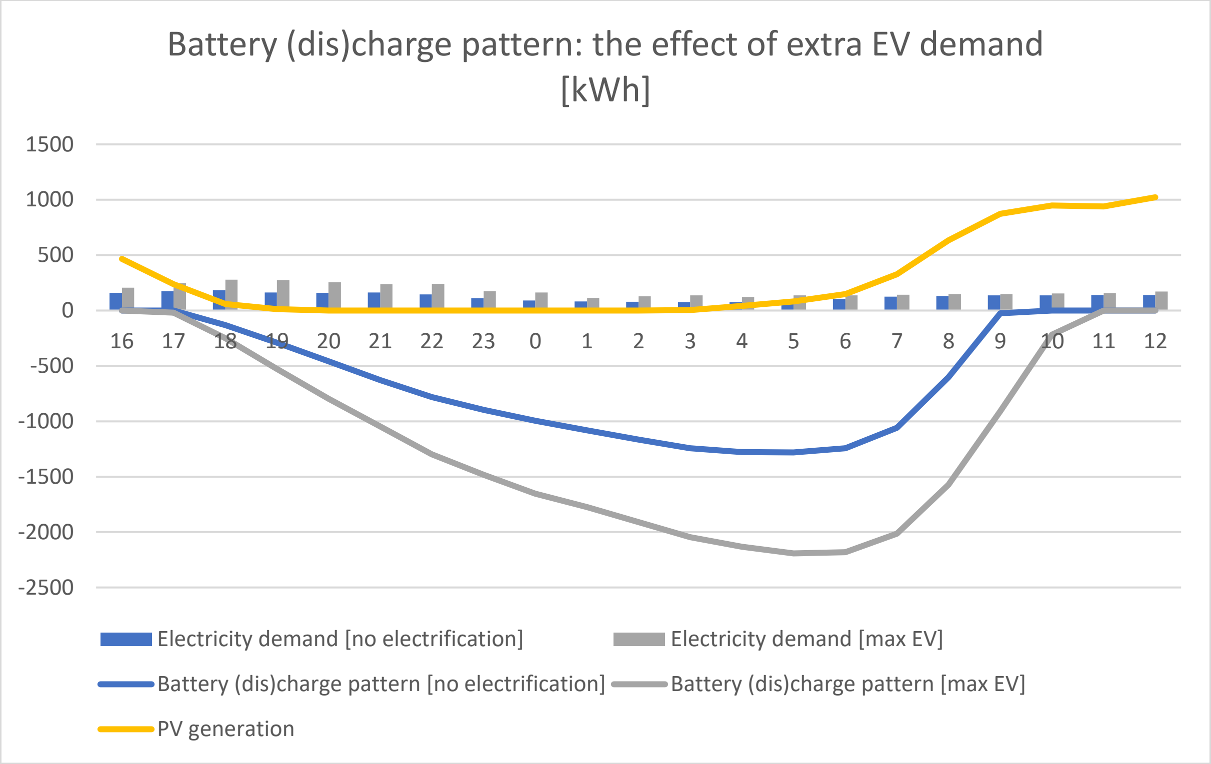
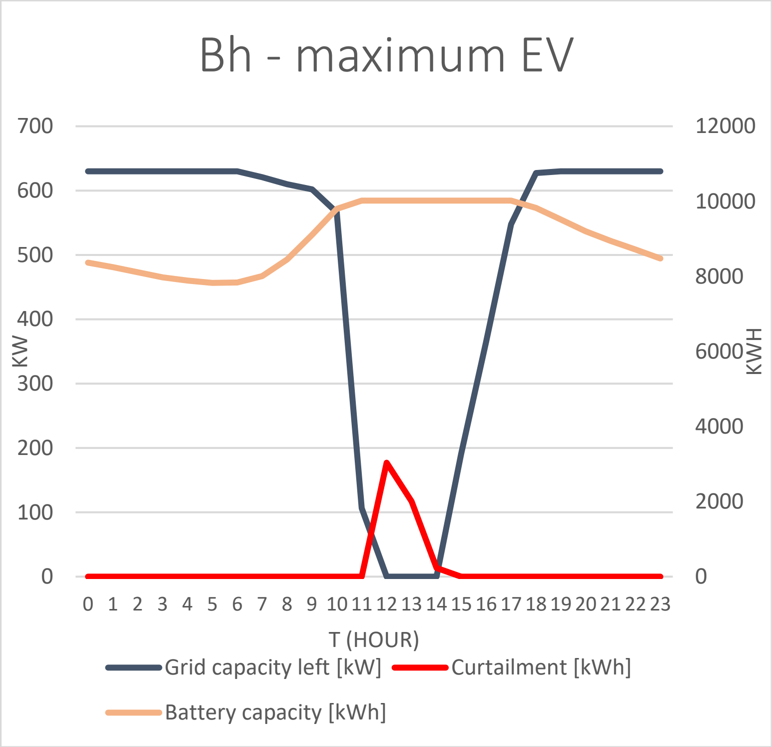


Figure 23: The battery (dis)charge pattern for batteries in the scenario *no electrification* versus the scenario *maximum EV*. The pattern is visualised for part of the period 4-5 july, 2019. The storage capacities of the batteries is 13.5 kWh. To make the (dis)charge pattern more explicit in relation to the opposed electricity demands, the full capacity of the batteries in the graph is shifted to be shown at 0 kWh. When it is discharged, it thus shows a negative value. Charging brings it back towards 0. Furthermore, the graph visualises the hourly electricity demand and the pattern of PV generation. The x-axis states the hour of day.



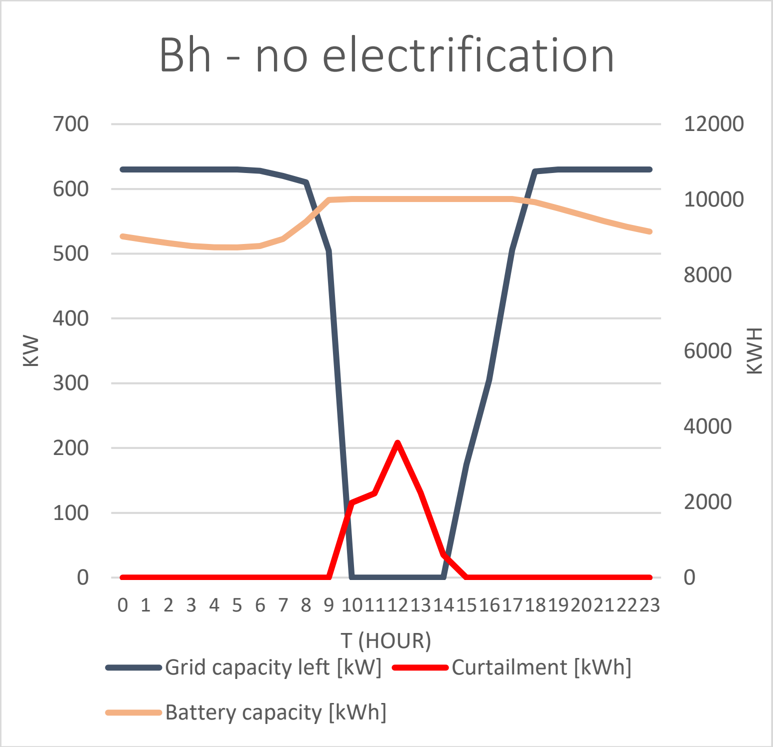


Figure 24: The patters of battery (dis)charge of the home battery (kWh) in relation to the available grid capacity (kW) and the needed levels of curtailment (kWh) are visualised for the *maximum EV* scenario (left) and the *no electrification* scenario (right). The patterns are shown for the day of 5 July. The x-axis states the hour of day. The left y-axis shows capacities (kW), the right shows energy (kWh).

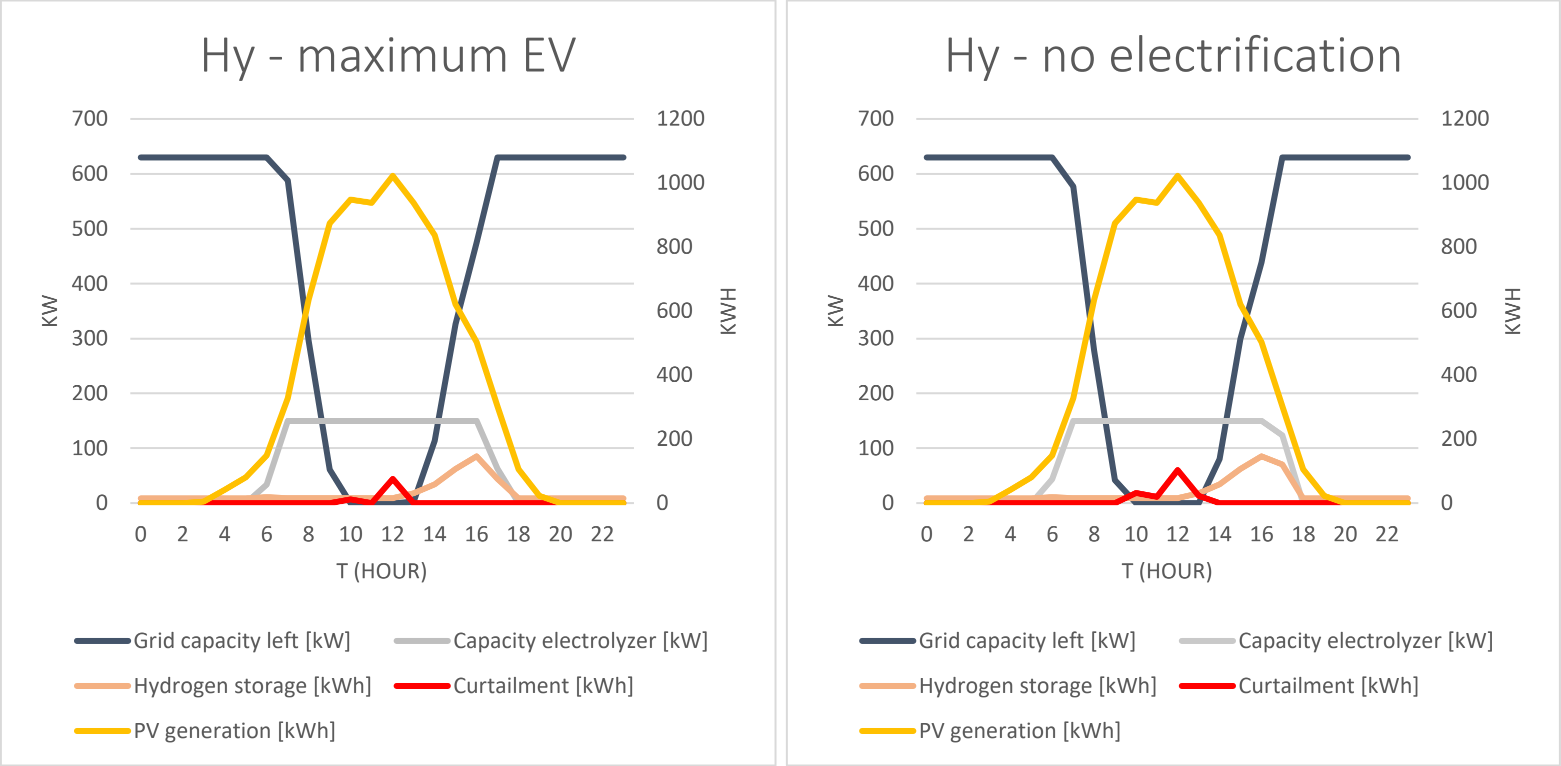


Figure 25: The patters of electrolyzer capacity (kW) and hydrogen storage (kWh) in relation to the grid capacity (kW) and the needed levels of curtailment (kWh). The scenarios *maximum EV* (right) and *no electrification* (left) are shown. The patterns are shown for the day of 5 July. The x-axis states the hour of day. The left y-axis shows capacities (kW), the right shows energy (kWh).

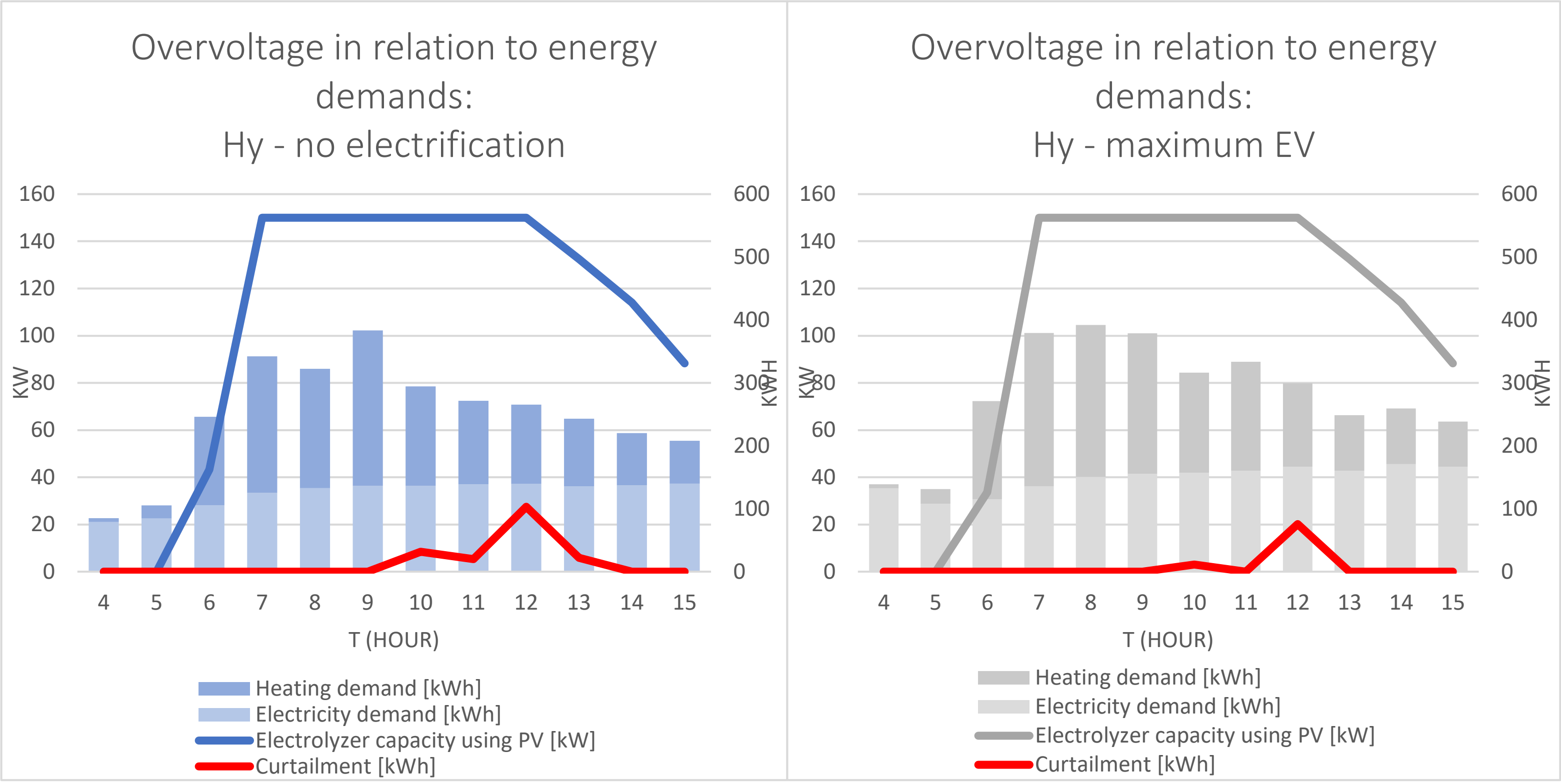


Figure 26: Capacity of the electrolysers using PV energy (kW), in the hydrogen conversion mitigation strategy, in relation to the energy demands (kWh) and levels of curtailment needed to mitigate overvoltage (kWh). The scenarios *no electrification* (left) and *maximum EV* (right) are visualised. The patterns are shown for the day of 5 July. The y-axis states the hour of day. The left x-axis show the electrolyser capacities (kW), the right shows energy (kWh).

Electrification scenario 4: electric cooking & maximum EV

In figure 27, the needed levels of curtailment per strategy can be seen as a percentage of the needed levels of curtailment for the conventional strategy of *Curtailment*, for a scenario where both energy demand for cooking and for all cars in the case study area are electrified (*electric cooking & maximum EV*). In this scenario, as opposed to the other three, home batteries are more effective as an overvoltage mitigation strategy than hydrogen conversion: compared to the conventional curtailment strategy with electric cooking and maximum EV's, hydrogen conversion (*Hy*) has curtailment levels of 15%, where home batteries (*Bh*) cause curtailment to drop to 12%. This effect can be explained by the same reasoning as is stated above in subsection *Electrification scenario 3: maximum EV*. The extra electrification demands cause the battery to discharge sooner and further as compared to the *no electrification* scenario. Therefore, their capacity is spared causing them to be more effective for moments of high PV irradiance, when overvoltage mitigation is needed. Again, for *Hy*, this effect does not add up as the capacity of the hydrogen storage tank is never completely full: there is a constant heating demand for hydrogen.

All in all, it shows that extra electricity demands due to electrification can have a very positive effect on overvoltage mitigation: it reduced the storage capacity needed. Demand response and smart charging have the potential to enlarge this effect.

Combining *home batteries* and *hydrogen conversion* in the electric cooking and maximum EV scenario diminishes curtailment levels to one percentage of the levels of the conventional *Curtailment* strategy. *Grid reinforcement* causes no overvoltage.

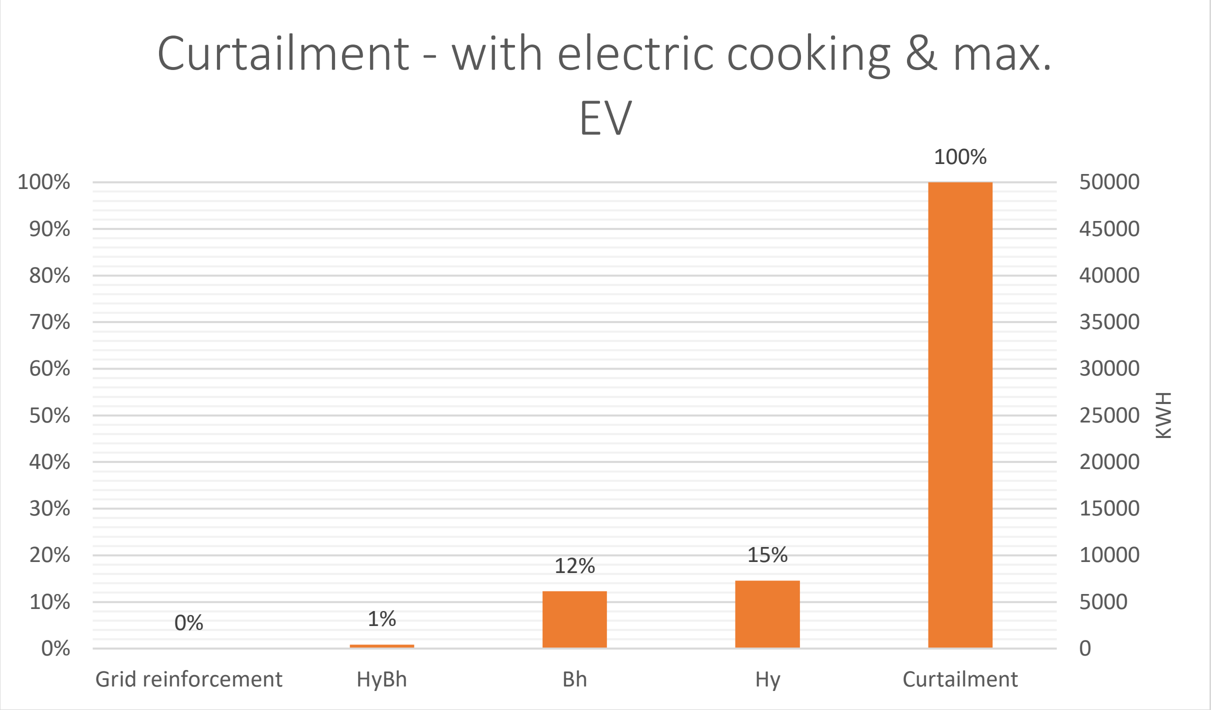


Figure 27: Percentage of curtailment needed per energy configuration, as compared to the conventional overvoltage mitigation strategy Curtailment (most right bar). For the scenario where both the cooking and cars are electrified. The y-axis on the right shows levels of curtailment in kWh.

Curtailment comparison for the electrification scenario's

In figure 28, the overview of the needed levels of curtailment (in kWh/year) of the energy configurations for all scenarios can be seen. A clear pattern can be seen for the different electrification scenario's: for all energy configurations curtailment is reduced with extra electrification. Electric cooking reduces the need for curtailment, having all cars EV's even more and a combination of the two is the most effective. This pattern is the strongest for the home battery configurations (*Bh*), as is explained above in subsection *Electrification scenario 3: maximum EV* and subsection *Electrification scenario 4: electric cooking & maximum EV.*

The overall effect can be explained by the fact that electrification poses an extra demand for the generated solar energy to be (directly) used. Depending on the demand and the match between generation and demand, overvoltage is reduced. This is observed in the four scenario's for the conventional *Curtailment* strategies (the four bars on the right in figure 28). Electrical storage and conversion strategies can further match generation and demand by storing the solar generated energy for a later moment of demand. Therefore adding storage and conversion further reduces overvoltage levels, and thus the need for curtailment. This is most effective for the configurations combining hydrogen conversion and home batteries (*HyBh*), as can be seen in figure 28. This combination together with the electrification of cooking and vehicles almost completely reduces overvoltage: for *HyBh* in the *Max EV & electric cooking* scenario, respectively 390 and 470 kWh of curtailment is needed yearly. To compare: for the same electrification scenario without batteries and conversion 44874 kWh/year of curtailment is needed and for the non-electrified (*no electrification*) scenario without batteries and conversion 56914 kWh/year is needed. Grid reinforcement is the most effective strategy to mitigate overvoltage (0 kWh of curtailment per year).

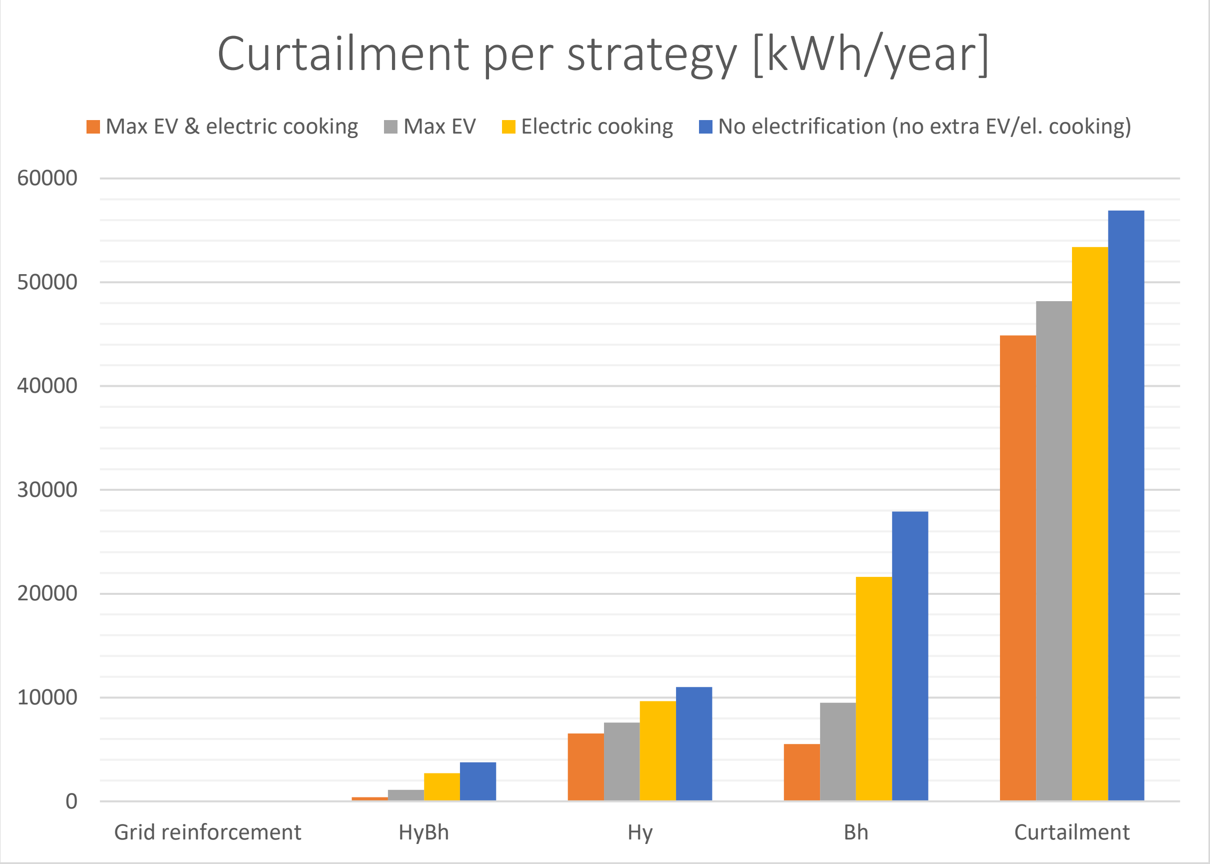


Figure 28: An overview of the curtailment levels (kWh/year) for all potential overvoltage mitigation strategies for the case study area Diamantbuurt, as compared for the different electrification scenario's.

Energy import from the grid

Next to curtailment, also the amount of energy imported from the grid says something about the energetic aspects for the different energy configurations and electrification scenario's. The less energy is imported, the more solar generated energy is effectively used within the neighbourhood system: either by storage and conversion or by direct use due to current demands. A neighbourhood energy system that imports little energy entails the system to be more independent from the grid, and thus more resilient. Moreover, needing less kWh per year poses a more sustainable energy system as then a part of the local energy demand is fulfilled with renewable generated electricity. Although, considering the expected energy transition, in future larger shares of the imported energy are also likely to be renewable.

The energy import per energy configuration, for each of the electrification scenarios can be seen in figure 29. The imported energy is the total of all imported electricity, natural gas and hydrogen needed for each of the energy configurations.

Firstly, when looking at figure 29, a remark should be made. It can be seen that the scenarios with full electrified vehicle sectors (*Max EV* and *Max EV & electric cooking)* have more import in general compared to *no electrification* and *electric cooking*, however, in the scenarios without max EV, cars have a fossil fuel demand which is not visible in the local energy flow, and thus not in this graph. For this reason, not much can be said about impact that max EV has on the energy import: comparing the non-EV scenarios and the max EV scenarios in terms of energy import should be done with care.

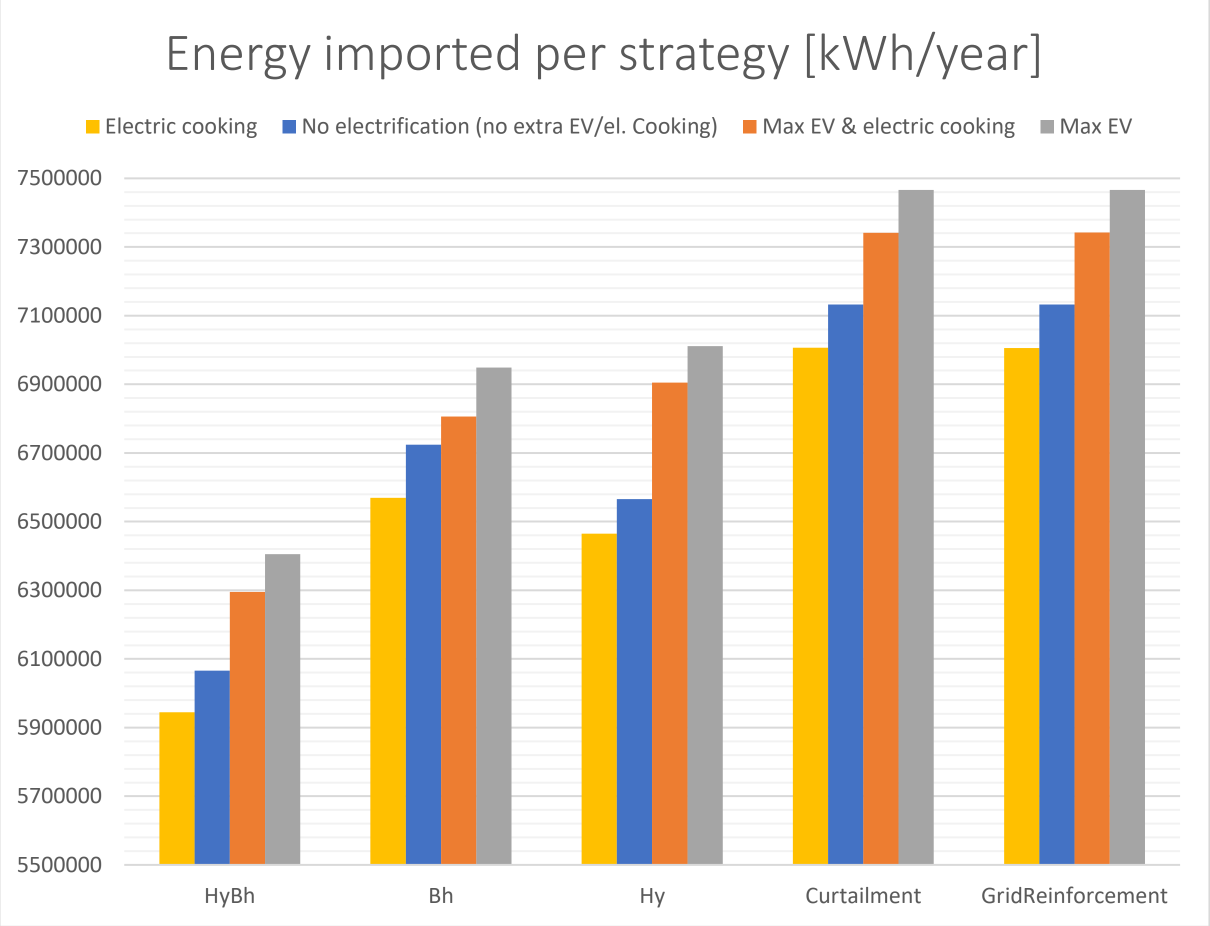


Figure 29: Energy import (kWh/year) per energy configuration for all electrification scenario's. The imported energy is the total of all imported electricity (kWh/year), natural gas (kWh/year) and hydrogen (kWh/year) for each of the energy configurations.

What can be seen is that electric cooking has a positive impact on energy import: comparing the scenarios *electric cooking* and *no electrification* for all energy configurations, it is clear that import decreases when cooking is electrified. Comparing the scenarios *Max EV* and *Max EV & electric cooking*, the same effect is visible. This can be explained for a large part by the fact that cooking with induction is more efficient than cooking with natural gas, but also partly because electrification causes more PV generated energy to be directly used.

Bh is slightly more effective than *Hy* for the scenarios with fully electrified vehicle sectors (*Max EV* & *Max EV and electric cooking*). For the other scenarios (*Electric cooking* and *No electrification*) hydrogen conversion (*Hy*) is more effective than home batteries (*Bh*). This can be explained by the effect as described before in subsection *Electrification: maximum EV* and subsection *Electrification: electric cooking & maximum EV* regarding curtailment levels: large electrified demands make home batteries more effective in mitigating overvoltage. This also translates to the energy import demand: as the extra electricity demands, coming forth of electrification, the batteries are discharged earlier and further causing them to have more storage capacity available in periods of high PV irradiation as to mitigate overvoltage. This stored 'overvoltage mitigation' electricity can subsequently be used in later moments of electricity demand, when otherwise electricity would have been imported. Therefore, electricity import demand is reduced. Again, as the hydrogen storage tanks of *Hy* never reach full capacity (see subsection *Electrification scenario 3: maximum EV* and subsection *Electrification scenario 4: electric cooking & maximum EV*), this effect is not seen for the strategy of hydrogen conversion. Apparently, the electrification demands of *electric cooking* are not large enough to make home batteries (*Bh*) more effective than *Hy*.

Extra electricity demands in times of PV generation, even if there is no overvoltage at that moment, can thus, next to its positive effect on overvoltage mitigation, also have a positive effect on the energy import demand. This shows the potential of system integration. Moreover, as also stated in section *Electrification scenario 3: maximum EV,* it promotes the need for demand response, smart charging and HEMS as shifting demands can improve the effective use of storage capacities of overvoltage mitigation strategies.

Regardless of the electrification scenario, the most effective strategy in terms of energy import is *HyBh.*

5.2.6.2 Costs

In this section, the assessment on the costs is done. This is done on infrastructure and energy import costs.

Infrastructure

In figure 30, the yearly needed costs for the infrastructure of the individual overvoltage mitigation strategies can be seen. The costs include CAPEX & OPEX and are divided by the lifetime of the infrastructure as to obtain a yearly number. Interest rates are disregarded in the calculation of the yearly costs.

The strategy of *Curtailment* clearly has the least costs involved, as no extra infrastructure is needed. Interestingly, *Grid reinforcement* is only slightly more expensive than *Curtailment* on a yearly basis. Reinforcing the grid is also cheap in comparison to the other individual mitigation strategies. This has to do with the total infrastructure costs being relatively low compared to some of the other strategies as well as the fact that the MVS and the cables have a long lifespan: respectively 40 and 65 years, as was validated with P. Bonfhof (Alliander) and T. Fens (TU Delft) (P. Bonhof, personal communication, July 19, 2021; T. Fens, personal communication, July 30, 2021).

Installing induction cooking plates for electric cooking (*Electric cooking*) is fairly cheap. Implementing charging stations for EV's (*Maximum EV*) is slightly over double the amount of costs, however compared to hydrogen conversion and batteries it still a lot more cost effective. This should be noted as both, and especially in combination with each other and with other mitigation strategies, reduce levels of curtailment needed to mitigate overvoltage (see figure 28). A remark should also be made regarding the extra infrastructure costs needed for implementing electric cooking plates: infrastructure costs are taken as a yearly number, considering depreciation. However, natural gas cooking plates would also impose such yearly depreciation costs, although these are not taken into account in this cost calculation. In case of a renovation where the existing (natural gas) cooking furnace is to be replaced, electric cooking plates can be installed. Then (part of) the yearly infrastructure costs for electric cooking can be neglected because otherwise these costs would have been made for a new natural gas furnace.

The infrastructure of home batteries (*Bh*) is a fair amount cheaper than hydrogen conversion (*Hy*).

In case costs are solely made for the mitigation of overvoltage, they would be assessed as mentioned in this section. However, taking in consideration wider purposes as the (local) energy transition, some infrastructure implementations might me made regardless of overvoltage mitigation. Then overvoltage mitigation can be an additional effect matching to the energy transitional plans. Therefore, infrastructure costs can be disregarded for the overvoltage mitigation strategy assessment. If Amsterdam's ambitions to transition the neighbourhood into a hydrogen-using heating district follow through, natural gas pipes will be retrofitted and hydrogen boilers need to be installed regardless of the overvoltage mitigation strategies. This will be further evaluated in step 6. In that case, these costs can be neglected. Then, costs for the infrastructure of *Hy* will be 33% less, making it cheaper than *Bh*. See figure 31.

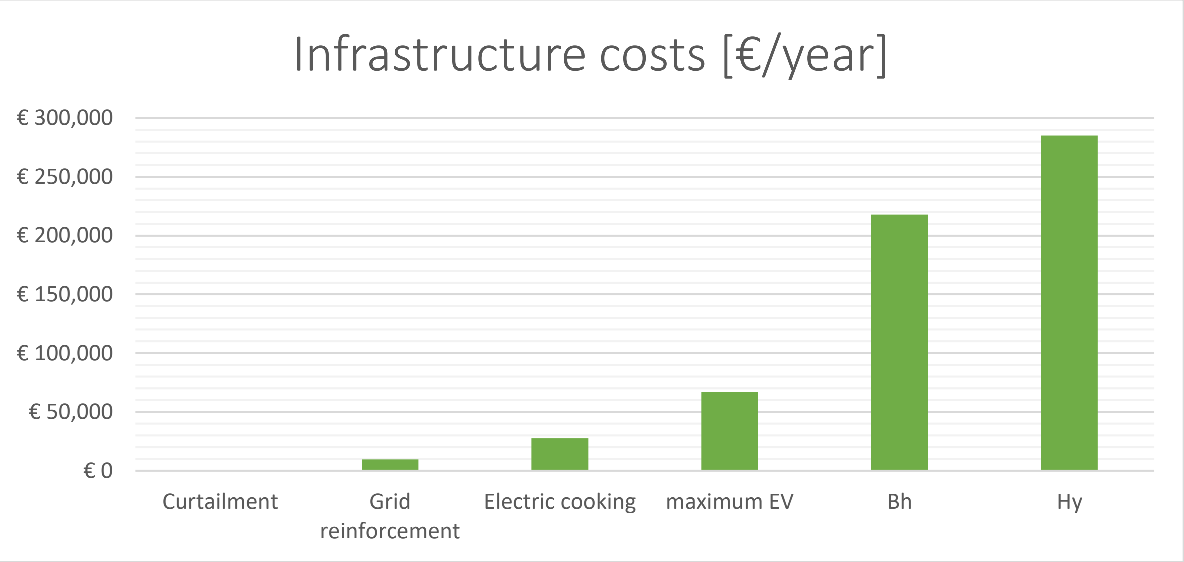


Figure 30: Yearly infrastructure costs (CAPEX & OPEX) [€/year] of individual overvoltage mitigation strategies.

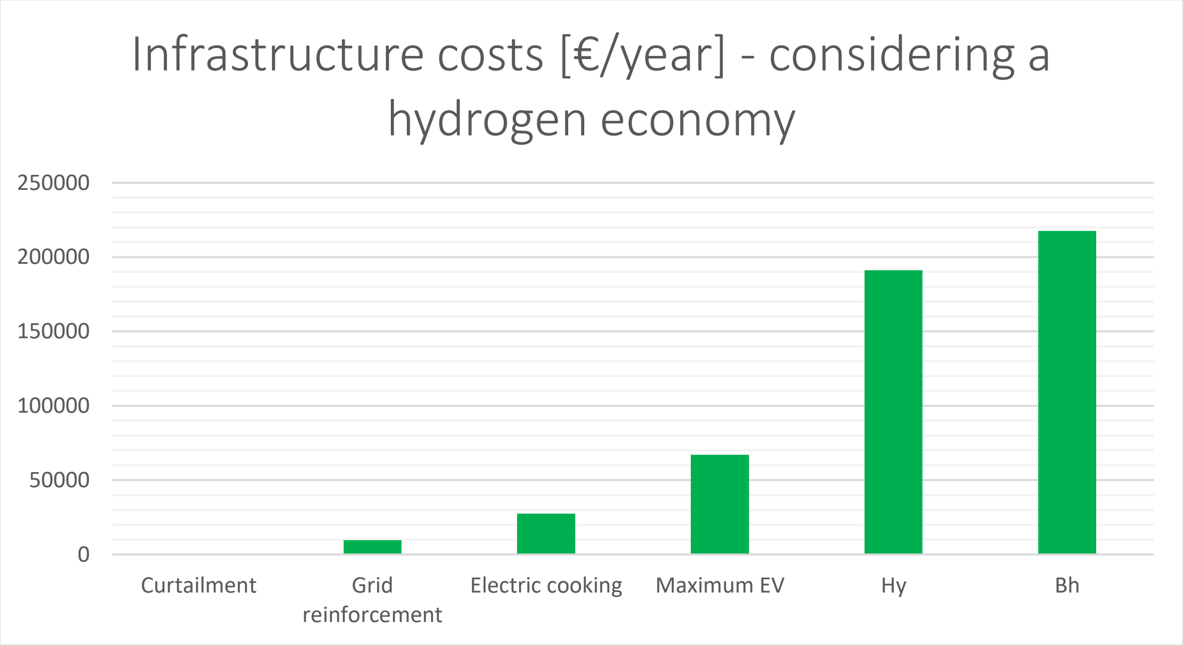


Figure 31: Yearly infrastructure costs (CAPEX & OPEX) [€/year] of individual overvoltage mitigation strategies considering an implemented hydrogen economy: natural gas grid is yet retrofitted for hydrogen purposes and hydrogen boilers are yet installed.

Infrastructure and energy import

Next to infrastructure, also (yearly) energy import is of consequence for the overall cost comparison between overvoltage mitigation strategies. One mitigation strategy can be much more efficient in terms of energy demand than another. Therefore it can also be cost efficient as less energy has to imported from the grid. In figure 32, the total yearly costs per household [€/year/hh] for each individual overvoltage mitigation strategy can be seen. The costs include infrastructure and energy import costs. The energy import costs include external electricity, natural gas and hydrogen demand.

Although more energy is imported than in some other system integration strategies, the conventional strategy of *Curtailment* is the most cost efficient strategy due to the lack of new infrastructure needed. *Grid Reinforcement* is most cost efficient after *Curtailment:* it is only slightly more costly due to the infrastructure investments needed. *Curtailment* is thus the MVC, meaning that solely from a financial perspective, *Curtailment* is, and in general conventional strategies are, the most cost-efficient.

In line with expectations, the combination of home batteries and hydrogen conversion is the most cost-intensive mitigation strategy as it requires high infrastructure investments. Using home batteries (Bh) or hydrogen conversion (*Hy*) as singular overvoltage mitigation strategy requires similar yearly costs per household. The two mitigation strategies are*,* €150 to €255 more expensive on a yearly basis per household than the conventional mitigation strategies *Curtailment* and *Grid reinforcement*.

From the non-conventional system integration mitigation strategies, *Bh* is the most economical. However, *Hy* is only slightly more costly. Thus, financially *Bh* and *Hy* are very comparable. The infrastructure costs for hydrogen conversion are more expensive than *Bh*, however, *Hy* makes up for this by having lower import costs.

Adding electrification in the form of cooking and/or EV infrastructure increases the costs, yet it does reduce levels of overvoltage. At the same time, some of these electrification-induced costs can be neglected as part of the depreciation costs for electric cooking infrastructure crosses out against the yearly depreciation of natural gas cooking infrastructure (as explained in detail before in subsection *infrastructure*). Moreover, as stated before in section 5.2.6.1, subsection *energy import from grid*, adding EV increases energy import and thus import costs. However, for conventional gasoline cars also energy is needed in terms of gasoline, which implies costs as well. This cannot be seen in this cost calculation. For this reason, comparing the (import) cost differences between the EV and the non-EV scenarios should be done with care.

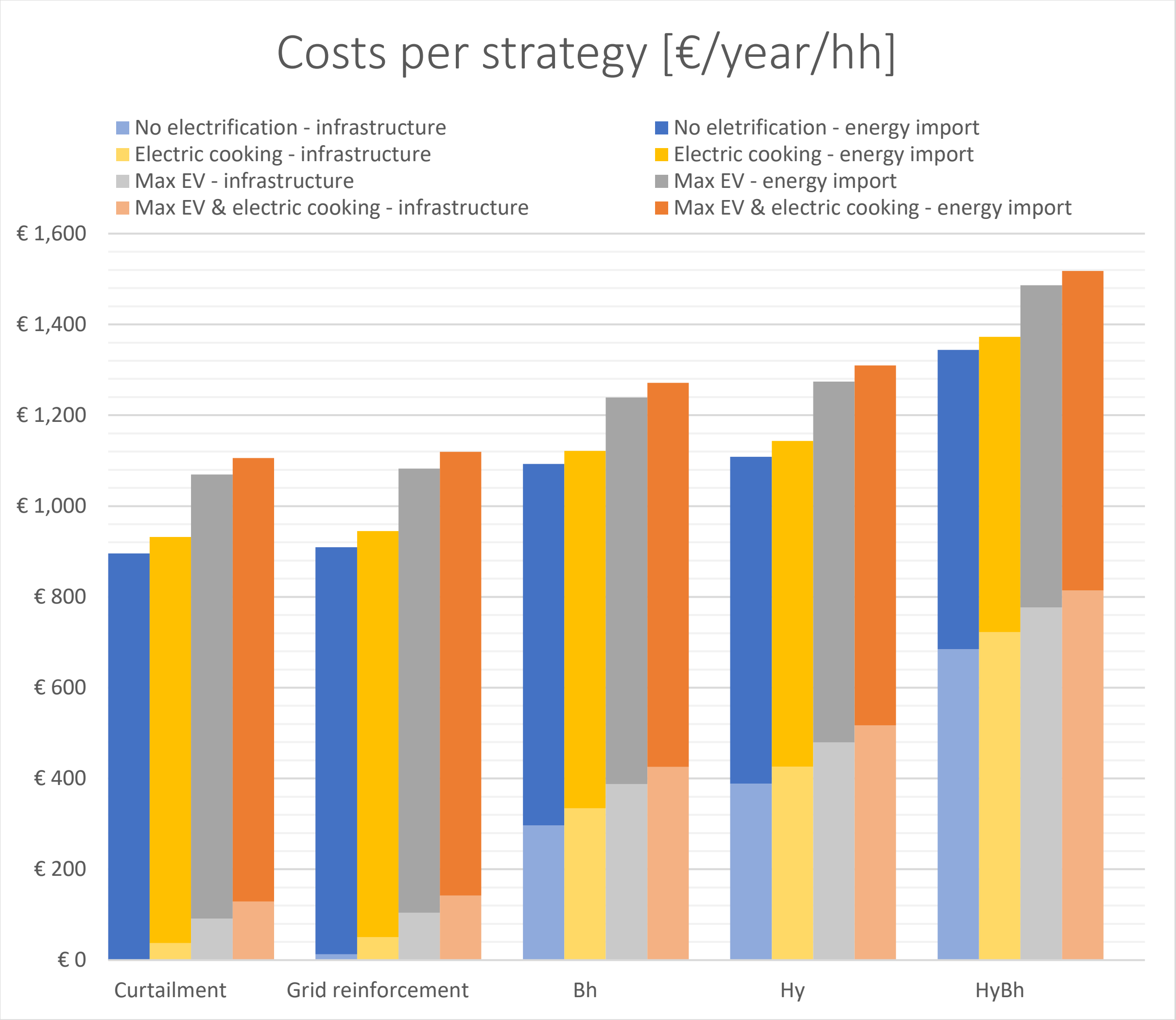


Figure 32: Yearly costs per strategy for each of the energy configurations, as shown per household [€/year/hh]. The total costs are a combination of infrastructure costs (CAPEX & OPEX) and costs coming from imported energy (electricity, natural gas & hydrogen).

In case the ambitions of Amsterdam will be realised, hydrogen will indeed be used as heating gas for the case study area Diamantbuurt. Then the costs of retrofitting the natural gas grid and installation of hydrogen boilers can be neglected as overvoltage mitigation costs: these costs will be made regardless of overvoltage mitigation. In that case, the *Hy* and *HyBh* strategies are the much more cost-efficient, as can be seen in figure 33. Now, combining hydrogen conversion and home batteries is interesting as *HyBh* is a lot cheaper and much more in the range of home batteries (*Bh*) on their own. Furthermore, the strategy of hydrogen conversion (*Hy*) is now cheaper than home batteries (*Bh*). On top of that, *Hy* is now also quite cost-competitive with the conventional mitigation strategies *curtailment* and *grid reinforcement*.

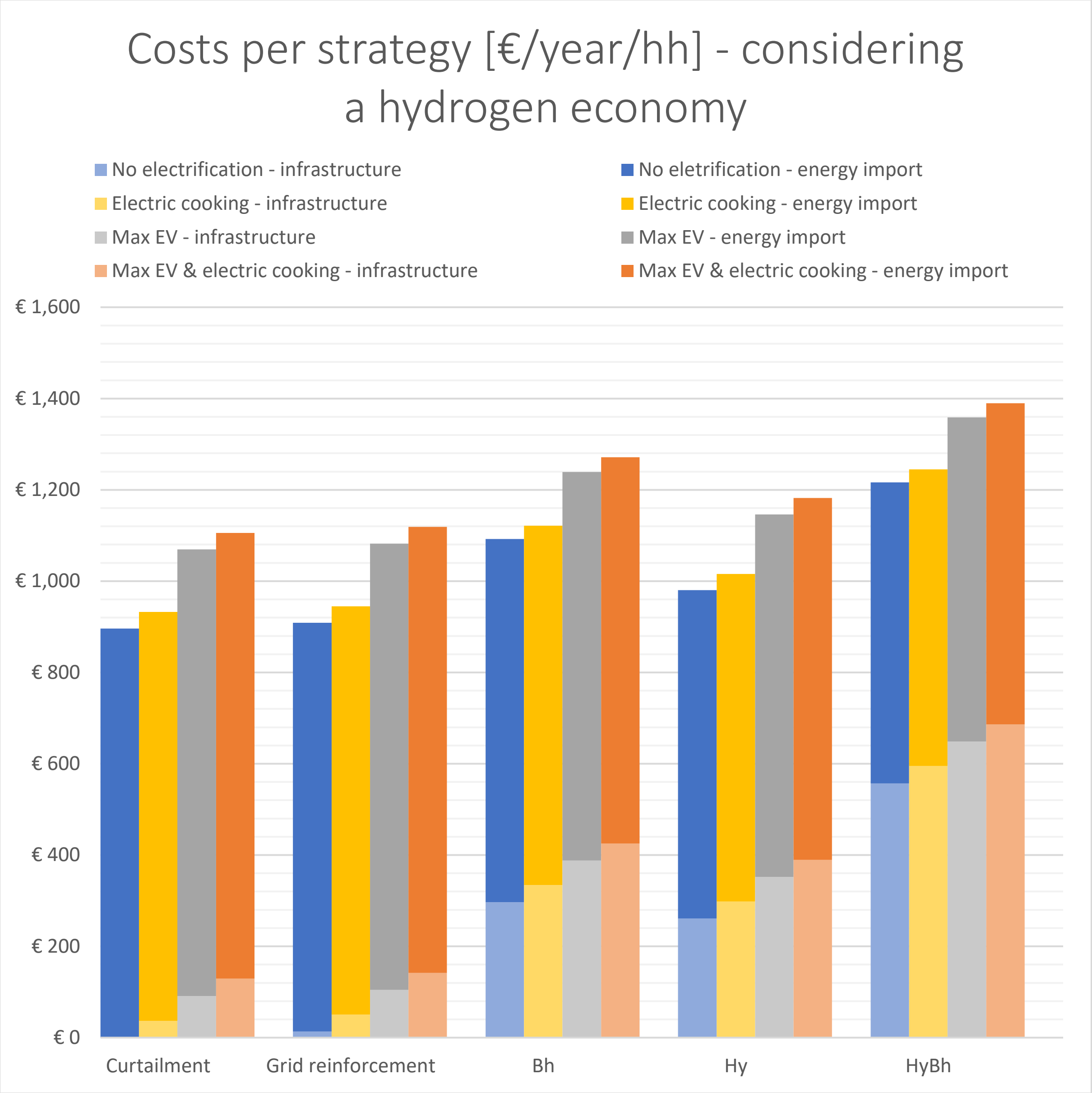


Figure 33: Yearly costs per strategy for each of the energy configurations, as shown per household [€/year/hh], while considering a hydrogen economy: natural gas grid is retrofitted for hydrogen and hydrogen boilers are installed. The total costs are a combination of infrastructure costs (CAPEX & OPEX) and costs coming from imported energy (electricity, natural gas & hydrogen).

Sensitivity analysis on the costs

The costs are calculated as an outlook towards the year 2030. They have been collected from literature estimating the costs in that near future. However, as it is an estimation these costs cope with uncertainties. For that reason, a sensitivity analysis is conducted on the costs for hydrogen conversion and home batteries. The lifespan of the necessary infrastructure might be longer or shorter than estimated. Moreover, the price per kg to import the various energy carriers from the grid and the infrastructure costs for mitigation systems could differ from current expectations. The effect that a change of each of the forementioned variables has on the costs for hydrogen conversion (*Hy*) and home batteries (*Bh*) is shown in figure 34 and 35. All variables are taken 25% larger and 25% smaller than current estimations.

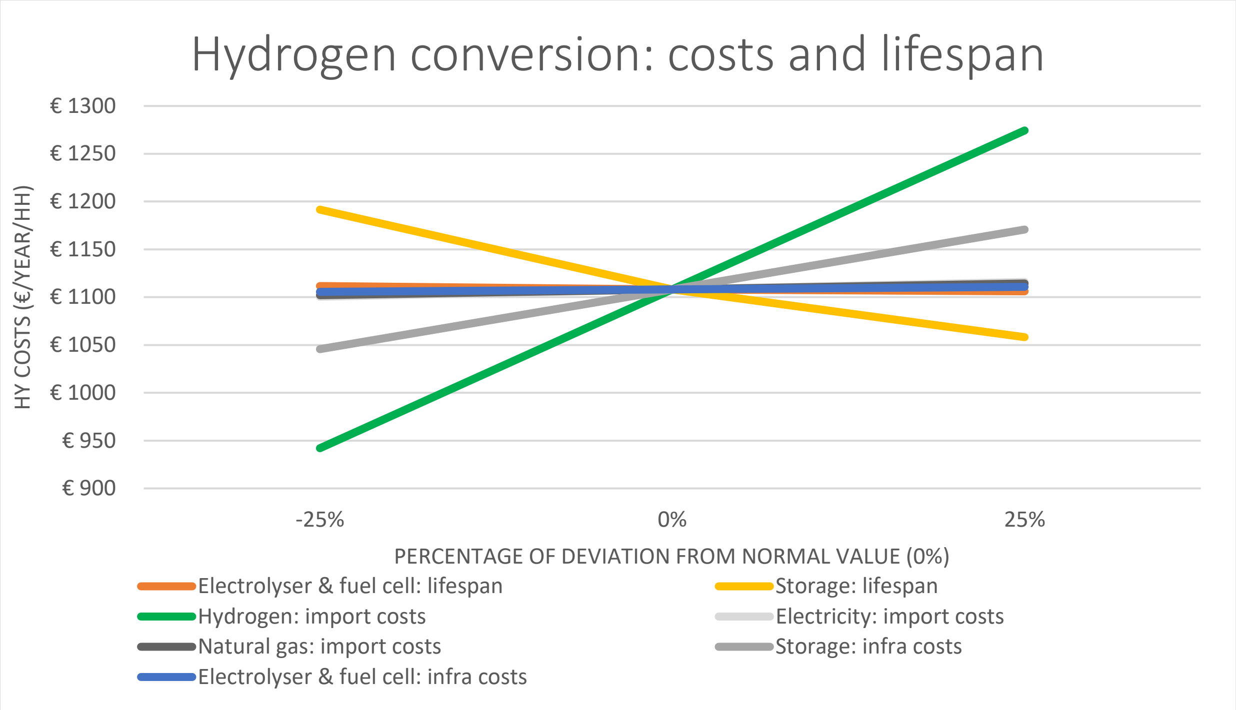


Figure 34: Sensitivity analysis of hydrogen conversion costs. The variables for energy import costs and the lifespan of the hydrogen systems are enlarged and reduced by 25%. This graph shows what the effect of a change in their estimated costs imposes to the total costs for the strategy of hydrogen conversion. The y-axis shows the total costs (€/year/hh). The x-axis shows the percentage (%) of deviation from the (currently estimated) normal value (0%).

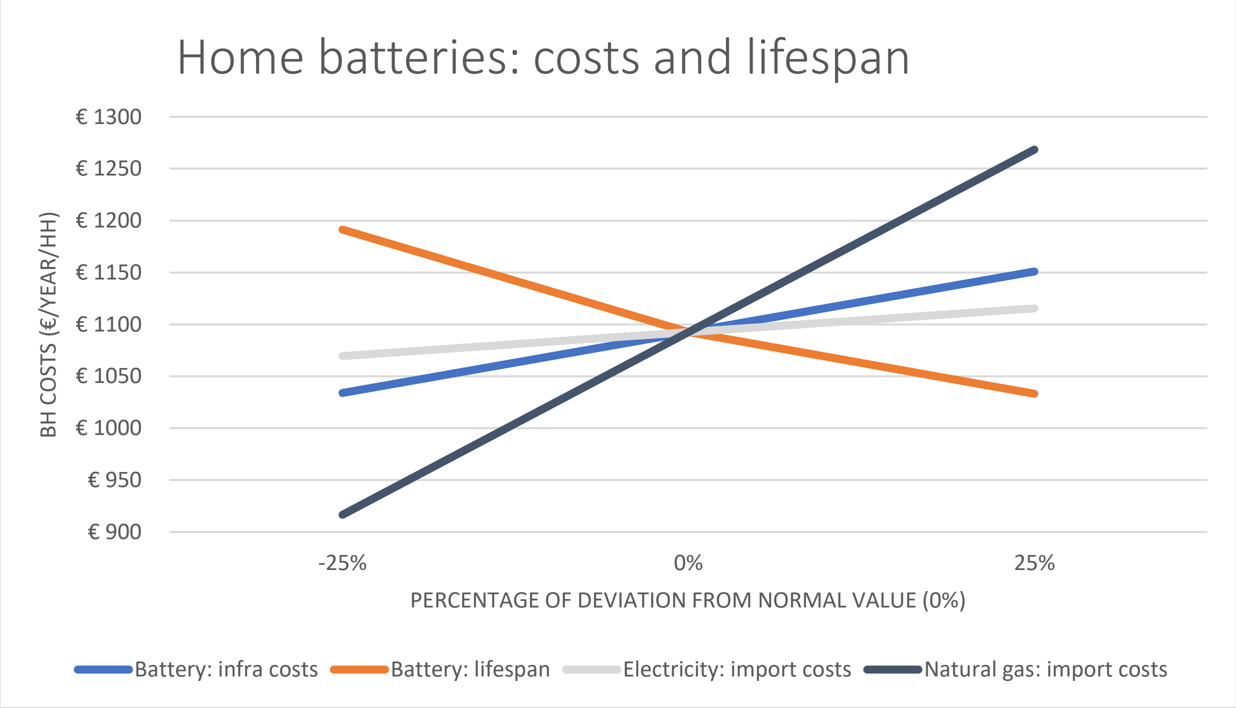


Figure 35: Sensitivity analysis of home battery costs. The variables for energy import costs and the lifespan of the battery systems are enlarged and reduced by 25%. This graph shows what the effect of a change in their estimated costs imposes to the total costs for the strategy of home batteries. The y-axis shows the total costs (€/year/hh). The x-axis shows the percentage (%) of deviation from the (currently estimated) normal value (0%).

For hydrogen conversion, the sensitivity analysis on the import costs and lifespan shows that the import costs for hydrogen are very sensitive. These costs impact the total costs for the strategy of hydrogen strongly: if the import costs of hydrogen would be 25% more expensive compared to current expectations, the total costs of the strategy grow 15%. Similarly, if they would be 25% less expensive, the total costs will be 15% less. 25% fluctuations in the infrastructure costs for hydrogen storage tanks show to increase or decrease the total costs of hydrogen conversion by 6%. Moreover, the lifespan of storage tanks is of importance. Reducing the lifespan by a quart increases costs by 7%. Improving the lifespan lowers the costs by 5%. Lastly, electricity and natural gas import costs show to have a small effect on the total costs for hydrogen conversion.

For home batteries, the sensitivity analysis shows that the price of natural gas imposes a large effect on the total costs of the strategy: 25% increase of natural gas price entails a 16% increase in total home battery strategy costs. 25% decrease entails a 16% decrease in total home battery strategy costs. Increasing or decreasing the lifespan of the battery by a quart changes strategy costs respectively -5% and +9%. 25% fluctuation of battery infrastructure costs implies 5% increase or decrease on the total strategy costs. Home battery strategy costs can be influenced by a 2% rise or decline if electricity import costs would be higher or lower, respectively.

Other than import and infrastructure costs and lifespan, also changing the storage and conversion capacities of a strategy can affect the total strategy costs. A sensitivity analysis on these effects for hydrogen conversion and home batteries is shown in figure 36 and 37.

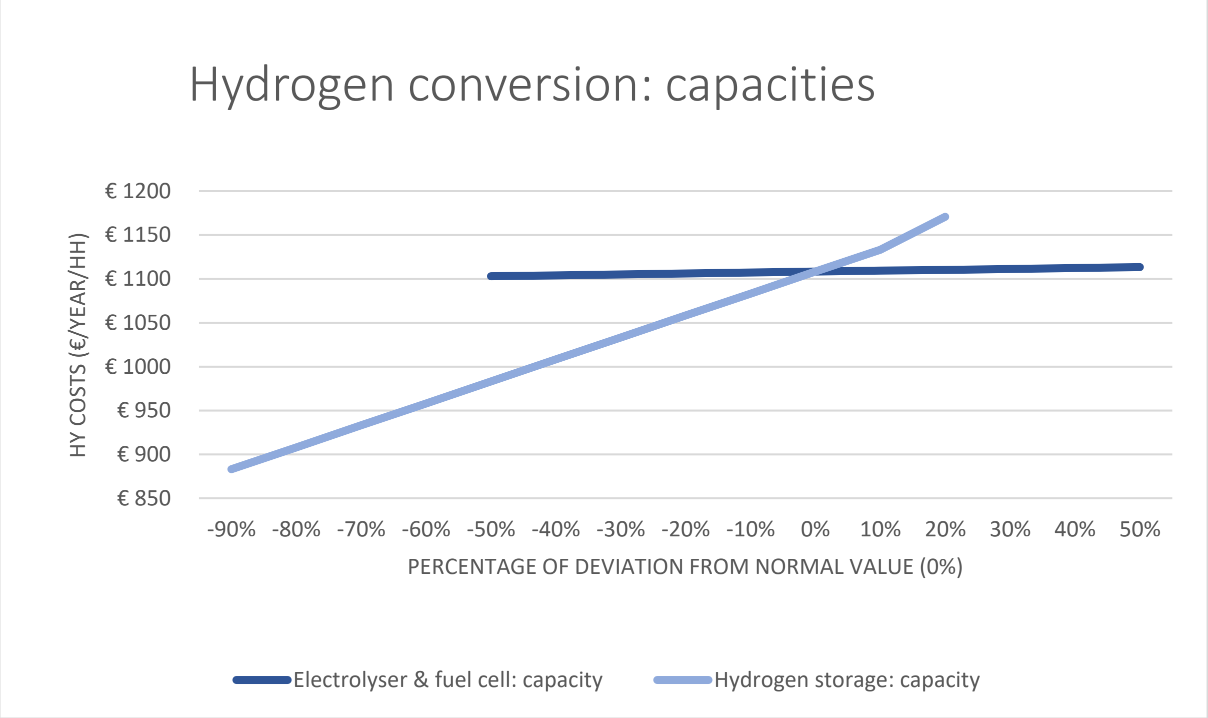


Figure 36: Sensitivity analysis of hydrogen conversion costs in relation to the capacity used for the hydrogen systems. The capacities of electrolyser & fuel cells and hydrogen storage systems are enlarged and reduced by 25%. This graph shows what the effect of a change in their used capacities imposes to the total costs for the strategy of home batteries. The y-axis shows the total costs (€/year/hh). The x-axis shows the percentage (%) of deviation from the (currently used) normal value (0%).

For hydrogen conversion, a change in the capacity of the fuel cells and electrolyser is not sensitive to the total strategy costs. The capacity of the used hydrogen storage tank is very sensitive for the costs of the total strategy of hydrogen conversion. A 50% reduction of capacity would entail 11% of costs to be spared. A 90% reduction would spare 20% of the total costs needed for hydrogen conversion. This is relevant as figure 38 shows that the hydrogen storage tank in *Hy* is never filled more than 150 kWh, although its capacity is 8000 kWh. This is similar for all the electrification scenarios. Only 2% of the storage capacity is used. This could reduce costs over 20%, making hydrogen conversion a very cost-efficient strategy. In case a storage capacity of 800 kWh or smaller would be used, the overvoltage mitigation strategy of hydrogen conversion would be more economical than the *Curtailment,* the MVC. This would further improve if the infrastructure costs of retrofitting the natural gas grid and installing hydrogen boilers are neglected due to the implementation of a hydrogen economy (see section *infrastructure and energy import*). The effect that this would have on the costs as compared to the other strategies can be seen in figure 39. As stated before, *Hy* is the most economical strategy of all strategies. Furthermore, combining hydrogen conversion with home batteries is more economical than home batteries on their own because adding hydrogen conversion decreases the import costs. To clarify once more: the costs shown in figure 39 are not the total costs needed for implementing all these systems in general. The figure shows costs needed solely for overvoltage mitigation. Here, retrofitting the natural gas grid for hydrogen and installing hydrogen boilers is disregarded as a costs needed for overvoltage mitigation. Namely, figure 39 shows a scenario where the hydrogen economy is expected due to which retrofitting costs and boiler costs are made regardless of overvoltage mitigation.

For home batteries, the used storage capacity also is sensitive to the total costs for the strategy of home batteries. A reduction of half of the capacity decreases costs with 14%. Installing 30% more storage capacity increases the strategy costs by 8%. This is relevant as the installation of home batteries is highly dependent on the willingness of residents. They are the ones that need to install them. Therefore, it is likely that less storage capacity is implemented. This would imply lower costs, but also larger levels of overvoltage, or curtailment needed.

Concluding, for hydrogen conversion hydrogen import costs and installed storage capacity are very impactful on the total strategy costs. Also changes in storage lifespan and infrastructure costs can be of consequence. Fluctuations to electricity and natural gas import costs shows not to be sensitive for the total strategy costs. For home batteries especially natural gas import costs and the lifespan of a battery are sensitive. Also the installed capacity is very important for the costs. The battery's infrastructure costs and electricity import costs less so. The effects described here should be taken in consideration when evaluating different strategies.

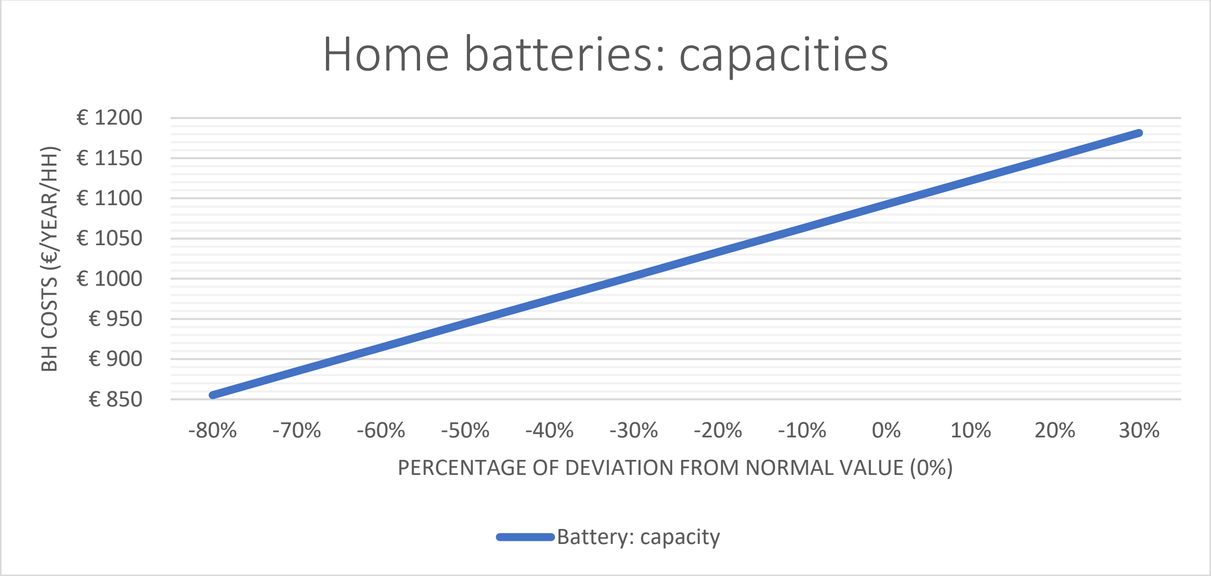


Figure 37: Sensitivity analysis of home battery costs in relation to the capacity used storage systems. The capacities of the home batteries are enlarged and reduced by 25%. This graph shows what the effect of a change in their used capacities imposes to the total costs for the strategy of home batteries. The y-axis shows the total costs (€/year/hh). The x-axis shows the percentage (%) of deviation from the (currently used) normal value (0%).

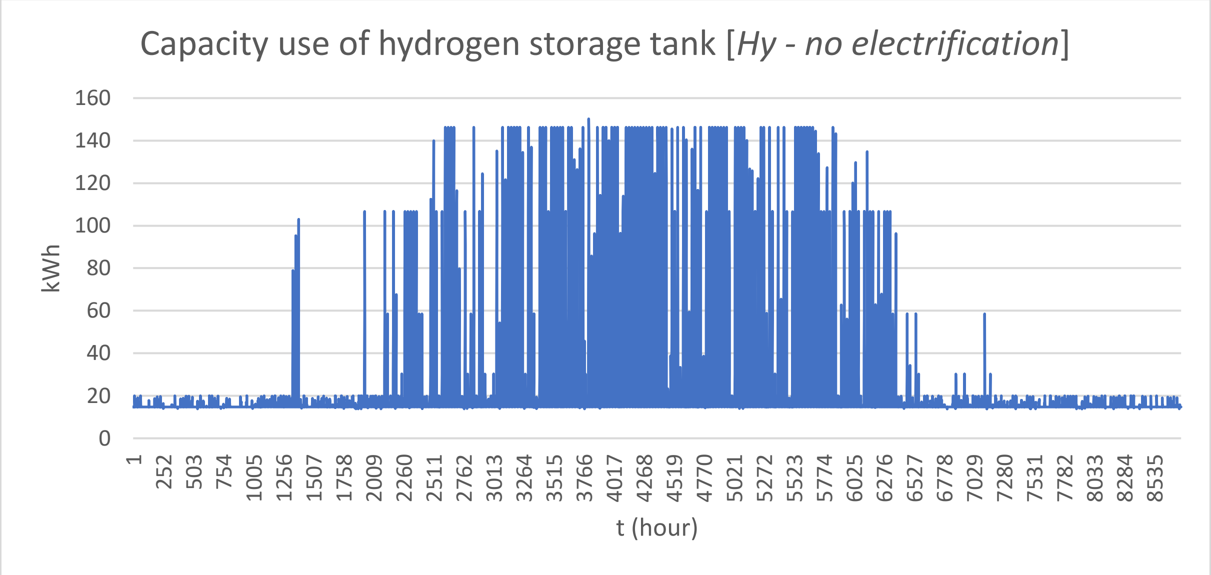


Figure 38: Capacity use of the hydrogen storage tank in the strategy of *Hy* (no electrification). The used capacity is shown per hour over the year of 2019.

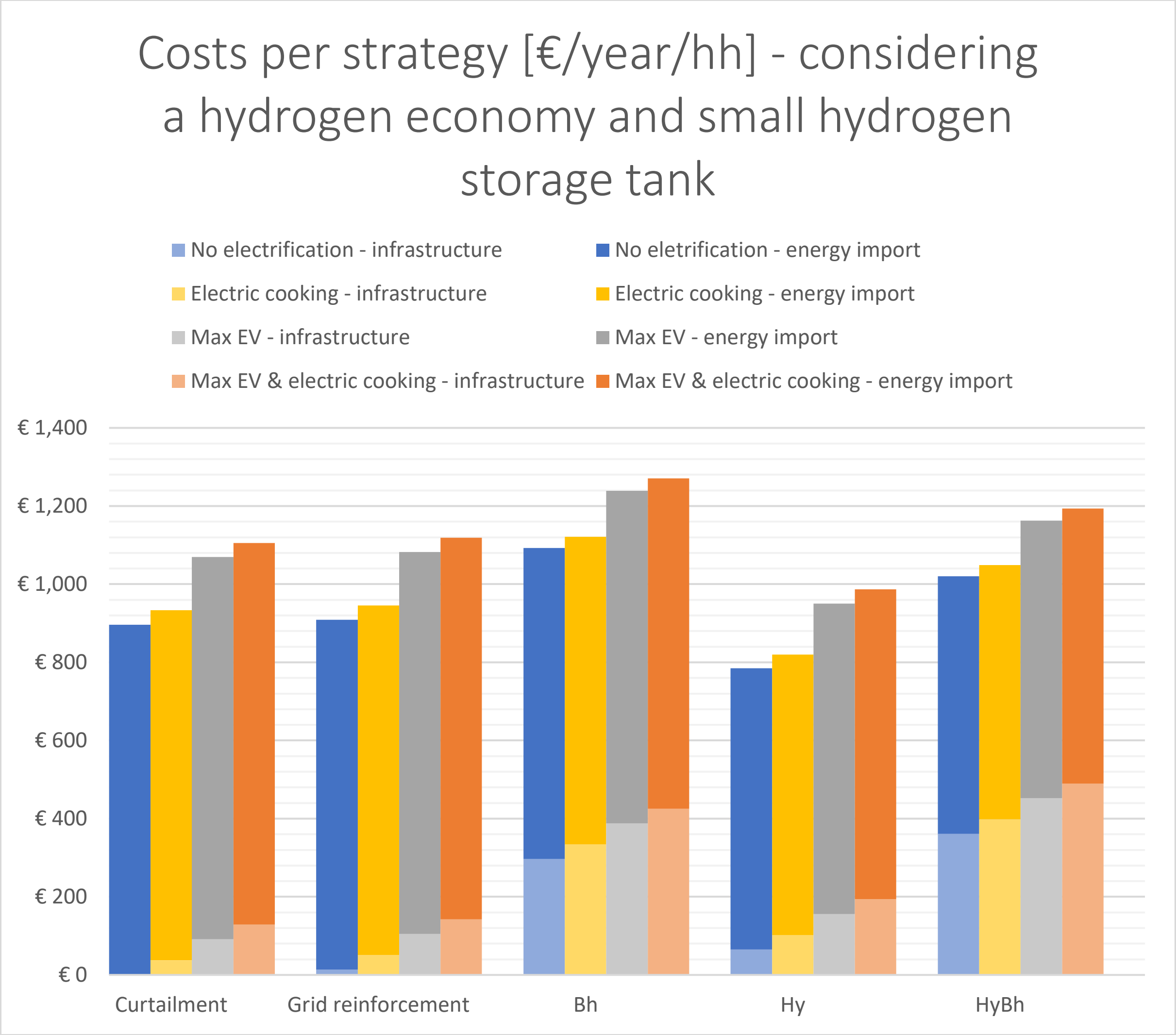


Figure 39: Yearly costs per strategy for each of the energy configurations, as shown per household [€/year/hh], while using a small hydrogen storage tank (800 kWh) for *Hy* and *HyBh* and while considering a hydrogen economy: the natural gas grid is yet retrofitted for hydrogen and hydrogen boilers are already installed. Therefore, these costs can be neglected The total costs are a combination of infrastructure costs (CAPEX & OPEX) and costs coming from imported energy (electricity, natural gas & hydrogen).

5.2.6.3 Spatial implications

	Spatial impact		
	public	*residential*	total
GridReinforcement	-	-	-
Curtailment	-	-	-
Bh	-	+	+
Hy	+++	-	+++
Cook	-	-	-
EVmax	+	-	+

Table 10: Spatial impact, both public and residential, for each of the individual strategies mitigating overvoltage.

In table 10, the spatial impact of all individual strategies mitigating overvoltage can be seen. The conventional strategies *Curtailment* and *Grid reinforcement* do not have any spatial impact. *Home batteries* have a small residential spatial impact. The mitigation strategy of *hydrogen conversion* has a large public spatial impact: the collective electrolyser, fuel cell and storage tank all require a space around the size of a standard container. Electrifying cooking demand does not have any spatial impact: induction furnaces have the same size as gas furnaces. Implementing charging stations for a fully electrified vehicle sector will have a small spatial impact in public space.

		Spatial impact		
		public	*residential*	total
Grid reinforcement	No electrification	-	-	-
	Electric cooking	-	-	-
	Max EV	+	-	+
	Max EV & electric cooking	+	-	+
Curtailment	No electrification	-	-	-
	Electric cooking	-	-	-
	Max EV	+	-	+
	Max EV & electric cooking	+	-	+
Bh	No electrification	-	+	+
	Electric cooking	-	+	+
	Max EV	+	+	++
	Max EV & electric cooking	+	+	++
Hy	No electrification	+++	-	+++
	Electric cooking	+++	-	+++
	Max EV	++++	-	++++
	Max EV & electric cooking	++++	-	++++
HyBh	No electrification	+++	+	++++
	Electric cooking	+++	+	++++
	Max EV	++++	+	+++++
	Max EV & electric cooking	++++	+	+++++

Table 11: Spatial impact, both public and residential, for all energy configurations.

In table 11, the spatial impact of all energy configurations can be seen. The mitigation strategy where home batteries and hydrogen conversion are combined, in a scenario where all vehicles in the case study area are electric and can be charged (*Max EV* and *Max EV & electric cooking*), has the largest spatial impact. The conventional strategies of *Curtailment* and *Grid reinforcement* in the scenarios without electrification (*no electrification*) and electrified cooking (*electric cooking*) have the smallest spatial impact. The strategies involving hydrogen conversion have a large impact due to their spatially demanding infrastructure in the neighbourhood.

From the non-conventional system integrational mitigation strategies home batteries are spatially the least impacting, although their impact is the only residential impact. This can be of importance for the willingness for residents to cooperate with (installing) a certain mitigation strategy. For residential spatial impact, the size of the residence should be taken in account. On average, the 1-floor apartments and the shops in the case study area Diamantbuurt have a surface of 80 m^2. The home batteries have a surface of 0.11 m^2 and a volume of 0.13 m^3 (see section 3.4.3) meaning that spatial impact in the buildings is small.

5.2.6.4 Social acceptance

As described in section 4.1.2, for social acceptance on the implementation of local energy technologies certain aspects are of importance: (a sense of) co-ownership, local benefits (grid independency, savings on yearly energy bill, using a high share of renewable energy) and involvement in the planning process (taking their needs and opinions seriously).

For mitigation strategies with residential impacts, installing home batteries (*Bh*), hydrogen boilers (*Hy*), induction furnaces (*electric cooking*), co-ownership is evident. It is wise to give notice on local benefits using HEMS that provide information on (local PV) energy use and energy bill savings. For the aforementioned strategies, involving citizens in the planning process is of crucial importance as they have to be encouraged to cooperate with the installation. This could for instance be done with subsidies and providing clear information. Here, it should be noted that most residences in the case study area are rental, and two-third is owned by a housing corporation. Therefore, commercial landlords and housing corporations should also be considered in the decision-making process. Furthermore, commercial landlords and housing corporations are likely to be the ones financing the needed residential infrastructures making it potentially easier to finance the implementation.

In case of the mitigation strategies that are implemented collectively in public space, it is more challenging to reach a sense of co-ownership. Again, transparent information provision is key: communicate what the use of the installed technologies is, and to where the energy is being provided (locally). Benefits of the installed energy technologies should be communicated clearly and ideally continuously (through for instance an app, via the energy bills or on a central informative screen in the neighbourhood next to the implemented infrastructure). Lastly, for collective mitigation strategies with a big spatial impact (*Hy and HyBh*), it is essential to let the local residents participate in the planning process, as it is directly impacting the public space in their neighbourhood.

Certain mitigation strategies cause a lot of temporary nuisance due to construction work. Especially *Grid reinforcement* due to the reinforcement of the electricity grid for which the streets have to be opened up and/or the MVS's have to be upgraded. This has an impact on the residents and could reduce acceptance.

Curtailment does not cause any impacts due to spatial use or maintenance nuisance, however it does let PV-owners lose free generated energy. This could also pose resistance.

All of the consequences named above should be regarded in the decision-making process.

5.2.6.5 Results

Previously, all potential overvoltage mitigation strategies have been assessed by their energetic, financial, spatial and social implications. The results of the assessment will be discussed in this section. This will be done by first stating some general effects. Next, the results are stated per electrification scenario. Subsequently, the results are evaluated taking into consideration various wider aspects such as the ambitions of Amsterdam, the differences between conventional and system integration strategies and the implication of a hydrogen economy. Lastly, some recommendations are made for local governments, planners, DSO's and policy makers.

Combining home batteries with hydrogen conversion (*HyBh*) to mitigate overvoltage is very effective, as can be seen in figure 28. Especially in combination with electrification of cooking demands and vehicles. *HyBh* requires the smallest amount of energy to be imported from the grid, making it an independent and thus resilient mitigation strategy. However, at the same time *HyBh* is the most expensive strategy and has the largest spatial impact.

More financially feasible is the individual implementation of home batteries, *Bh*, or hydrogen conversion (*Hy*). These energy configurations have similar costs involved. Installing home batteries requires the least spatial impact, although it is residential impact. Therefore, it is dependent on the preference of citizens and planners as well as on the available public or residential space whether home batteries or hydrogen conversion is a more favourable overvoltage mitigation strategy. Regarding levels of curtailment it is dependent on the electrification scenario if home batteries or hydrogen conversion is more effective. For the scenario where all vehicles and cooking demands are electrified *Bh* is the most effective. Otherwise, if only vehicles are electrified, only cooking is electric or without electrification, hydrogen conversion is more favourable.

If choosing between *Hy* and *Bh*, regarding also the difference in energy import, it depends on the electrification scenario which one is the most advantageous overvoltage mitigation strategy as a whole for case study area Diamantbuurt. For the *no electrification* and the *electric cooking* scenarios *Hy* imports the least energy. For *Max EV* and *Max EV & electric cooking* mitigation strategy *Bh* imports the least. Again, as is explained in section *Infrastructure and energy import*, this is because batteries, having a capacity that is easily filled, benefit well from increased electricity demands, or electrification, as it spares their storage capacity for overvoltage mitigation. Therefore, more excess PV generation can be stored for later moments, reducing import demands. The costs for the strategy of *Hy* are very dependent on the hydrogen storage capacity installed. Capacity levels in the case study show to be only filled up to 150 kWh. Therefore, only a small storage capacity would be needed. In that case, hydrogen conversion is the most cost-efficient strategy of all mitigation strategies, including the conventional strategies. Now, the combination of *HyBh* also is cost-competitive as a overvoltage mitigation strategy. A small hydrogen storage capacity can be installed as hydrogen is not stored because it is used for heating the built environment. Therefore, using small storage capacities is only possible in a scenario where the hydrogen economy is realised.

In the following sections, first, the scenarios without the consideration of a hydrogen economy are evaluated. Subsequently, the results are stated in case the hydrogen economy is regarded. The following can be concluded for the different electrification scenarios:

Max EV & electric cooking

Bh is the best overall overvoltage mitigation strategy for the electrification scenario with all vehicles and cooking plates electrified: *Bh* has the least curtailment demand, the least energy demand and the smallest spatial impact compared to hydrogen conversion. Costs are competitive, although *Bh* is slightly cheaper than *Hy*.

No electrification

For the scenario without extra electrification, *Hy* is the most advantageous regarding curtailment need and energy import. Price-wise *Bh* and *Hy* are almost similar - *Hy* is only slightly more expensive than *Bh,* but the difference can be disregarded. Therefore, *Hy* is the best overvoltage mitigation strategy in the *no electrification* scenario. *Hy* does require more spatial impact than *Bh*, although the impact of home batteries is residential which complicates the implementation.

Electric cooking

For the electrified cooking scenario, *Hy* is also the most advantegous regarding curtailment need and energy import. Price-wise, *Bh* and *Hy* are almost similar - *Hy* is only slightly more expensive than *Bh,* but the difference can be disregarded. Therefore, *Hy* is the best overvoltage mitigation strategy in the *electric cooking* scenario. *Hy* does require more spatial impact than *Bh*, although the impact of home batteries is residential which complicates the implementation.

Max EV

In the electrification scenario where all vehicles are EV's and can be charged in the case study area (*Max EV*), it is a bit more ambiguous. *Bh* is the most efficient scenario in terms of energy import and spatial impact. Whereas *Hy* is more effective against curtailment, and thus overvoltage. Regarding the costs, they are fairly similar – *Bh* is slightly cheaper than *Hy*. For all aspects, differences are fairly small, thus choosing one over the other could depend on local choices being made: will a hydrogen economy be realised and heating be done using hydrogen? Do citizens' prefer public spatial impact or residential spatial impact? etc. The choice will depend on citizens' and planners' preferences.

From the case study perspective, as *Hy* is more advantageous against overvoltage and taking into account that Amsterdam ambitions to use sustainable gas – hydrogen – for heating the built environment, this is the favourable overvoltage mitigation strategy in the *Max EV* scenario.

Limited available (public) space

In case there is little to no (public) space available for the implementation of overvoltage mitigation strategies, the aforementioned arguments on energy-efficiency and costs can be overruled by the spatial implications of the mitigation strategies. In that case, using home batteries, *Bh*, is more favourable over *hydrogen conversion*. However, in the case study area Diamantbuurt, there is spatial potential on Smaragdplein, the square in the middle of the neighbourhood. Possibly, infrastructure could even be installed underneath the sports field.

Social acceptance

For the overvoltage mitigation strategies to succeed in reality, they need to be accepted by local stakeholders. For this, the following aspects are of importance: co-ownership, local benefits and involvement in the planning process.

For systems implemented within residences, (home batteries, electric furnaces, hydrogen boilers) co-ownership is straightforward. For collective systems as for hydrogen conversion reaching (a sense of) co-ownership is more challenging. Therefore, transparent information provision is key: communicate clearly what the (local) benefits of a technology or energy system are on for instance the yearly energy bill and the environment. This could for instance be done by having a centralised platform, online or outside in the neighbourhood, and by giving additional information on yearly energy bills. Such information on the benefits of a strategy is also recommended for the residential systems.

Lastly, involvement of the stakeholders in the final-decision making process is key. This should be done in a participation process. When making decisions, the needs and concerns of local stakeholders should be taken seriously. This will improve social acceptance drastically, causing the strategies to be more likely to succeed in reality.

Ambitions of Amsterdam

The municipality of Amsterdam ambitions to use a ‘sustainable gas’, as for instance hydrogen, for heating the built environment in the Diamantbuurt. Therefore, citizens can apply for subsidies that can be used to help realising the transition from getting the city ‘off the gas’ (see section 5.2.4). Up to €5000 can be obtained if the investments are in line with the city’s plans (using hydrogen), or up to €3000 if they are for an alternative. Considering this, *Hy* can be seen as an interesting overvoltage mitigation strategy as costs will be relieved from citizens and therefore social acceptance is likely to be higher.

Electrification

As seen in figure 28, electrification in general helps reducing curtailment levels and thus mitigates overvoltage. Therefore, from an overvoltage perspective, it is wise to encourage electrification of cooking and the mobility sector. Especially the mobility sector as the amount of EV’s is expected to increase 6.5x by 2040 (Agentschap NL, 2019), and Amsterdam ambitions to ban polluting vehicles from the city by 2030 (Gemeente Amsterdam, z.d.-c). Thus, more charging infrastructure has to be installed. At the same time, by imposing large new electricity demands due to electric vehicles it must be considered that the grid could also be overloaded. Therefore, smart charging is needed to make sure that the EV’s use the PV generated electricity wisely. Else, it is likely that the electricity grid still has to be reinforced (T. Fens, personal communication, 19 November, 2021).

From a wider energy transition perspective encouraging electrification is also advantageous as electrification can help decarbonising the mobility and built environment sectors. Policies and subsidies can help catalysing the process of electrification.

Choosing conventional or system integration

Financially, *Curtailment* is the cheapest of all overvoltage mitigation strategies: *Curtailment* has the MVC, therefore looking at a purely financial perspective, conventional strategies are favourable over system integration strategies. Cost-wise, *Curtailment* is followed by G*rid reinforcement* being only slightly more costly. *Grid reinforcement* also is the most effective strategy to battle overvoltage as no curtailment is needed. Furthermore, both *Curtailment* and G*rid reinforcement* do not cause any spatial impact. Therefore, they still should be regarded as potential overvoltage mitigation strategies.

At the same time, both C*urtailment* and *Grid reinforcement* require the most energy to be imported from the grid, making the case study area more grid dependent and thus less resilient. High imports also mean that there is no possibility to influence the amount of green energy that is being used. Therefore, aiming for little import needs is a good way to promote sustainable energy sources. In that line of thought, non-conventional system integration overvoltage mitigation strategies are more favourable. At the same time, if the energy transition will take flight over the coming decades, the overall share of renewable energy in the grid will grow. Then the latter argumentation does not add up. However, using energy storage and conversion strategies will make the neighbourhood less grid dependent and thus more resilient. Furthermore, effectively using a bigger share of the locally generated solar energy in the local environment will also foster the realisation of the energy transition as a whole: system integration strategies couple the built environment sector (space and tap water heating), the mobility sector (EV/electric boats) and the energy sector (PV generation). This allows for the integration of energy flows between the three sectors, optimizing the overall energy use and therefore realising a more resilient and sustainable energy system. Another benefit of system integration is that generated PV energy is used close to where it is produced, benefitting local communities and thus increasing social acceptance. Moreover, system integration strategies are easy to scale, causing overvoltage mitigation to be more flexible and locally optimal. Bearing in mind the aforementioned wider goals as reducing global emissions and the energy transition, overvoltage mitigation using system integration is more favourable than the conventional strategies of *reinforcing the grid* or *curtailing*.

Considering a hydrogen economy

In case the hydrogen economy is realised, a small hydrogen storage capacity can be installed as there is a continuous hydrogen heating demand. Moreover, grid retrofitting and hydrogen boiler costs can be neglected. Then, hydrogen conversion imposes less costs. In such a scenario, the combination of home batteries and hydrogen conversion is the most effective overvoltage mitigation strategy. It requires very small levels of curtailment to mitigate overvoltage, it has the lowest energy import demand and it is more economical than home batteries alone. However, it is more expensive than the conventional overvoltage mitigation strategies and *Hy.* Furthermore, the combined strategy does imply the largest spatial impact – both communal and residential. This should be taken into consideration for the decision making process with local stakeholders.

Considering the hydrogen economy, *Hy* is the most economical strategy and therefore also an interesting option. It has lower energy import levels than *Bh*. Moreover, in electrification scenarios *no electrification, electric cooking* and *maximum EV*) it is more effective against overvoltage than *Bh*. It does have more spatial impact than *Bh*, however its impact is in public space instead of residential which might be of consequence. At the same time, *Bh* imposes more sense of ownership as it is owned by residents. This should all be considered.

The sensitivity analysis showed that the hydrogen import costs are a very impactful factor for the total strategy costs of hydrogen conversion. This is an important consideration for the decision-making process as it can imply that costs for the hydrogen strategies end up to be higher than currently expected.

Recommendations for local governments, policy makers, planners and DSO's:

1) When the ambitions of Amsterdam are realised and the case study area will indeed be heated using hydrogen as a sustainable gas, then it is recommended to use hydrogen conversion as an overvoltage mitigation strategy: retrofit the gas grid for hydrogen and install an electrolyser, a fuel cell and a hydrogen storage tank in the neighbourhood. In that case, the infrastructure is not solely implemented for overvoltage mitigation purposes, but also for the realisation of the energy transition and the hydrogen economy. This strengthens the business case for both purposes. In this case the needed hydrogen storage capacity is small which positively influences the costs greatly. Moreover, as the costs for retrofitting the grid and installing hydrogen boilers now have to be made regardless of overvoltage mitigation strategies, they can be neglected for the needed overvoltage mitigation costs. This causes hydrogen conversion to be the most economical overvoltage mitigation strategy. On top of that, citizens can apply for subsidies to help pay for the implementation of infrastructures needed for the transition to use hydrogen instead of natural gas for heating. For instance, for installing a hydrogen boiler and electric cooking plates (as cooking cannot be done with natural gas anymore). Therefore, it is likely that citizens will be more acceptant towards this transition. All of this makes hydrogen conversion as an overvoltage mitigation strategy even more promising.
2) In case the city's ambitions are not followed through, the (local) hydrogen economy will not be realised and hydrogen is not used for heating the built environment. Then, it is

recommended to use home batteries for overvoltage mitigation instead of hydrogen conversion. Home batteries proof to function well as overvoltage mitigation strategy with high extra electric demands due to electrification. Especially in combination with EV’s. Not only do EV’s pose extra electric demands, they can function as extra battery capacity – also supplying back electric energy when needed, potentially offering even better system integration. However, this functionality was not simulated in the case study (see recommendations in section 6.2.6). As further electrification in the mobility and built environment sectors is expected towards the future, home batteries can pose a good opportunity for system integration. Especially in addition to demand response, smart charging and/or HEMS. These should thus be promoted. Furthermore, home batteries benefit the PV-owners better as they hold ownership over their own stored energy.

3) It is inevitable that the mobility sector will be electrified. For this reason, sooner or later, electric charging stations are needed. In 2030 it is expected that there will be more than 5x the amount of EV’s as compared to 2019, in 2040 even 6.5x (Agentschap NL, 2019). It is wise to implement as many electric charging stations as possible in the neighbourhood, close to solar production, as it helps reducing peak solar generation induced overvoltage in the electricity grid. The costs are relatively low, and they are not solely for overvoltage mitigation: they help the mobility sector transition into an electric and more sustainable one and therefore help realise the energy transition. As the electrification of vehicles is inevitable and serves multiple purposes, the costs can be neglected for overvoltage mitigation costs.

4) In case house owners renovate their kitchen and are implementing a new furnace, it is recommended to promote electric cooking plates. Electrification due to electric cooking reduces overvoltage levels, and as otherwise a natural gas furnace would have been installed, the infrastructure costs can (partly) be neglected as costs for overvoltage mitigation.

5) As slightly more than half of the inhabitants has a migration background, it is wise to pay extra attention on informing and involving residents in the decision making process on the various options for overvoltage mitigation. Furthermore, employment rate as well as the average income of residents is lower than the Dutch average. This should be considered when making decisions on overvoltage mitigation strategies in terms of financial implications.

6) The majority of residences are rental. Moreover, almost two-third is owned by housing corporations. This should be considered for the implementation of residential overvoltage mitigation infrastructure (installing hydrogen boilers, home batteries or electric cooking plates) as not only inhabitants but also property owners should be involved. It is likely that the latter will need to finance the infrastructure.

6. Discussion

The discussion is two-fold. First the functionality of the TENOMF is discussed whereafter the case study and its results are considered.

6.1 Discussion on TENOMF

As the case study results show, the TENOMF can be used as a generic framework to depict low-voltage grid overvoltage mitigation strategies. However, some limitations and points of discussion should be mentioned. These can be categorised in four themes: general, assessment criteria, concept development and data gathering. Subsequently, recommendations for the further improvement of the TENOMF are stated.

6.1.1 General

Overall, having the right information available, the TENOMF can be used to depict various overvoltage mitigation strategies as fitting for the local environment. At the same time, the framework is not very strict: in each step, a lot is left up for interpretation and choice of the user. The framework does not pose absolute guidelines that are necessary to follow. Instead, it hands a bounded outline which helps guiding the user but at the same time leaves room to make choices up to own preference.

Due to this, not one single solution as overvoltage mitigation strategy comes out of the TENOMF. Instead, multiple optional strategies are presented, accompanied by their advantageous and drawbacks as well as the considerations of why (and in what situation) one strategy could be chosen over another.

Some could argue this to be a flaw. Scientific literature on energy system design as Jansen et al. (2020) does have a selection step included in their approach. However, their assessment of energy systems is solely based on technical aspects, making it easier to argue for one or two ideal solutions. Murray, Orehounig, Grosspietsch & Carmeliet (2018) do not select one strategy. Their study shows a variety of solutions for the case studies while considering technical and financial aspects. They state that ultimately it is up to the preferences of decision-makers to decide what the ideal solutions are. Similar thoughts where considered while creating the TENOMF, although with the important addition that the preferences of local stakeholders should be considered as well. When planning the energy transition in a complex environment as the city, and especially in the small scale of a neighbourhood taking into account the needs and wishes of many local stakeholders, there will never be one absolute solution. Therefore, it is good to have multiple options so that final decisions can be made together with local stakeholders using participation strategies. This is in line with the conclusions of Hettinga et al. (2018), who state that including local stakeholders in the decision-making process improves the acceptance and likeliness of an energy strategy to succeed locally.

Currently, the TENOMF advises policy makers and planners to consider the potential overvoltage mitigation strategies and recommendations coming out of step 6 of the framework. Hereafter, the TENOMF advises to involve citizens as to participate in the final decision-making. This is analogue to what Hettinga et al. (2018) propose on how it should be done in neighbourhood energy system planning and design. However, in the TENOMF, this participation decision-making process – the steps-to-take after step 6, are left in the dark and can thus be interpretated differently by various policy makers or planners. An improvement to the TENOMF would be to make the steps-to-take after step 6 explicit: the steps for the decision-making process with the participation of local stakeholders should be included. The six-step framework of Hettinga et al. (2018) on stakeholder involvement for energy system planning shows potential to add onto the TENOMF: the potential strategies and recommendations coming out of the TENOMF could be used as input for the framework of Hettinga et a. (2018). However, both frameworks in their current forms have overlapping steps. For instance the framework of Hettinga et al. (2018) also makes an impact analysis of the potential strategies. Therefore, as this is already (partly) done by the TENOMF, further research should evaluate if and how the TENOMF and the 'multi-stakeholder decision support system for local neighbourhood energy planning' as coined by Hettinga et al. (2018) could be combined as an improvement on wholistic overvoltage mitigation planning.

6.1.2 Assessment criteria

In this section, the limitations and points of discussion concerning the assessment criteria of the TENOMF – energetic implications, costs, spatial impact and social acceptance – are discussed.

6.1.2.1 Energetic implications

Overvoltage simulation using PtX

The biggest limitation to the effectiveness of the TENOMF in its current form is the model used for the calculation of the energetic implications: the PtX model. This is because PtX is not designed specifically for the purpose of calculating overvoltage levels in electricity grids. The overvoltage calculations of PtX are therefore an oversimplification of reality. This is due to three reasons.

1) The time interval of PtX's calculations is hourly.
2) Overvoltage is measured in a rule-based way and is solely based on the capacity of the MVS: the capacity of the MVS is X. If the capacity X is used at time t, PtX states overvoltage at time t.
3) PtX does not calculate voltage fluctuations and power quality in the electricity grid. It does not consider fundamental electrotechnical parameters.

In the following section, the implications that the three aforementioned limitations impose on the effectiveness of the TENOMF are discussed more elaborately. Subsequently, recommendations for improvement are stated.

As mentioned, PtX's workflow is hourly: both the inputs it uses and the outputs it gives are hourly. Therefore, PtX is less accurate in noticing high solar irradiation peaks as these can also occur for shorter periods of time. This entails PtX to be less accurate in identifying PV peak induced overvoltage which has direct consequences for the calculations of the energetic implications of overvoltage mitigation strategies. A higher time-granularity in PtX's calculations could improve this limitation. The higher the granularity, the more realistic the calculations. However this also makes the simulations heavy as the amount of calculations that need to be done for a year increases drastically. Furthermore, data on a higher time-granularity for solar irradiance should be available. Therefore, it is recommended for further research to identify what an optimal time interval would be for the calculation of overvoltage.

Next to PtX's level of detail, also the definition it uses for overvoltage is a basic representation of reality: for each hour the available capacity of the MVS is calculated based on electricity and supply. Whenever this capacity is completed, the model notes overvoltage. The calculations are thus rule-based, not based on fundamental physical principles. Actual voltage-levels in the MVS and LV grid are not calculated. As PtX measures overvoltage based on capacity, it does not consider voltage stability nor power quality.

The results of PtX's overvoltage calculations in the development phase of the case study were discussed with M. Verkou (PVMD group, TU Delft). Verkou researches PV induced overvoltage in LV-grids, and developed a model that calculate voltage levels. After comparison with his calculations, it was concluded that the levels of overvoltage identified by PtX were too little: with a similar PV capacity installed for the same graphical location, the model of Verkou showed overvoltage, while PtX did not. For that reason, it was decided to exaggerate the physical amount of solar panels that can be implemented in reality in the case study area. In that way similar overvoltage levels are obtained for the case study of TENOMF compared to Verkou's calculations. This impacts the energetic and financial results of the case study greatly: there is more PV generation available such that the neighbourhoods energy flow, and its energy import demands are effected. However, although the energy values might not approach the reality of the tested neighbourhood, at least the effectiveness of different overvoltage mitigation strategies could be compared amongst each other. It could be seen as a theoretical case study, as the exaggeration was the same for all simulations: stated the given case study scenario, it could be evaluated how the various mitigation strategies cope with the PV generations and energy demands. Relative differences between the mitigation strategies can be identified.

Another impact of the fact that overvoltage calculation is only based on the MVS's capacity entails that meshed grid cannot be simulated using PtX. As PtX only considers the MVS capacity, it disregards voltage-levels and power quality for its overvoltage calculations. This not only makes the overall calculations less precise, it also poses a specific problem for the calculations of case studies encompassing a meshed grid. Meshed grids are in connection with multiple MVS's. The MVS's in meshed grids have no specified service area. Therefore, it is impossible to tell what the MVS capacity of a bounded area is. However, to use PtX for overvoltage calculations it is a necessity to set an MVS capacity. This is problematic. To be able to use PtX for the case study, the service area of the MVS was estimated. The estimations were done looking at the spatial division of MVS's in the wider area of the case study and by assuming that all buildings in one housing block are connected to the same MVS. This does not represent reality and thus poses large uncertainties for the case study simulations.

To improve the energetic assessment of the TENOMF, the overvoltage calculation should be made more realistic. For this, the overvoltage definition in PtX needs to be improved. Firstly, this could be done by enlarging the time-granularity: calculate PV generations and energy demands for shorter time periods. Further research should look into an optimal time-scale for this purpose. Secondly, the overvoltage definition of PtX could be improved by considering voltage-levels and power quality in the electricity. Overvoltage calculations should not be rule-based. Overvoltage simulations should be done by calculating voltage levels while considering fundamental electrotechnical principles. The electricity grid has alternating voltages in a sinewave form. The ideal sine waveform, for which the voltage levels in the electricity grid are constant, have a certain constant amplitude and frequency. Fluctuations in amplitude and the frequency of the waveform cause differences in the voltage level. This impacts voltage stability. Fluctuations to the amplitude and frequency of the waveform that are large or for longer periods of time, cause overvoltage (van Oirsouw, & Cobben, 2011). Therefore, a model that aims to simulate realistic levels of overvoltage should calculate voltage levels by considering fluctuations to the sinewave form of the alternating voltage in the electricity grid. By Ohm's law ($U= I*R$), voltage (U) is dependent on current (I) and resistance (R). Thus, fluctuations to the alternating voltage sine waveform can be caused by an increasing or decreasing resistance in the electricity grid. This for instance happens when there is a high load. High loads imply resistance in the electricity grid such that the voltage levels decrease. The opposite scenario is when there is low load and high PV generation. Due to the low load, voltage levels in the grid were still normal. As PV generated electricity is now fed into the grid, voltage levels rise above normal values. This can cause overvoltage. An existing model that calculates overvoltage in such way, based on Ohm's law and the sine wave form, is Alliander's GAIA model. This model is specifically developed as to evaluate voltage levels for electricity grids. It simulates the situation of a case study based on opposite worst-case scenarios: high load, no PV generation and low load, high PV generation. Hereby it can evaluate for a specified grid if overvoltage will occur (P. Bonhof, personal communication, 6 December, 2021). This model cannot be used for the purposes of the TENOMF as it can solely calculate voltage levels for a statical scenario: it does not consider a time-scale. Therefore, it would not be possible to evaluate the effectiveness of various overvoltage mitigation strategies. Another model developed to calculate overvoltage levels is the model developed by TU Delft researcher M. Verkou (PVMD group). His model also works on fundamental electrotechnical principles as it is developed according to the principles for electricity grid calculations as stated in the book 'Phase-to-Phase'. (van Oirsouw, & Cobben, 2011; M. Verkou, personal communication, 25 March, 2021). This book describes the specifics and electrotechnical principles of Dutch electricity grids in detail. Unfortunately, the exact specificities of the calculations of Verkou's model, and if it would be suitable as an addition to the TENOMF are unknown. It is recommended to further explore the nature of this model by consulting M. Verkou. Then it can be evaluated if his model could be used as an addition to the TENOMF. More specifically, it could be evaluated if it can replace PtX, or be combined with PtX. Or that similar calculations as Verkou's model could be integrated within PtX. If all of this is not the case, then it is recommended to improve overvoltage calculations of PtX by implementing calculations based on fundamental electrotechnical principles – Ohm's law – instead of its current rule based definition.

To conclude, the biggest limitation to the TENOMF as it currently is, are the overvoltage calculations done by the PtX model: these are oversimplified and unrealistic. This should be improved by calculating energy flows on a smaller time scale than hourly. Further research should identify what an ideal time-scale would be. Furthermore, overvoltage calculations should not be rule based nor only consider MVS capacity. Instead, they should use fundamental electrotechnical principles by considering Ohm's law and calculating the sine wave form of the alternating voltage, alternating currents and resistances in the electricity grid. Further research should identify if such models currently exist and if they can be used for the purpose of the energetic and financial assessment of the TENOMF. If such models exist, they should be able to calculate overvoltage using a time-scale. Otherwise they are not suitable for the purposes of the TENOMF. In that case it should be evaluated if they can be used to improve the PtX model.

Housing typologies in PtX

To further have the energy assessment approximating reality, the amount of housing typologies in PtX could be extended. For instance, by distinguishing corner-apartments and apartments with a roof from enclosed apartments as this has an influence on the apartments heating demands. Currently, adding more building typologies in PtX is a time-consuming process. Simplifying this process would increase the TENOMF's ability to approximate the energy demands of the neighbourhood-to-assess, and thus improve the energetic assessment.

Assessment of system integration

Improvements could be made to the sub-criterion of the energetic assessment of the TENOMF: energy import demand. Currently in the TENOMF, an energy configuration with small energy import levels is considered more efficient and resilient compared to another. It is assumed to have more system integration. In scientific literature on energy system design different ways to evaluate a similar characterisation have been found.

In the SUI approach coined by Jansen et al (2020), the KPI's used to evaluate the neighbourhood energy systems also regard energy import. Likewise to the TENOMF, they have a KPI that evaluates a neighbourhood energy system on its energy import demand: the *Net energy input, per energy carrier*. However, where the TENOMF uses energy import demand to evaluate resilience and system integration, the SUI approach has a specific KPI to assess this, which they call autonomy: the KPI *Fraction of autonomy*. *Fraction of autonomy* is measured by dividing *Directly used local renewable energy generation* by *Total energy input needed for the area*. To have an assessment criterion specifically evaluating autonomy and/or system integration could be a valuable addition to the TENOMF. Currently this is considered by looking at energy import levels while weighing various additional aspects that could be of influence for the import levels. For instance: additional EV poses additional energy import levels, but can simultaneously improve system integration as it couples mobility and built environment sectors. While gasoline needed for gasoline vehicles is not seen in the energy flow. In a similar assessment criterion as the fraction of autonomy this problem would be solved as the evaluation is done as a fraction in regards to the configuration's own *total energy input needed for the area*: for a scenario with EV this would include EV demand and for a scenario without EV would not include this demand. For that reason it is more subjective than the assessment of the TENOMF.

In the study by Murray, et al. (2018), no assessment criterion for system integration or autonomy is considered. Instead, they regard CO2-emissions coming forth of a certain energy system. It can be argued that if a system is low in CO2-emissions, it is effective in system integration as it manages to use a large share of (stochastic) renewable energy for its (continuous) demands. Therefore, it shows to be able to load-shift by using storage systems. Furthermore, it can also entail the system to be autonomous, although similarly it could mean that it just imports large volumes of (low-emitting) renewable energy. Therefore, energy import could be considered additionally to the assessment of CO2-emmisions, or an assessment likewise to *fraction of autonomy* could be regarded. Such a combination of assessment criteria to evaluate system integration and autonomy could improve the TENOMF. However, adding CO2-emissions as a criterion ideally requires to conduct a life-cycle assessment of the energy systems used. PtX is not created for such a task. Adding this would be a time-consuming effort.

Another alternative way of improving the evaluation of a neighbourhood energy system's capability for system integration is to consider energy export next to energy import. This could be done with the current output of PtX as these export values are already calculated in the simulations. Less export implies that the neighbourhood is able to put to use its locally generated renewable energy effectively: self-consumption. In order to reach full system integration this is essential, as is also promoted by Petkov, Gabrielli & Spokaitem (2021) and Voulis, Warnier & Brazier (2017). Both studies regard energy export as an important evaluation for system integration. In the forementioned example of EV imposing extra import demands while simultaneously improving system integration, energy export levels could help indicate system integration: a configuration with more system integration will have lower export levels. Unless it generates so much renewable energy that it produces more energy than there are demands. In such case all local demands will be fulfilled and energy export can happen. However, then energy import levels would be zero. Thus, this can be evaluated easily.

An improvement to the TENOMF could thus be to use a coupled energetic assessment criterion analysing energy import and export. If this value is low, then the neighbourhood energy system has managed to match its energy generations and demands better, improving sector coupling. Moreover, if the total is high but the export levels are low, it still manages to locally put to use its renewable generated energy. Therefore it has better system integration. Although, like stated above, with the exception for when import levels are 0. Then export levels do not indicate low system integration: the neighbourhood has fulfilled its own energy demands, reaching complete internal system integration, after which it can export energy. Another exception is that the strategy of *curtailment* could potentially show high levels of import and low levels of export, as more PV generation is curtailed. An additional assessment criteria as SUI's *fraction of autonomy* could prevent such a strategy from being analysed as one with good system integration: *fraction of autonomy* would show that *curtailment* has lesser autonomy as a low share of its energy demand is fulfilled with local PV generated energy. It is thus recommended to add export and *fraction of autonomy* to the energetic assessment criteria of the TENOMF**.** In section 6.1.4, where the case study results are discussed, a first consideration is done on an energetic assessment criteria combining import and export levels.

6.1.2.2 Costs

In case energy export is added to the energetic assessment of the TENOMF – as is recommended in section 6.1.2.3, likewise, export should be regarded in the financial assessment: export costs (costs gained by selling hydrogen to the grid) should be subtracted from the import costs. To note, renewable generated electricity cannot be sold to the grid from 2031 in Amsterdam (Milieu Centraal, 2021), thus this does not have an effect on export costs.

The financial assessment, as it was done in the current study, is split in infrastructure and energy import costs. The infrastructure costs are transformed in to a yearly unit (€/year) as to be able to sum and compare them with the energy import costs. The transformation is done by a linear division by the infrastructure's lifespan. This is an oversimplification of reality. Costs are likely not to be spread over the course of the infrastructure's lifespan, but need to be paid at once. This could influence financial impacts and thus decision-making. The payment can also be done periodically using a loan. However, interest rates and inflation are then extra factors influencing the costs. The financial assessment of the TENOMF could be improved by regarding these yearly fluctuating cost components.

Furthermore, within the financial assessment of the TENOMF, all infrastructure costs are summed and compared between the overvoltage mitigation strategies as similar expenses. In reality, there is a difference between infrastructures that citizens need to pay and infrastructures that will be paid by the municipality. Due to this difference, costs will change as citizens have to pay taxes, whereas governments do not. This impacts the financial overview and should be regarded in the assessment of the TENOMF as well as in the evaluation of the various proposed overvoltage mitigation strategies in step 6.

6.1.2.3 Spatial impact

In the TENOMF, spatial impact is roughly classified using somewhat subjective criteria. These could be further specified. At the same time, it may also be argued that a rather rough classification suffices as the impact of space in a neighbourhood is quite subjective: one may experience it differently than another, moreover, aspects as design, colour and placement can be of great influence. For that reason it was decided to keep the classification rough and slightly up for interpretation. This is considered to suffice as the assessment of spatial impact is not used in a very quantitative way in the TENOMF: the impact is considered in a reasoning manner.

The TENOMF adds to scientific literature on energy system design and overvoltage mitigation by including spatial impact as an assessment criterion. The need for this criterion can be seen in the results as obtained by Murray et al. (2018). Their analysis on feasible storage systems for neighbourhood energy systems was done by an optimization of technical and financial aspects of storage systems. Their results showed that the optimal energy systems, chosen by the optimization algorithm, often include infeasible hydrogen storage systems: They would be too large for reality. For that reason, spatial impact is an important assessment criterion to add to energy system design. Technical and financial parameters do not tell the whole story for the successfully implementation of an energy system in a local context.

6.1.2.4 Social acceptance

The assessment of social acceptance in the TENOMF is introduced as being one of the four assessment criteria, however it is used quite differently than the other three as it is – even more than spatial impacts – a subjective matter. The assessment criterion of social acceptance is used as a discussion starter, to force the user to think about social impacts other than those quantifiable. This is deemed important to have technological solutions succeed in the social reality. Potentially, this does make the TENOMF vague and the guidelines of its use up for interpretation. However, the line of reasoning, and the aimed goal, is similar to the conclusions of Kelly & Pollit (2011) and Hettinga et al. (2018). Ketty & Pollit (2011) state that local governments working together with local stakeholders create larger impacts when implementing energy strategies, moreover, they are more likely to succeed. Hettinga et al. (2011) state that by including 'boundary conditions' as indicated by local stakeholders and taking into account the local context in the decision-making process, instead of only considering technical parameters indicating an energetically optimal energy system, a neighbourhood energy initiative is enriched and, on top of that, it enlarges the local support greatly. In this respect, the TENOMF makes an improvement to existing literature regarding (overvoltage mitigation) energy system design, that mostly considers technical (energetic) parameters and sometimes additional financial parameters for the assessment of a strategy. Various examples of such energy system design literature, that do not regard other aspects than technical and financial implications are stated: The SUI approach (jansen et al., 2020) only regards technical implications. Mehleri et al. (2012) assess optimal systems on technical and financial aspects. Petkov et al. (2021) also solely regard technical and financial aspects. Likewise for Murray, et al. (2018), although their technical implications also regard CO2-emissions. Hashemi Toghroljerdi & Ostergaard (2016) do state certain socially impacting aspects of the various proposed overvoltage mitigation strategies they discuss. Hhowever, these aspects are briefly named and their research considers a general overview of overvoltage mitigation. It is not an energy system design for a specific area.

6.1.3 Concept development

Bejan et al. (1996) defined the five steps of energy system design, where the second step is concept development. According to Jansen et al. (2020), most literature focussing on energy system design do not focus on this phase as they do not regard local area potentials, or as they focus too much on problem definition. For overvoltage mitigation, in existing scientific literature no generic method for energy system design existed yet, especially not one regarding wider energy transition ambitions. The TENOMF has a large focus on concept development and the local context. Therefore, this is a contribution to existing scientific literature. That being said, it should be stated that the step of concept development in the TENOMF can be improved. This has to do with boundaries due to the functionality of the used model: PtX.

In the TENOMF, after all overvoltage mitigation potentials of the neighbourhood are identified, neighbourhood fitting overvoltage mitigation strategies are chosen in step 5. Subsequently, they are simulated by PtX. Thus, it should be possible for a developed concept of an energy configuration to be added into PtX. If this is not the case, then the energy configuration cannot be assessed quantitatively using the TENOMF. Therefore, the step of concept development is bounded by the functionality of PtX. For this reason, the in step 5 chosen overvoltage mitigation strategies, to assess in the TENOMF, do not encompass all identified neighbourhood potentials as it could be that some cannot be added into PtX. This is unwanted as, according to Jansen et al. (2020), concept development is the most important phase of energy system design. In that phase, neighbourhood fitting energy configurations are explored and defined. Jansen et al. (2020) see this phase as the most important phase of energy system design because it allows for the creation of innovative and alternative locally fitting strategies as it takes into consideration local potentials and other important contexts. For that reason, this phase is needed to identify optimal ways for system integration. Therefore, it is of crucial importance that the chosen model can be used to simulate all developed concepts (potential overvoltage mitigation strategies). In the current version of PtX this is not possible as certain characteristics of strategies for storage and conversion cannot be simulated. Examples are: 1) If a certain energy configuration includes hydrogen production and a local hydrogen storage tank without grid connection (no export allowed), in reality the storage capacity of hydrogen storage tanks could be are full at a certain moment. However, the PtX model will then decide to export hydrogen as it cannot deal with a full tank. In reality, this would cause overvoltage, however, in PtX it de facto means the tank can be stored unlimited. 2) Demand response or smart charging cannot be simulated. 3) PtX calculates potential heat recovery due to losses of fuel cells and electrolysers per hour. However, the recovered heat cannot be used to fulfil the heating demands in the simulation of PtX. 4) In PtX, EV's operate one-way. They demand extra electricity, however, they cannot act as an additional battery that is able to return electricity to the neighbourhood when needed. This concept operating in a two-way is called vehicle-to-grid.

An example of an overvoltage mitigation potential of the case study that was named step 4 but not simulated in PtX, and thus not regarded in the case study results, is the potential of charging electric boats in the case study area. As recreational boats often sail during sunny periods, and Amsterdam ambitions all boats to be electric by 2040, this is an interesting opportunity for overvoltage mitigation. Especially in combination with battery storage: the battery could charge during the peaks of solar irradiance, when the boats are sailing. Subsequently, the boats dock overnight with an empty battery and could be charged using the stored energy. This could, however, not be simulated in PtX as this concept would have to be added to the PtX model, and as charging patterns for recreational boats could not be found.

Furthermore, demand response and using EV's as battery storage (vehicle-to-grid) were identified as a potential (additional) overvoltage mitigation strategies. Both strategies are considered very promising. This will be elaborated with arguments in section 6.2.3. As stated before, these could also not be simulated. Thus, due to the functionality of PtX certain identified strategies or potentials could not be considered in the assessment for the overvoltage mitigation strategies, diminishing the ability to assess alternative developed local fitting concepts.

The PtX model and its settings can be completely adjusted to the needs and wishes of the user, moreover, new functionalities can be added if the user is familiar with Python coding. However, this is a time-consuming task and the user should have expertise in Python coding. Therefore, the PtX model as it is in its current form, is not ideal for the TENOMF. It should be updated with extra functionalities to be able to optimally complement the TENOMF. To start out with the forenamed things: 1) A limit on the hydrogen storage tank, without the option to export. 2) Demand response, or smart charging functions. 3) Effective heat recovery of fuel cells and electrolyzers. 4) EV's should have the functionality of a battery, also able to discharge electricity to the neighbourhood (vehicle-to-grid). Next to updating the PtX's functionalities, if the TENOMF would be used by local governments, policy makers, DSO's and planners, it is recommended to create a more user-friendly interface such that it can be used without Python coding expertise.

6.1.4 Data gathering

For the data gathering in steps 2 and 3, the availability of open-source data is assumed in the TENOMF. For the Netherlands, this is often the case. However, for the TENOMF to be a generic framework it should be scalable to other countries as well. Open-source data on neighbourhood demographics, energy demands and energy infrastructures might not be available everywhere. This could pose a hiccup for the use of the TENOMF in other countries.

6.1.5 Biggest limitations to the TENOMF

To conclude, the biggest limitations to the TENOMF as it currently is, is the model used for the assessment of energy configurations: PtX. Its overvoltage calculations are oversimplified. They should be improved by considering fundamental electrotechnical principles, instead of its current rule-based definition of overvoltage concerning MVS capacity. Moreover, the time-scale of PtX should be more detailed as PV irradiance occurs in a highly fluctuating manner. Therefore, overvoltage levels will be higher in reality than PtX identifies. Lastly, PtX diminishes the concept development phase (step 5) of the TENOMF as the functionality of the current version of PtX is not suitable to simulate all identified overvoltage mitigation and system integration potentials.

6.1.6 Recommendations for the improvement of the TENOMF

1. It is recommended to improve the PtX model. This should be done by implementing overvoltage mitigation calculations based on electrotechnical principles: by considering Ohm's law and calculating (alternating) voltage-levels, currents, and resistances in the electricity grid. Moreover, the used time-scale for calculations should be shortened. It should be researched what an optimal time-scale is to improve overvoltage calculations, while not making the simulations to heavy for longer periods of time. Lastly, certain functionalities should be added to PtX to improve the concept development phase of TENOMF: 1) a hydrogen tank with a limit, without energy export. 2) Demand response and smart charging functionalities. 3) Effective heat recovery functionalities of electrolysers and fuel cells. 4). Vehicle-to-grid functionalities for EV's. Moreover, to make the PtX, and therefore the TENOMF, more user friendly for policy makers and planners, its interface should be improved. Instead of having to alter settings directly in the Python script, a user-friendly tool could be developed where the user can adjust all settings to its preferences.
2. It is recommended to add steps after step 6, on the decision-making phase that should be done together with local stakeholders. Further research should evaluate if and how the TENOMF and the 'multi-stakeholder decision support system for local neighbourhood energy planning' as coined by Hettinga et al. (2018) could be combined as an improvement on wholistic overvoltage mitigation planning.
3. For the TENOMF's assessment of system integration, as a part of the energetic assessment, it is recommended to add export and a criterion as SUI's *fraction of autonomy* to the energetic assessment criteria of the TENOMF. This helps to improve the evaluation of system integration. Export levels indicate higher levels of self-consumption. In addition, *fraction of autonomy* will help distinguishing system integration from a strategy with high levels of curtailment (this would impose low export levels).

4. The TENOMF's financial assessment could be improved by considering yearly fluctuating cost-components (e.g. interest, inflation) and by adding VAT to the expenses of residential strategies. As these would need to be paid by citizens instead of governments.

6.2 Discussion on case study results

The TENOMF was tested on the case study area Diamantbuurt. This resulted in various recommendations for the implementation of local overvoltage mitigation strategies that enhance the local energy transition by fitting overall ambitions of the municipality. Certain choices during the implementation of the case study might have impacted the results. Limitations coming forth of the case study are discussed in this section. Moreover, the results are compared to the results of scientific literature on energy system design. The discussion on the case study results is done in four themes: uncertainty due to the year of analysis, energetic and financial assessment, concept development and results. Lastly, recommendations for further research are stated.

6.2.1 Uncertainty due to the year of analysis

The biggest limitations in the case study, other than those coming forth of the limitations due to the used PtX model as were described in section 6.1, are the uncertainties for future characteristics of the evaluated energy systems. Efficiencies of energy storage, conversion and generation systems are estimated with the outlook of 2030. Similarly, prices for the import of various energy carriers (natural gas, electricity, hydrogen) are estimated for the outlook of 2030. The assessment of energetic and financial implications, and therefore the case study results, thus depend on estimations. This brings about uncertainties. A sensitivity analysis was done to evaluate uncertainties. The uncertainties and the outcomes of the sensitivity analysis are discussed more elaborately in the following section.

The financial assessment of the overvoltage mitigation strategies is done by regarding costs in the perspective of the year 2030: assumed 2030 prices per kWh for natural gas, electricity and hydrogen as well as 2030 infrastructure costs were used. This is done as there is currently no overvoltage yet due to PV generation in the case study area: only a few panels have been installed in the neighbourhood. Furthermore, there is no clear estimation of when this will happen. However, bearing in mind the energy transition and growth in panels to be installed, levels of overvoltage are assumed to grow towards 2030, as was validated with M. Verkou (M. Verkou, personal communication, 25 March, 2021). Costs could also have been analysed for a current scenario. However, in a current scenario hydrogen would not be cost-competitive to electricity and natural gas. As overvoltage is a future problem for many neighbourhoods, it was deemed more interestingly to consider potential future solutions for the case study. As aforementioned, efficiencies for storage and conversion are also taken as expected towards 2030.

Future costs come with uncertainties as they are estimated. Therefore a sensitivity analysis was done for the strategies of hydrogen storage and home batteries. This showed that for hydrogen conversion especially the hydrogen import price is a sensitive variable. For home batteries foremostly the battery's lifespan and the natural gas import costs are sensitive variables. These variables named for both strategies make the outcomes of the case study uncertain. Strategies are assessed on their financial implications, and conclusions are made stating which strategy is more cost-efficient than another. Such results should be considered bearing in mind the uncertainties coming forth of the sensitive variables. The sensitivity analysis was done by increasing and decreasing the variable by 25%. This was an estimated range that had the function to show how fluctuations could be towards the future. However, to make the sensitive analysis and its outcomes stronger, this range should not be estimated. Instead, a literature review or expert consultation could be done to obtain a realistic range for possible fluctuations of a certain variable. Then, the outcomes of the sensitivity analysis can be used to make stronger conclusions on the likeliness that total system costs will change due to the uncertainty of a variable. For further research, it is recommended to do this. Then, current results can be put in perspective better.

The sensitivity analysis in this research was solely financial. It analysed import prices of various energy carriers, infrastructure costs and infrastructure lifespans. As an addition to the financial analysis, also efficiencies of the storage and conversion systems should be regarded. Likewise, an energetic sensitivity analysis should be done on the efficiencies of the storage and conversion systems as they can impact energetic implications (needed curtailment levels and energy import). Also the sensitivity of the PV panels used in the PtX simulation should be analysed. In the case study, current state-of-the-art solar panels were depicted, growth in capacity and efficiency towards 2030 was disregarded. This was done as it is expected that not all panels will be installed at the same moment: their amounts will grow over the years. Therefore, it is likely that by 2030 not all PV panels are installed with 2030 state-of-the-art efficiencies. However, as this is an estimation there are uncertainties. The effect that efficiency differences would imply for generated energy, import energy demands and overvoltage levels for the different overvoltage mitigation strategies should be evaluated. For further research it is recommended to consider additional uncertainty analyses to make stronger conclusions on the uncertainties with which the different strategies cope. These additional uncertainty analyses should be done on the efficiencies of storage, conversion and generation (PV) systems.

For the case study neighbourhood’s energy demands, current demands are used. It is assumed that these will remain similar towards 2030 unless electrification of certain sectors happens. In that case, the electrification scenario’s cover the neighbourhoods future energy demands.

6.2.2 Energetic and financial assessment

A limitation in the energetic as well as financial assessment of the case study is that demi-water demand for the production of hydrogen is not taken into account. The efficiencies of electrolyser include the further purification of drinking water into demi-water used for hydrogen (E. van der Roest, personal communication, 19 November, 2021). However, the use of electrolysers does imply extra drinking water demands. Therefore, more energy is used in the water treatment plant. This will cause a higher energy demand. Moreover, it implies costs to rise. Although this is not seen in the energy or cost flow of a neighbourhood. Still, it should be considered when hydrogen conversion is used as a strategy. It is recommended to further investigate what the effect is that hydrogen conversion poses to the energy demands and costs for a water treatment plant. To fully understand such implications, that are out of the scope of the energy flows of the considered neighbourhood, a life cycle analysis could be done.

6.2.3 Concept development

In step 5, Concept development, electric energy storage is used in the form of residential batteries. Collective batteries are also an option, however, this is not considered in the case-study. This has to do with the fact that the amount of PtX simulations had to be limited due to the time-constraints of this thesis study. Including collective batteries as an option next to home batteries would impose many new energy configurations because collective batteries could be a strategy on its own or it could be combined with all the existing overvoltage mitigation strategies. In reality, collective batteries would differ from residential batteries energetically due to extra transport losses from PV to battery. However, such losses are expected to be small (T. Fens, personal communication, 29 July, 2021), moreover, they are not taken into account in PtX. Therefore it may be argued that energetically, home batteries and collective batteries would be similar in the simulations of PtX. The outcomes of a simulation with a collective battery is thus also assumed to be similar to home batteries. The difference is that a collective battery will have a smaller storage capacity compared to all home batteries together. Therefore it is likely to be less effective in mitigating overvoltage and in integrating systems. However, it could be an interesting addition to hydrogen storage. Or in combination with home batteries, as it could reduce the need for home batteries. This is favourable as collective batteries are more cost-effective (IRENA, 2017). Furthermore, no residential space is needed, which could be a reason to prefer one over another. Therefore it is still an interesting (additional) strategy to consider. It is recommended to take into consideration collective batteries as a strategy for further research to overvoltage mitigation that enhances the energy transition.

6.2.4 Results

In this section, the most important results of the case study are repeated, after which they will be discussed against existing scientific literature on energy system design and overvoltage mitigation.

The results of the case study in this master study show that the conventional overvoltage mitigation strategies are optimal in reducing overvoltage levels. From an energy transition perspective, system integration mitigation strategies in combinations with some levels of curtailment are more favourable. The combination of home batteries and hydrogen conversion shows to be the best in mitigating overvoltage, and has the lowest import demands. However, this combination is also the most expensive and spatially impacting strategy. Depending on the electrification scenario home batteries or hydrogen conversion is more effective. Hydrogen conversion is seen as a promising strategy as it can match existing ambitions of local governments on the energy transition. Amsterdam wants to use hydrogen for heating the built environment. Otherwise, home batteries are recommended as they show to be an effective overvoltage mitigating strategy in combination with large electrification demands, especially EV’s. Combined, batteries and EV’s show the potential for systems integration and sector coupling. The share of EV’s in the city is expected to grow tremendously towards the future. Therefore this is an interesting option to consider. Forementioned results will be discussed in relation to existing literature on energy system design and overvoltage mitigation.

In a study done by Petkov et al. (2021), the effectiveness of different storage and conversion technologies and their combinations were compared for various types of (urban) neighbourhoods. Petkov et al. (2021) state that for optimal sector coupling, and system integration, combinations of energy storage systems (heat, electrical and hydrogen) are key. Especially a mix of long-term and short-term storage technologies performs well. For instance, hydrogen storage (long-term) combined with home batteries (short-term). Murray et al. (2018) did a study on the effectiveness of different energy storage technologies in urban versus rural neighbourhoods. Their urban case study had many similarities to the case study in this master thesis: an urban neighbourhood with maximum PV potential installed and feed-in tariffs banned. Furthermore, hydrogen could be injected into the natural gas grid as a mixture with natural gas. Similar to Petkov et al. (2021), Murrey et al. (2018) also found that in urban neighbourhoods, a combination of batteries and small hydrogen systems is effective. However, they conclude that hydrogen systems do not provide seasonal storage as the available renewable energy is too small due to spatial limits for installing PV. This is in line with the results found in the case study of this master thesis. In the combination of home batteries and hydrogen storage, hydrogen was not stored for long periods as there was a constant hydrogen demand for heating purposes. From a technical perspective, the combination of batteries and hydrogen conversion was the most effective non-conventional mitigation strategy. Thus, the outcomes of the case study are in line with Murray et al. (2018). Similarly, the conclusions of Petkov et al. (2021) can be related: in the case study of this master thesis, the combination of hydrogen conversion (and storage) and home batteries provided the best system integration as the lowest levels of yearly energy import were noted. Moreover, combining batteries and hydrogen conversion posed the lowest levels of yearly overvoltage.

On the other hand, from a financial perspective, Murray et al. (2018) state that hydrogen is not feasible in urban neighbourhoods where hydrogen systems are used solely for load-shifting. Too little renewable energy is available. Then, batteries are more efficient. In this study, hydrogen conversion solely for load-shifting was not simulated. However, similar recommendations were made: if Amsterdam would not pursue its ambitions to use hydrogen for heating the built environment, it is recommended to use home batteries as overvoltage mitigation strategy.

A first consideration was done on a mixed assessment of energy import and export as was discussed in section 6.1.2.1. The results can be seen in Figure 40. Here it is clear that the combination of hydrogen conversion and home batteries provide the best system integration, having much lower import + export values than the individual system integration strategies (*Hy* and *Bh*) and the conventional strategies (*Curtailment* and *Grid reinforcement*). Moreover, it can be seen that the scenarios *Maximum EV* and *Maximum EV & electric cooking* have small export values. Therefore, it shows that extra electrification, and especially electric vehicles, are promising for good system integration. This is in line with the results of the case study: it was shown that electrification and specifically EV's reduce levels of overvoltage. Local generated PV is thus used more effectively. This first analysis on export levels as an assessment criterion further strengthens the argument that EV's and other electrification demands have the ability to provide systems integration.

At the same time, EV's enlarge energy import levels. This can be explained by the fact that the results do not show gasoline demands for vehicles in the non-EV scenarios. However, still the neighbourhood demands more electricity and is thus more grid dependent as compared to a non-EV scenario. This should be noted.

When EV's are combined with home batteries, it shows that energy import levels drop greatly relative to how import levels drop for the strategy of hydrogen conversion in combination with EV's. EV's and home batteries complement each other: EV's discharge batteries in moments of little PV generation. Therefore, batteries have more capacity available for moments of high PV-irradiation, when overvoltage mitigation is needed. This shows the potential of system integration and sector coupling (mobility, built environment and renewable energy generation). Moreover, it hints at the need for demand response and smart charging, or HEMS. Namely, overvoltage mitigation is more effective if other energy demands discharge their storage capacities in times when no overvoltage mitigation is needed. Demand response was not simulated in this case study, however the aforementioned is in line with the results of Voulis et al. (2017). They investigate the effect that smart charging has on the effective use of individual residential electrical storage systems, in a mixed residential and commercial urban neighbourhood's energy system. Their results show that smart charging can increase the use of renewable energy in mixed residential and commercial urban neighbourhoods by 39%. Energy export decreases to almost a third. The neighbourhood's self-sufficiency (reducing its import demands) is improved by over a fifth. On top of that, smart charging drastically improves peak-shaving, by 55%. Thus, in their study the same effect is noted as the effect described above: the combination of EV and home batteries spares storage capacity for overvoltage mitigation, or peak-shaving. Smart charging further improves this effect. All in all, it shows that smart charging enhances self-consumption, sector coupling and system integration as well as peak-shaving. Therefore, it provides overvoltage mitigation. The study of Voulis et al. (2017) was tested on a case study in a mixed residential and commercial neighbourhood the city centre of Amsterdam. As the case study of this master thesis was also done on a mixed residential and commercial neighbourhood in Amsterdam, the results of Voulis et al. (2017) are very interesting as comparison for this master thesis. Voulis et al. (2017) focussed on peak-shaving, not specifically on overvoltage mitigation, therefore it is recommended to further explore the exact effect that demand response might have on reducing levels of overvoltage. This could be done by inte-

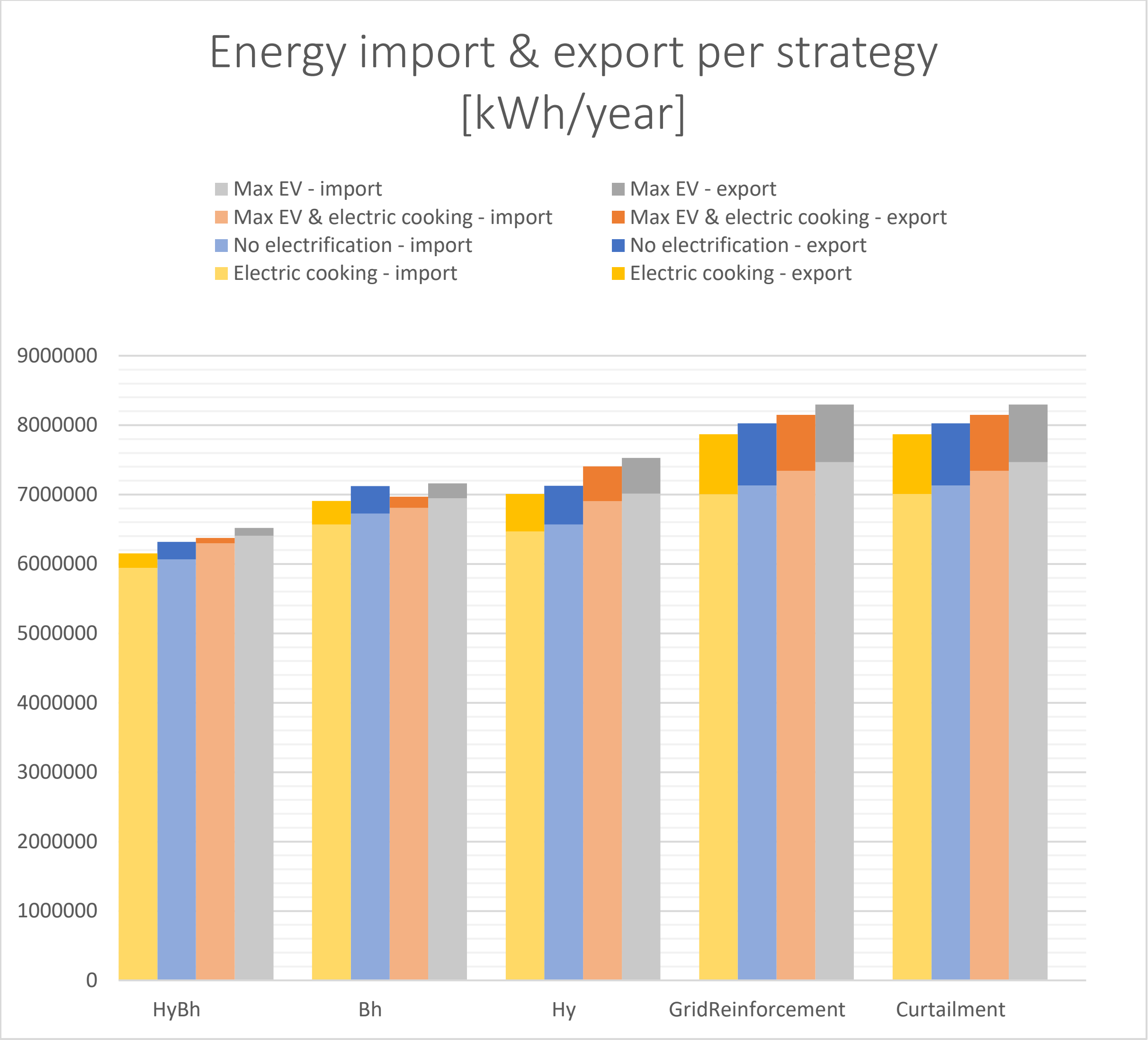


Figure 40: Energy import & export (kWh/year) per energy configuration for all electrification scenario's. The imported energy is the total of all imported electricity (kWh/year), natural gas (kWh/year) and hydrogen (kWh/year) for each of the energy configurations. Likewise, the exported energy is the total of all exported electricity (kWh/year), natural gas (kWh/year) and hydrogen (kWh/year).

grating demand response functionalities in PtX. PtX only takes in account current energy generations, demands and storage availability. For simulating demand responsive charging, PtX should also consider forecasted demands and generations, as is done in the study of Voulis et al. (2017).

In the case study of this master thesis, EV's were simulated to pose a 'one-way' electric demand. In reality, EV's also have the potential to act as an external battery that is able to return stored electricity to the neighbourhood when demanded: operating in a 'two-way' mode. So called vehicle-to-grid further couples the mobility sector to the built environment and renewable energy sectors while reducing the energy system's emissions and costs (Murray, Carmeliet & Orehounig, 2020). This could have great potential for overvoltage mitigation and system integration as it implies extra battery storage. Moreover, it could reduce costs as it reduces the need for costly home batteries. The amount of EV's is expected to grow drastically towards the future (Agentschap NL, 2019), regardless of overvoltage mitigation strategies. Therefore, EV's could be regarded as 'free' extra storage capacity.

It is recommended to further research the contribution of vehicle-to-grid as a two-way battery in regards to overvoltage mitigation, especially in combination with smart charging. This could for instance be done by adding two-way EV storage and demand response functionalities in PtX.

6.2.5 Biggest limitations

To conclude, the biggest limitations of the case study results came forth of the uncertainties of system characteristics and prices estimated for 2030. The uncertainty analysis showed that for hydrogen conversion the hydrogen import price is the most sensitive variable. An increase or decrease in this price, as opposed to the estimation used in this study, can have a great effect on the total strategy costs of the hydrogen conversion strategies (*Hy* and *HyBh*). A 25% increase or decrease in hydrogen price would change hydrogen conversion strategy cost by 15%. For home batteries, natural gas import price and the lifespan of the battery are the most sensitive variables. 25% fluctuations of natural gas price entails a 16% increase or decrease in the total home battery strategy costs. Increasing or decreasing the lifespan of the battery by a quart changes strategy costs respectively -5% and +9%. The aforementioned changes would have a large effect on the outcomes of the case study results, potentially making home batteries or hydrogen conversion a lot more or less cost-effective. Therefore, these sensitive variables should be carefully considered while evaluating the results.

6.2.6 Recommendations

In this section, the recommendations for further research in relation to the case study results, as have been mentioned in section 6.2, are repeated. Also recommendations coming forth of the case study are named.

1) To improve the strength of the sensitivity analysis it is recommended to validate the range of potential increase or decrease for each of the analysed variables. Now, they are all taken +25% and -25%. By doing a literature review and consulting experts, an expected sensitivity range can be estimated, specified for each of the variables. Then, the outcomes of the sensitivity analysis can be used to make stronger conclusions on the likeliness that total system costs will change due to the uncertainty of a certain variable.
2) Additional uncertainty analyses should be done on the efficiencies of storage, conversion and generation (PV) systems. These could potentially also effect the outcomes of the case study greatly. With these additional analyses, stronger conclusion can be made on the uncertainties that different strategies have.
3) It is recommended to further explore the exact effect that demand response or smart charging might have on reducing levels of overvoltage. This was not simulated, but is seen to be promising as it could further aid mitigating overvoltage and enhance a more optimal use of renewable produced energy. Furthermore, it optimizes local system integration and can therefore be a good addition to all other system integration overvoltage mitigation strategies. The effect of demand response could be researched by integrating demand response functionalities in PtX. This should thus be added to the PtX model.
4) Vehicle-to-grid is seen as an additional promising overvoltage mitigation and system integration strategy. It was not simulated for the case study. Simulations on one-way EV addition to the neighbourhood energy system showed that it reduces levels of overvoltage. Moreover, in combination with home batteries, it shows promising results on improving system integration. Vehicle-to-grid could even further improve this. It is recommended to further research the contribution of vehicle-to-grid as a two-way battery in regards to

overvoltage mitigation, especially in combination with smart charging. This could be done by adding two-way EV storage and demand response functionalities in PtX.

5) It is recommended to take into consideration collective batteries as an additional strategy for further research to overvoltage mitigation that enhances the energy transition. Collective batteries could be interesting as an addition to (reduce the need for) home batteries and hydrogen conversion. They are more economical than home batteries.
6) Hydrogen conversion entails extra energy demands due to the need for more drinking water purification in water treatment plants. The effect that this has on the total energetic and financial implications should be researched.
7) As the mobility sector will be electrified, and charging infrastructure needs to be implemented, it should be investigated to what extend the electricity grid can handle this extra demand before the grid needs to be reinforced.
8) Asides EV's also (recreational) boats will be electrified towards 2040 by the ambitions of Amsterdam. Close to the case-study area already few charging stations for electric boats are implemented. It is recommended to further investigate the potential of charging electric boats as overvoltage mitigation strategy as it has the potential of matching energy production and demand periods: recreational boats often sail during sunny days, coinciding with overvoltage periods. Batteries coupled to the charging station could be charged with the excess PV energy. Subsequently, boats can be charged after they dock overnight using the battery charge. More charging infrastructure could thus be implemented on the Amstelkanaal bordering the case study area.

7. Conclusion

Three gaps in scientific literature on overvoltage mitigation planning have been identified:

1. Socio-economic and spatial factors are disregarded in overvoltage mitigation
2. System integration is not considered in overvoltage mitigation
3. Generic approaches to create and depict overvoltage mitigation strategies for a local context do not exist

Taking these, this study aimed to answer the following research question:

How can a generic framework be developed to depict energy transition-enhancing overvoltage mitigation strategies, against PV-induced overvoltage in the low-voltage grid, that fit the local context of a neighbourhood?

As a result, the TENOMF is established. The TENOMF is a promising generic approach for energy transition-enhancing overvoltage mitigation strategy design. It should be noted that the PtX model used for the overvoltage calculations shows to be a limiting factor in approaching a realistic energetic image. The overvoltage calculations of PtX are oversimplified. Therefore, it is recommended to improve PtX's overvoltage mitigation modelling by considering fundamental electrotechnical principles for (over)voltage calculations. Moreover, the time-granularity of the calculations should be improved.

Other than the modelling software, the method of the framework shows to be effective. The TENOMF can be used by local governments, policy makers, planners and DSO's as a guide to depict overvoltage mitigation strategies that fit the local context of a neighbourhood and enhance the local energy transition. The TENOMF provides a non-absolute guide that leaves room for the user's own interpretations and choices in a wholistic approach. The TENOMF helps identifying neighbourhood-specific potentials for mitigating PV induced overvoltage by considering the following aspects:

i. Local energy demands and supplies

ii. Neighbourhood characteristics and demographics

iii. Wider governmental ambitions and plans concerning the energy transition for the local context

iv. System integration

For the assessment of mitigation strategies the TENOMF considers energetic, financial and spatial implications as well as the needs of local stakeholders. In that way, it helps depicting fitting overvoltage mitigation strategies by regarding quantitative as well as qualitative aspects. It assures that energetically feasible energy strategies not only work as a technical concept, but that the strategies can also count on the support of local stakeholders. Therefore, they are more likely to be implemented and succeed in reality.

Because the energy transition is a complex matter containing the wishes of many stakeholders, especially in a local neighbourhood context, not one absolute local fitting solution against overvoltage can be given. Therefore, the TENOMF provides multiple optional solutions with their advantageous and drawbacks, as well as the considerations of why to choose one over the other. Having these, recommendations for overvoltage mitigation in the local context can be stated. These can be used by local governments, policy makers, planners and DSO's. Subsequently, various strategies can be presented to local stakeholders after which final decisions can be made using participation strategies.

The TENOMF adds to scientific literature on overvoltage mitigation by being the first generic approach to develop overvoltage mitigation strategies for a neighbourhood energy system. Similarly, it does so by considering system integration. It adds to energy system design literature in general by considering spatial and socio-economic aspects for the evaluation of energy systems.

To conclude, using the TENOMF, strategies mitigating PV induced overvoltage in the LV grid can be chosen that fit the local context of a neighbourhood. By using system integration, the TENOMF matches overvoltage mitigation strategies with energy transition ambitions. Therefore, using the TENOMF, overvoltage mitigation can be seen as an opportunity as it helps catalysing the energy transition as a whole.

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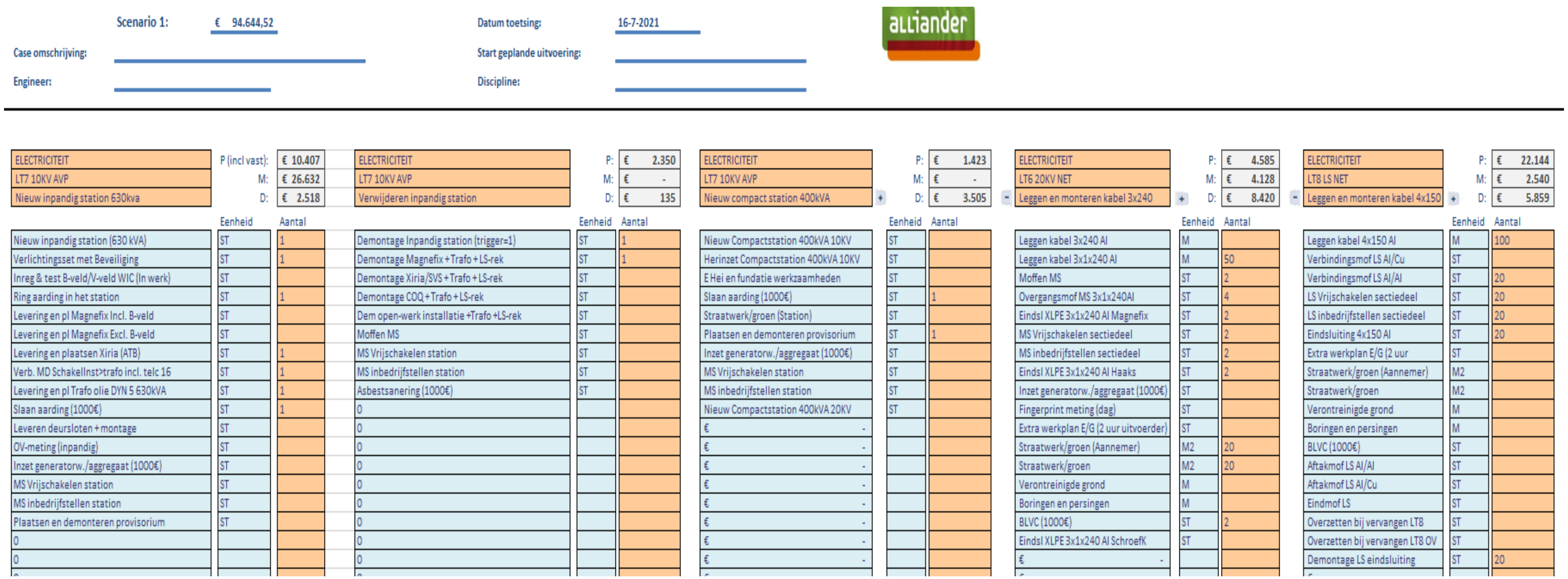
Appendix A.



Scenario 1: € 94.644,52

Case omschrijving:

Engineer:

Datum toetsing: 16-7-2021

Start geplande uitvoering:

Discipline:

ELECTRICITEIT
LT7 10KV AVP
Nieuw inpandig station 630kva

P (incl vast): € 10.407
M: € 26.632
D: € 2.518

	Eenheid	Aantal
Nieuw inpandig station (630 kVA)	ST	1
Verlichtingsset met Beveiliging	ST	1
Inreg & test B-veld/V-veld WIC (In werk)	ST	
Ring aarding in het station	ST	1
Levering en pl Magnefix Incl. B-veld	ST	
Levering en pl Magnefix Excl. B-veld	ST	
Levering en plaatsen Xiria (ATB)	ST	1
Verb. MD Schakelinst>trafo incl. telc 16	ST	1
Levering en pl Trafo olie DYN 5 630kVA	ST	1
Slaan aarding (1000€)	ST	1
Leveren deursloten + montage	ST	
OV-meting (inpandig)	ST	
Inzet generatorw./aggregaat (1000€)	ST	
MS Vrijschakelen station	ST	
MS inbedrijfstellen station	ST	
Plaatsen en demonteren provisorium	ST	
0		
0		

ELECTRICITEIT
LT7 10KV AVP
Verwijderen inpandig station

P: € 2.350
M: € -
D: € 135

	Eenheid	Aantal
Demontage Inpandig station (trigger=1)	ST	1
Demontage Magnefix + Trafo + LS-rek	ST	1
Demontage Xiria/SVS + Trafo + LS-rek	ST	
Demontage COQ + Trafo + LS-rek	ST	
Dem open-werk installatie +Trafo +LS-rek	ST	
Moffen MS	ST	
MS Vrijschakelen station	ST	
MS inbedrijfstellen station	ST	
Asbestsanering (1000€)	ST	
0		
0		
0		
0		
0		
0		
0		
0		
0		

ELECTRICITEIT
LT7 10KV AVP
Nieuw compact station 400kVA

P: € 1.423
M: € -
D: € 3.505

	Eenheid	Aantal
Nieuw Compactstation 400kVA 10KV	ST	
Herinzet Compactstation 400kVA 10KV	ST	
E Hei en fundatie werkzaamheden	ST	
Slaan aarding (1000€)	ST	1
Straatwerk/groen (Station)	ST	
Plaatsen en demonteren provisorium	ST	1
Inzet generatorw./aggregaat (1000€)	ST	
MS Vrijschakelen station	ST	
MS inbedrijfstellen station	ST	
Nieuw Compactstation 400kVA 20KV	ST	
€ -		
€ -		
€ -		
€ -		
€ -		
€ -		
€ -		
€ -		

ELECTRICITEIT
LT6 20KV NET
Leggen en monteren kabel 3x240

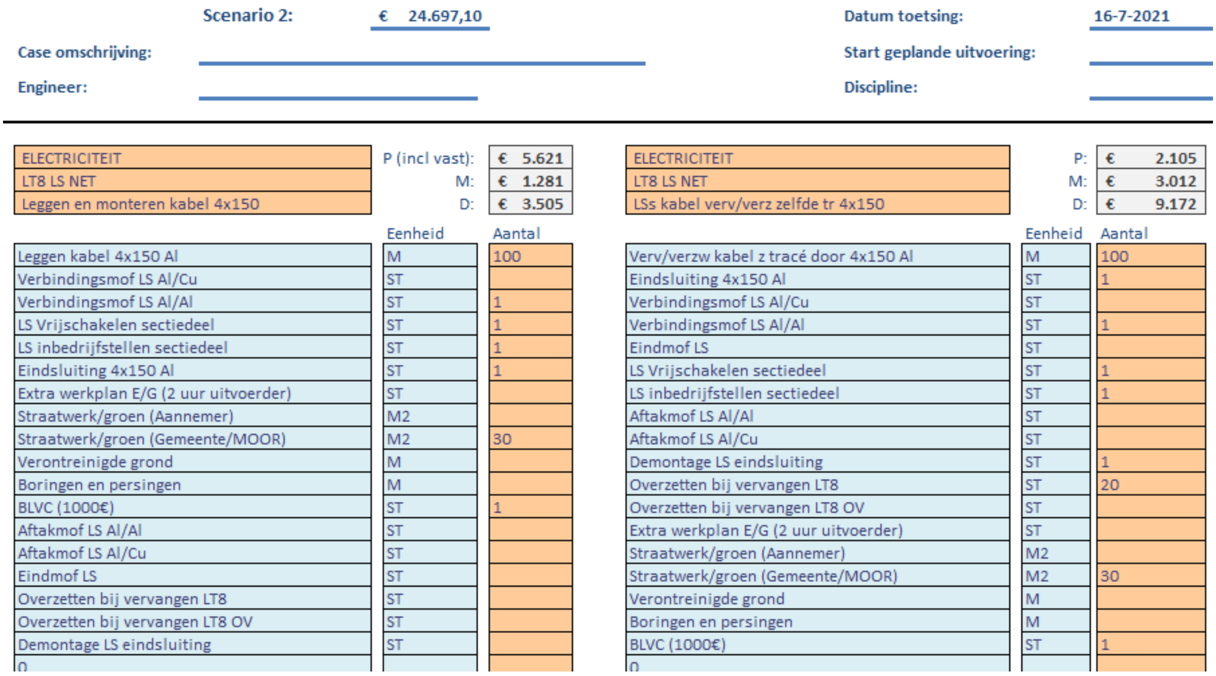
P: € 4.585
M: € 4.128
D: € 8.420

	Eenheid	Aantal
Leggen kabel 3x240 Al	M	
Leggen kabel 3x1x240 Al	M	50
Moffen MS	ST	2
Overgangsmof MS 3x1x240Al	ST	4
Eindsl XLPE 3x1x240 Al Magnefix	ST	2
MS Vrijschakelen sectiedeel	ST	2
MS inbedrijfstellen sectiedeel	ST	2
Eindsl XLPE 3x1x240 Al Haaks	ST	2
Inzet generatorw./aggregaat (1000€)	ST	
Fingerprint meting (dag)	ST	
Extra werkplan E/G (2 uur uitvoerder)	ST	
Straatwerk/groen (Aannemer)	M2	20
Straatwerk/groen	M2	20
Verontreinigde grond	M	
Boringen en persingen	M	
BLVC (1000€)	ST	2
Eindsl XLPE 3x1x240 Al SchroefK	ST	
€ -		

ELECTRICITEIT
LT8 LS NET
Leggen en monteren kabel 4x150

P: € 22.144
M: € 2.540
D: € 5.859

	Eenheid	Aantal
Leggen kabel 4x150 Al	M	100
Verbindingsmof LS Al/Cu	ST	
Verbindingsmof LS Al/Al	ST	20
LS Vrijschakelen sectiedeel	ST	20
LS inbedrijfstellen sectiedeel	ST	20
Eindsluiting 4x150 Al	ST	20
Extra werkplan E/G (2 uur	ST	
Straatwerk/groen (Aannemer)	M2	
Straatwerk/groen	M2	
Verontreinigde grond	M	
Boringen en persingen	M	
BLVC (1000€)	ST	
Aftakmof LS Al/Al	ST	
Aftakmof LS Al/Cu	ST	
Eindmof LS	ST	
Overzetten bij vervangen LT8	ST	
Overzetten bij vervangen LT8 OV	ST	
Demontage LS eindsluiting	ST	20



Scenario 2: **€ 24.697,10**

Datum toetsing: **16-7-2021**

Case omschrijving:

Start geplande uitvoering:

Engineer:

Discipline:

ELECTRICITEIT	P (incl vast):	€ 5.621
LT8 LS NET	M:	€ 1.281
Leggen en monteren kabel 4x150	D:	€ 3.505

	Eenheid	Aantal
Leggen kabel 4x150 Al	M	100
Verbindingsmof LS Al/Cu	ST	
Verbindingsmof LS Al/Al	ST	1
LS Vrijschakelen sectiedeel	ST	1
LS inbedrijfstellen sectiedeel	ST	1
Eindsluiting 4x150 Al	ST	1
Extra werkplan E/G (2 uur uitvoerder)	ST	
Straatwerk/groen (Aannemer)	M2	
Straatwerk/groen (Gemeente/MOOR)	M2	30
Verontreinigde grond	M	
Boringen en persingen	M	
BLVC (1000€)	ST	1
Aftakmof LS Al/Al	ST	
Aftakmof LS Al/Cu	ST	
Eindmof LS	ST	
Overzetten bij vervangen LT8	ST	
Overzetten bij vervangen LT8 OV	ST	
Demontage LS eindsluiting	ST	
0		

ELECTRICITEIT	P:	€ 2.105
LT8 LS NET	M:	€ 3.012
LSs kabel verv/verz zelfde tr 4x150	D:	€ 9.172

	Eenheid	Aantal
Verv/verzw kabel z tracé door 4x150 Al	M	100
Eindsluiting 4x150 Al	ST	1
Verbindingsmof LS Al/Cu	ST	
Verbindingsmof LS Al/Al	ST	1
Eindmof LS	ST	
LS Vrijschakelen sectiedeel	ST	1
LS inbedrijfstellen sectiedeel	ST	1
Aftakmof LS Al/Al	ST	
Aftakmof LS Al/Cu	ST	
Demontage LS eindsluiting	ST	1
Overzetten bij vervangen LT8	ST	20
Overzetten bij vervangen LT8 OV	ST	
Extra werkplan E/G (2 uur uitvoerder)	ST	
Straatwerk/groen (Aannemer)	M2	
Straatwerk/groen (Gemeente/MOOR)	M2	30
Verontreinigde grond	M	
Boringen en persingen	M	
BLVC (1000€)	ST	1
0		

Appendix B.

Electric cooking demand housing category ‘day care/community centre’

Assumption cooking demand day

Community centre: It is assumed that 1x a week for 25 people, for 45 weeks a year is cooked at the community centre. That entails 25 meals a week.

Day care: 0x cooking a week

On average, the combined category (day care and community centre) thus cooks 12.5 meals a week. For an apartment it is assumed that they cook 45 weeks a year, 7x a week for 1.7 persons: around 12 meals a week. This is almost similar.

Therefore we assume that both housing categories (‘one floor apartment’ and ‘day care/community centre’) have the same electricity demands for cooking: 175 kWh/year.

Appendix C.

2019				
electricity price	0.205	€/kWh	¤¤	met BTW 21prct
natural gas price	0.094	€/kWh	¤¤	met BTW 21prct

2030				
electricity price	0.18	€/kWh	µµµ	zonder BTW
natural gas price	0.081	€/kWh	µµµ	zonder BTW
hydrogen price	3.090	€/kg	*	zonder BTW
hydrogen price	0.078	€/kWh	*	
natural gas price	0.83	€/m3	µµµ	
natural gas conver.	10.2	kWh/m3		

Grid reinforcement ***

39557	€	MVS	
2485	€	Removing old MVS	
4928	€	Temporary MVS	
47676	€	Maintenance, cables and connections	
94646	€	total	
40	years	lifespan MVS	
0		O&M costs (MVS)	

Assumed to stay the same towards 2030
no inflation regarded

10407	€/100m	adding LV cables (reinforcing)	
14289	€/100m	replacing old LV cables	
33	10^2 m	length cables replaced	¤
0	€	total add	
471537	€	total replace	
65	years	lifespan cables	(50-80 year)
0.01		O&M costs (cables)	

Hydrogen boiler & grid reinforcement

2250	€/boiler	boiler & install.	¥
734		# boilers	
1304685	€	total ex BTW	
15	years	lifespan boiler	¥

373	€/house	pipeline retrofitting	*
734		# houses	
273782	€	total	
40	years	lifespan pipeline	*

no O&M assumed for pipelines and boiler

above are prices for 2030 ¥

assumed that gas boiler in 2030 will be similar to nat. gas boiler today

Electric cooking

800	€/house	infrastructure	****
600	€/house	installation	****
100	€/house	new pans	****
697		# houses	
1045500	€	total inc BTW	
825945	€	total ex BTW	
30	years	lifespan furnace	¥

above are prices for 2030 ¥

assumed induction infrastructure and installation prices will be similar to today's

Bh

8240	€/13.5 kWh	battery	ex btw	
494.4	€/13.5 kWh	6% btw (houses older 10yr)		
2200	€/battery	installation (€1100-3300)		
742		# batteries (13.5 kWh)		
0.571	%	price 2030 {-42.9% 2020-2030}		µ
7746480	€	total 2020 ex BTW		
4423240	€	total 2030 ex BTW		
1.71	%	lifetime increase 2030		µ
12	years	lifespan Battery 2020		*
20.52	years	lifespan Battery 2030		
0.01		O&M costs		

Bh 2030: µ

Bh {Li-Ion NMC}: 2016-2030 > - 60 % {energy installation costs: Capital + installation, see figure 27, 34}

2020-2030 > - 42.9prct

Bh: lifetime doubles 2016-2030 {fig 50}

> 2020-2030: +71.4prct

Curtailment

0	€	infrastructure	

Hy

500	€/kW	electrolyser	*
500	€/kW	fuel cell	*
150	kW	size electrolyser	*
150	kW	size fuel cell	*
150000	€	total	*
20	years	lifespan electrolyser fulltime	*
450	€/kWh	storage & compression (200 bar)	
8000	kWh	size storage	
3600000	€	total	
20	years	lifespan storage unit	**
0.02		O&M costs	*

above are prices for 2030

Evmax

2475	€/station	infrastructure & installation	µµµµ
130.5		# new stations {2 sockets}	
85%	%	price decrease {2030}	¥
274539.4	€	total inc BTW	
216886.1	€	total ex BTW 2030	
10	years	lifespan station	µµµµ
15	years	lifespan station 2030	¥
475	€/year	O&M costs	µµµµ
404	€/year	O&M costs 2030	¥

assumed to decrease 15 percent: ¥
decrease in price towards 2030

Sources:

¥ assumption

* Van der Roest, E., Fens, T., Bloemendal, M., Beernink, S., Van der Hoek, J. P., & Van Wijk, A. J. M. (2021). The Impact of System Integration on System Costs of a Neighborhood Energy and Water System. Energies, 14(9), 2616. https://doi.org/10.3390/en14092616

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µ IRENA, (2017), storage and renewables: costs and markets to 2030. Int Renew Energy Agency, Abu Dhabi

µµµ PBL. (2021). ONTWIKKELINGEN IN DE ENERGIEREKENING TOT EN MET 2030. https://www.pbl.nl/sites/default/files/downloads/pbl-2020-ontwikkelingen-in-de-energierekening-tot-en-met-2030-4306.pdf

µµµµ NKL. (2016). Benchmark Kosten Publieke Laadinfrastructuur 2016. https://www.nklnederland.com/uploads/files/08_Benchmark_Kosten_Publieke_Laadinfrastructuur_2016_-_Concept_26_aug_1.pdf

Appendix D.

The parameter files for the PtX simulations of the different energy configurations. First (1), the full parameter file of one simulation is stated (*curtailment*). Next (2), all changes to these parameters for the simulations of the other energy configurations given.

1. Full parameter file of curtailment, as an example of default parameters

```
# -*- coding: utf-8 -*-
"

Created on Mon Mar 13 14:04:15 2017



@author: duijvla

File with inputs and parameters for Power to X

"

import pandas as pd

name              ="curtailment"
startDate          = "20180901"      # Start date of the simulation in format "YYYYMMDD"
endDate            = "20200101"      # End date of the simulation in format "YYYYMMDD"

priority           = 1            # Priority of sustainable electricity, generating heat (1) or H2 (2)
con_ModFlow          = 0            # Connection with ModFlow for temperature acquifer off (0) or on (1)
con_houses_ptx        = 1             # Connection between excess energy from houses and Power-to-X
on (1) or off (0)
con_ptx_houses        = 1             # Connection between excess energy from Power-to-X to houses on
(1) or off (0)
saltcavern_stor       = 0           # [-] if 1.0, the system tries to fulfill all its needs from hydrogen storage
before energy is taken from the grid
curtailment          = True          # If True: max_cap_fuelcell, max_E_Electrolyser, hp_max,
e_cap_battery_coll, e_cap_battery, e_cap_battery_other are 0. If False, they are not.
Eheating            = False          #if True, spaceheat & tapwater are electric, if False they are 0 (natural
gas demand)
Ecooking            = False          #if True, cooking is electric, if False, cooking is nat. gas.: demand = 0
H2boiler            = False          # if True hydrogen can be used for heating (spaceheat and tapwater),
else not
# If you want to use weather & electricity price predictions to calculate
# what the model should do in the coming 2 days, set this parameter to 1,
# otherwise 0. When 1 make sure that you have the KNMI Data and surface water
# temperature up until the day before the enddate. When predicting for today
# and tomorrow, the endDate should be todays date
predict             = 0
## project location - for weather predictions
```

```
latitude              = 52.351             #[degrees] latitude of project location in 3 decimals
longitude              = 4.905               #[degrees] longitude of project location in 3 decimals

# Run with startvolume of heat in the system
steady_state           = False          # when True run with heat in the system
gridname              = '31dec-2014-5j-50gr_1MWHP'

##### The water system of Power to X  #####

# Rainwater collection
#name_rain             = 'KNMIdata_year.xlsx'   # Name of Excelfile with rainwaterdata
name_rain             = 'Externe_Inputgegevens_model/KNMIData.xlsx'   # Name of Excelfile with
rainwaterdata
# source: http://projects.knmi.nl/klimatologie/uurgegevens/selectie.cgi
sheet_rain            = 'De Bilt2'       # Sheet of Excelfile with the data
start_row             = 33              # row in sheet with headers
factor_rain           =  0              # Set this parameter to 0 if you don't want to collect the rainwater from
the solar panels. Else put 1.0

# Rainwater sieve
y_sieve              = (100.0 - 2.0)    # [%] recovery from sieve

# Rainwater buffer
V0_rain              = 0               # [m3] volume of tank at t = 0, default is 150.0 m3
p_buffer_pump         = 3.0             # [bar] heigth difference of pump to and from rain water buffer

# Self cleaning filters
y_scf               = (100.0 - 2.0)    # [%] recovery from filters
p_scf_feed           = 200.0           # [kPa] min feed pressure of scf
deltap_scf           = 50.0           # [kPa] max pressure drop
n_lp_pump            = 60.0            # [%] overall efficiency of low pressure pump
deltap_lp            = 250.0           # [kPa] required head

# Reverse Osmosis
y_RO                = 90.0           # [%] recovery of RO
n_ro                = 80.0           # [%] overall efficiency of pump of RO
p_ro_feed            = 700.0          # [kPa] required feed pressure

# Reverse Osmosis buffer
V0_RO               = 0              # [m3] volume of tank at t = 0, default is 150.0 m3
p_tank_ro            = 1.5             # [bar] head difference of pump to RO
V_pump_max           = 150.0           # [m^3/hr] max capacity of one pump

# CEDI system
y_cedi              = 95.0           # [%] recovery of CEDI system
n_cedi              = 60.0           # [%] overall efficiency of pump of CEDI
deltap_cedi          = 300.0          # [kPa] required head for pumping
f_cedi              = 24.0           # [-] amount of hours for which the buffer capacity should be large
enough, coupled to water demand of the electrolyser
```

```
# Demi water demand
# Number water demand from VEWIN, Watergebruik Thuis 2016
# patterns from SIMDEUM - https://www.kwrwater.nl/tools-producten/simdeum/
name_demiwater        = 'Externe_Inputgegevens_model/Demiwater_demand.xlsx'
sheet_demiwater_dish    = 'dish'
sheet_demiwater_wash    = 'wash'
sheet_demiwater_wc      = 'wc'
dishwasher            = 2.5             # [lpppd] average water demand of dishwasher
washingmachine        = 14.1            # [lpppd] average water demand of washing machine
wc                    = 34.6            # [lpppd] average water demand of wc
demiwater_factor      = 0               # [-] when 1.0 - use demiwater, when 0.0 no demiwater

##### The hydrogen system of Power to X  ####
NmH2_H2O              = 1.24            # [m3 H2 / L H2O]
purity                = 99.999          # [%] purity of water in electrolyser

# Electrolyser
NmH2                  = 11.1            # [Nm3/kg] conversion of kg H2 to Nm3 H2
E_electrolyzer        = 49.25           # [kWh/kg H2] energy for electrolysis i.e.
http://www.hydrogenics.com/wp-content/uploads/HyLYZER_600_3MW.pdf
E_purification        = 0.0             # [kWh/kg H2] energy for purification from paper Oldenbroek
eff_heat_el           = 75              # [%] approximate percentage of heat that can be recovered -
assumption

# Fuel cell
if curtailment == True:
   max_cap_fuelcell   = 0
else:
   max_cap_fuelcell    = 5              # [kW] max capacity (el) of the fuel cell (Based on Hydrogen-Bromine
Flow Battery doi:10.3390/pr8111492)
eff_fuelcell_appr     = 60.0            # [%] approximate effciency fuel cell in 2030- to be replaced by a
function later on
e_h2                  = 39.4            # [kWh/kg] energy content of a kg of hydrogen (HHV)
eff_heat_fc           = 80              # [%] approximate percentage of heat that can be recovered -
assumption

# First compression + storage in tube trailer
E_comp_30_200         = 1.5             # [kWh/kg H2] energy for compression to medium pressure for
storage in tube trailer

# Hydrogen fuelling station
#E_comp_high          = 1.8             # [kWh/kg H2] energy for compression from tube trailer to hydrogen
fuelling station (700 bar)
E_comp_30_880         = 3.2             # [kWh/kg H2] energy for compression from 30 bar to 880 bar for
refuelling at 700 bar
E_comp_200_880        = 1.8             # [kWh/kg H2] energy for compression from 200 bar to 880 bar for
refuelling at 700 bar
```

```
#E_cooling_HSF          = 0.2             # [kWh/kg H2] energy required for cooling the gas during fuelling at
hydrogen fuelling station
#v_storage_station_200   = 400              # [kg H2] hydrogen storage tank at 200 bar at the hydrogen
fuelling station > kon gebruik niet vinden in model. storage size gegeven in 119
n_trailertractors       = 1.0             # [-] amount of trailer tractors
n_tubetrailers          = 1.0             # [-] amount of tube trailers

### Fuel production ###
h2_target              = 1               # [kg h2/year] target of yearly h2 production, if 0, there is no cap on the
production
tubetrailer_as_storage  = 1                # If tube trailer is used as storage, put 1, if there is a seperate
storage, put 0
if curtailment == True:
   max_E_Electrolyser  = 0
else:
   max_E_Electrolyser  = 75                # [kW] max capacity (el) of electrolyser
max_v_h2tank           = 200             # [kg H2] [7.5 kg is 300 kWh] maximum volume of H2 storage tank
>[specific energy H2: 143MJ/kg or 40kWh/kg], default is 200.0 kg
sell_v_h2tank          = 0            # [kg H2] [27.75 kg is 1110 kWh] amount of hydrogen sold per tube
trailer when tank is full - when zero, all extra production is exported immediately, default is 740.0 kg
min_v_h2tank           = 0.375            # [kg H2] [0.375 kg is 15 kWh] minimum volume of H2 storage
tank, default is 10.0 kg
V0_H2tank              = 0.375           # [kg H2] initial volume of H2 storage tank, default is 100.0 kg
name_tankpattern       = 'Externe_Inputgegevens_model/Tank_pattern.xlsx'# Excelfile with tankpattern
sheet_tankpattern      = '70'            # Sheet of Excelfile with tankpattern
Tankpattern_factor     = 0.0             # to multiply the tankpattern with (for multiple tankstations/extra
hydrogen demand)

### Hydrogen storage in salt cavern ###
V0_H2sc                = 0.0             # [kg H2] initial volume of H2 storage tank

##### The electricity system of Power to X  ####

# WRK elec demand      >niet relevant voor thesis
baseload_demand        = 1900.0          # 1900 [kWh] baseload demand Waternet
name_WRKpattern        = 'Externe_Inputgegevens_model/Waternet Meetdata WCB 2015 en 2016.xlsx'
# excel with elec pattern WRK 2015 & 2016
sheet_WRKpattern       = 'Hourdata'       # name of the sheet with hourly data
wrk_factor             = False           # set to True if the WRK pattern should be taken into account, set to
False if it should be left out of the run

# Solar panels         >> panel case study: REC Alpha Pure Black 405 Wp;
https://solarmagazine.nl/productzoeker/484/zonnepanelen/rec-alpha-pure#productimage-2
T_cNOCT                = 44.0            # [Celsius] nominal cell temperature        >default 45.0
T_aNOCT                = 20.0            # [Celsius] surrounding temperature of defined NOCT (at test
conditions)
G_tNOCT                = 800.0 / 1000      # [kW/m2] radiation of defined NOCT
n_mp_STC               = 21.9            # [%] efficiency panel at maximum power          >default 17.0
alfa_p                 = -0.26           # [%/Celsius] temperature coefficient of power      > default -0.41
T_cSTC                 = 25.0            # [Celsius] STC temperature
```

```
talfa              = 0.9            # [-] transmission of panel    >default 0.9  #uitleg: the solar transmittance
of any cover over the PV array *the solar absorptance of the PV array, soshinskaya et al, 2014


Y_pv               = 0.2189         # [kW/m2] rated capactiy of panel  >default 0.19375
f_pv_start           = 0.98           # [%] derating factor   >default 0.98
f_pv_year            = 0.92           # 81% yearly derating over 25 years linear   >default 0.81
f_losses           = 0.9            # [-] losses due to cables, temperatures, dust etc. >default 0.9
f_losses_nf          = 0.8            # [-] losses due to cables, temperatures, dust etc. >default 0.8
[northfield]
G_tSTC              = 1.0            # [kW/m2] STC radiation

N_solar_s           = 0.0         # 5.5MWp [-] Amount of solar panels south
turning_p           = 0.0            # [-] If the panels follow the sun, set this value to 1.0, otherwise 0.0
A_panel             = 1.85           # [m2] surface of single solar panel south   >default 1.63
N_solar_e           = 0.0            # [-] Amount of solar panels east or west
N_solar_w            = 0.0            # [-] Amount of solar panels east or west
turning_p_ew          = 0.0             # [-] If the panels follow the sun, set this value to 1.0, otherwise 0.0
N_solar_s_nf         = 0.0          # [-] amount of panels facing south on northern field WRK
N_solar_n_nf         = 0.0          # [-] amount of panels facing north on northen field WRK


latitude            = 52.351         # [-] latitude of the solarpanels  >default is 52.01
beta_s              = 15.0          # [degrees] slope panel with south orientation
beta_ew              = 15.0           # [degrees] slope panel with east-west orientation
beta_nf_s            = 13.0           # [degrees] slope panel on the northen field > is vgm van WRK, niet
nodig
beta_nf_n             = 10.0           # [degrees] slope panel on the northen field > is vgm van WRK, niet
nodig
psi_e              = 90.0           # [degrees] orientation of panels, east     >cs 77  >default 90.0
psi_w               = 270.0          # [degrees] orientation of panels, west     >cs 257  >default 270.0
psi_s              = 180.0          # [degrees] orientation of panels, south    >cs 167 >default 180.0
psi_n              = 0.0           # [degrees] orientation of panels, north  >cs 347 >default 0.0
psi_sw              = 225.0          # [degrees] orientation of panels, southwest >cs 212 >default 225.0

name_azimuth          = 'Externe_Inputgegevens_model/SunEarthTools_AnnualSunPath_2010-2024.xls'
# source https://www.sunearthtools.com/dp/tools/pos_sun.php

# Windturbines - GE 3.2 MW
#h_meter              = 10.0           # [m] height of windspeedmeter
#h_hub              = 85.0          # [m] distance turbine platform to rotor turbine
#z_O              = 0.3           # [m] surface roughness in m
#cut_on_speed          = 2.0            # [m/s] windspeed at which turbine is turned on
#cut_off_speed         = 25.0           # [m/s] windspeed at which turbine is turned off
#p_wind_max            = 3200.0          # [kW] maximum power of wind turbine
#N_wind              = 2.0            # [-] amount of windturbines used

# Lagerwey 4.5 MW Windturbine - 120 m
h_meter              = 10.0           # [m] height of windspeedmeter
```

```
h_hub                = 120.0          # [m] distance turbine platform to rotor turbine
z_O                 = 0.7            # [m] surface roughness in m
cut_on_speed          = 2.5            # [m/s] windspeed at which turbine is turned on
cut_off_speed         = 25.0           # [m/s] windspeed at which turbine is turned off
p_wind_max            = 4500.0         # [kW] maximum power of wind turbine
N_wind               = 0.0            # [-] amount of windturbines used


# Lagerwey L100-2.5 Windturbine - 75 m
#h_meter              = 10.0          # [m] height of windspeedmeter
#h_hub                = 75.0          # [m] distance turbine platform to rotor turbine
#z_O                 = 0.3            # [m] surface roughness in m
#cut_on_speed          = 2.5            # [m/s] windspeed at which turbine is turned on
#cut_off_speed         = 25.0           # [m/s] windspeed at which turbine is turned off
#p_wind_max            = 2500.0         # [kW] maximum power of wind turbine
#N_wind               = 0.0            # [-] amount of windturbines used

#Gamesa 132-5.0MW onshore - 95 m
#h_meter              = 10.0          # [m] height of windspeedmeter
#h_hub                = 95.0          # [m] distance turbine platform to rotor turbine
#z_O                 = 0.3            # [m] surface roughness in m
#cut_on_speed          = 1.5            # [m/s] windspeed at which turbine is turned on
#cut_off_speed         = 27.0           # [m/s] windspeed at which turbine is turned off
#p_wind_max            = 5000.0         # [kW] maximum power of wind turbine
#N_wind               = 3.0            # [-] amount of windturbines used

ext_loss             = 0              # [%] loss due to external factors such as wake-effects, blade degradation,
icing measures, shadow curtailment, etc)

# DC/DC splitter
n_DCDC               = 95.0           # [%] efficiency of DCDC splitter

# AC/DC converter
eff_ACDC             = 98.0           # [%] efficiency of converter from AC to DC
eff_DCAC             = 98.0           # [%] efficiency of converter from DC to AC

# Grid capacity
grid_cap              = 630          # [kW] grid capacity for a certain location - > default 750 kW for
neighbourhood with 200 homes (based on Netbeheer NL, 2019 ) (~1.5kW cap. per huis vuistregel)
grid_cap_extra           = 0          # [kW] extra grid capacity
cosinus_phi             = 1.0         # [] a value that is used to incoporate transportation losses of
electricity

# Cable
l_cable              = 0.0            # 2500 [m] length of cable from solar panels to neighbourhood
l_ls_cable           = 1400           # [m/MW] length LS cable per 1 MW of extra grid capacity
l_ms_cable            = 850            # [m/MW] length MS cable per 1 MW of extra grid capacity

# Transformator stations
```

```
ms_ms                 = 10              # [MW] capacity of a medium power transformator building (10-23 kV,
10-40 MVA, 20 per city )
ms_ls                 = 0.63            # [MW] capacity of a medium to low power transformator building (10-
23 - 0.4 kV, 0.1-1MVA, 25 per neighbourhood) > default is 1.0 MW  #op trafohuis.nl voorbeelden te
vinden

## Geothermal ###
T_HP_cond             = 50.0 #65.0      # [degrees] temperature at the condenser of the Heat Pump (max
temp from heat pump)
T_treshold            = 43.0            # [degrees C] temperature of the warm aquifer at which the mode of
operation of the heat pump should change
T_threshold_medium    = 4.0             # [degrees C] temperature of the medium aquifer at which the
mode of operation of the heat pump changes
T_threshold_warm      = 30.0            # [degrees C] temperature of the warm aquifer at which the
connection with the aquifers is switched off
t_hp_cond_dir_dhn     = 43.0            # [degrees C] temperature at the condenser side of the Heat
Pump when it is directly coupled to the grid
t_surfwater_threshold   = 14.0          # [degrees C] threshold temperature of surface water extraction
T_HE_loss             = 1.5             # [degrees] temperature loss over the heat exchanger
T_DHN_retour          = 25.0            # [degrees] temperature of the retour stream that comes back from
building/houses
T_DHN_in              = 44.0            # [degrees] appr. temperature in district heating network
if curtailment == True:
   hp_max             = 0.0
else:
   hp_max             = 75.0            # [kW] max capacity of heatpump
c_w                   = 4.18E3          # [kJ/m3/K] specific heat capacity of water
T_aq_m_ini            = 26.5            # [degrees C] initial value of the medium aquifer
T_aq_w_ini            = 45.92           # [degrees C] initial value for the warm aquifer
V0_W_aq               = 1.0             # [m3] initial volume of water stored in the warm aquifer - should at
least be 10
V0_M_aq               = 1.0             # [m3] initial volume of water stored in the medium aquifer - should at
least be 10
alpha_m               = 0.2             # [-] the thermal storage efficiency at low-medium temperatures
T_aq_amb              = 12.0            # [degrees C] ambient ground water temperature
L_borehole            = 65.0            # [m] length of the borehole of the aquifers
d_well                = 0.7             # [m] diameter of the borehole for the aquifers
L_terrainpipe         = 100.0           # [m] lengt of pipes between heat pump, aquifers and heat
exchanger(s)
max_debiet_aq         = 75              # [m3/hr] maximum flow in 1 bron
factor_heat_sun       = 1.3 #1.5        # [-] factor to multiply the heat demand with, so there is more
heat stored than used and heat loss decreases
factor_heat_grid      = 1.0             # [-] factor to multiply the heat demand with, so there is more heat
stored than used and heat loss decreases
e_pumps_dhn           = 2.0             # [kWh elec/kWh heat] energy needed for pumps in heat grid
heat_recovery         = 0.0             # [] set this parameter to 0.0 when you don't want heat recovery
from fuel cell or electrolyser, and to 1.0 if you do

name_surf_water       = 'Externe_Inputgegevens_model/RWS oppwater per 10 min.xlsx'
sheet_sw              = '2010-2020'
```

```
dfsurfwa = pd.read_excel(name_surf_water, sheet_name = sheet_sw, usecols = "T,U,W")
# source https://waterinfo.rws.nl/#!/nav/expert/ via 'download meer data'

## Electricity storage ###

# Collective battery
if curtailment == True:
    e_cap_battery_coll  = 0.0
else:
    e_cap_battery_coll  = 2500           # [kWh] size of collective battery storage    >2500 for cs
e_battery_ini_col      = 0.0            # [kWh] initial value of collective battery
eff_battery_coll       = 95.0           # [%] efficiency of battery storage one way
max_cap_charge         = 30.            # [%] maximum capacity that can be charged of discharged per
hour
dod                    = 0.8            # [-] depth of discharge of the battery
eff_h2_battolyser      = 0.0            # [kWh/kg] efficiency battolyser hydrogen production (at 1 bar)

# Battolyser
#e_cap_battery_coll     = 2000.0         # [kWh] size of collective battery storage
#e_battery_ini_col      = 1500.0         # [kWh] initial value of collective battery
#eff_battery_coll       = 89.4           # [%] efficiency of battery storage one way
#max_cap_charge         = 25.            # [%] maximum capacity that can be charged of discharged per
hour
#dod                    = 0.8            # [-] depth of discharge of the battery
#eff_h2_battolyser      = 48.8           # [kWh/kg] efficiency battolyser hydrogen production (at 1 bar)

### Heat demand ###
if Eheating == True:
    E_tapwater_new_ap      = 15   #aanname, 3x apprtmnt. wel veel mensen, niet elke dag vaatwas, geen
wasmachine #appartement I, 1929, pbl # [GJ] heat demand for domestic hot water each year for a new
house - Functioneel ontwerp Vesta v4 - PBL (2019)   p.52/53 >default is 5.7
    E_tapwater_reno_ap     = 4.95 #appartement I, 1929, pbl    # [GJ] heat demand for domestic hot
water each year for a renovated house- Functioneel ontwerp Vesta v4 - PBL (2019)  >default is 5.5
    E_tapwater_ter         = 5.6  #appartement II,1929, pbl    # [GJ] heat demand for domestic hot water
each year for a new house - Functioneel ontwerp Vesta v4 - PBL (2019)   >default is 7.3
    E_tapwater_shop        = 1.5 #???? assumptie
    E_spaceheating_new_ap   = 65.88           # [GJ] heat demand for space heating each year for a new
house - according to BENG norm of 50 kWh/m^2   >default 14.4                   spaceheat factor 4.05,
rendement 0.98 (2onder1-kap, label G)
    E_spaceheating_reno_ap  = 21.52           # [GJ] heat demand for space heating each year for a
renovated house- combination of CBS & Vesta data for label B appartment class I 1975-1991   >default
17.7        spaceheat factor 1.47, rendem 0.9 (app. label D)
    E_spaceheating_new_ter  = 26.1           # [GJ] heat demand for space heating each year for a new
house - according to BENG norm of 50 kWh/m^2   >default 21.6           spaceheat factor 1.78,
rendement 0.9   (appartement, label D)
    E_spaceheating_shop     = 19.66      #label C - dus iets minder dan app.1 floor/reno_ap
spaceheat factor 1.39, rendement 0.9  (appartement, label C)
else:
    E_tapwater_new_ap      = 0
    E_tapwater_reno_ap     = 0
```

```
    E_tapwater_ter          = 0
    E_tapwater_shop         = 0
    E_spaceheating_new_ap   = 0
    E_spaceheating_reno_ap  = 0
    E_spaceheating_new_ter  = 0
    E_spaceheating_shop     = 0
T_base                  = 15.5          # [Celsius] base temperature inside house  >default 14.0   #UK 15.5 is
often taken [spinoni et al. 2014]
T_base_cooling          = 22.0          # [Celsius] base temperature for cooling > default 22.0  #Uk is 22.0
[spinoni et al.,2014]
hp_mode                 = 'air'         # mode of the heatpump can be air, water or booster
if H2boiler == True:
    hp_hybrid           = True          # True when houses can partly be heated by hydrogen when hp eff is
too low + for tapwater
else:
    hp_hybrid           = False
H2_boiler_eff           = 98            # [%] Hydrogen boiler efficiency  HHV
n_house_new_ap          = 2     #'other': day care/buurthuis          # [-] Number of new houses in
apartment buildings that need to be heated
n_house_reno_ap         = 594.0   #appartement 1 verdieping met dak      # [-] Number of renovated
houses that need to be heated
n_house_new_ter         = 101.0   #appartement 2 verdiepeing met dak     # [-] Number of new houses
(single) that need to be heated
n_house_shop            = 37    #shop
phousehold              = 1.7           # [p/household] average amount of people per household    #cbs 2019
p_household_new_ap      = 30            # [p/household] assumption for people in new apartment
#aanname day care en buurthuis
p_household_reno_ap     = 1.6           # [p/household] assumption for people in renovated apartment
594x1.6 + 101x2.4 / 594+101 is 1.7 gemiddeld
p_household_new_ter     = 2.4           # [p/household] assumption for people in a terraced home
p_household_shop        = 1             # aanname

a_h_appartment_new      = 750.     #hele gebouw is 1500m2 # !Also change line 293! [m^2] surface of
the house (all floors combined) >default 60.     (m2 * 50 kWh/m2 * 3600 / 1000 000 = ... GJ
spaceheating
a_h_appartment_reno     = 80.           # !also change line 294! [m^2] surface of the house (all floors
combined) >default 60.
a_h_terraced            = 145.          # !also change line 295! [m^2] surface of the house (all floors
combined) >default 120.
a_h_shop                = 80.
#e_spaceheat            = 25.0          # [kWh/m^2/year] BENG norm for newly build homes (building
related energy use)

# Solar parameters
n_pv_roof_new_ap        = 54            # [-] amount of solar panels on the roof
n_pv_roof_reno_ap       = 4.0724        # [-] amount of solar panels on the roof
n_pv_roof_new_ter       = 4.0724        # [-] amount of solar panels on the roof
n_pv_roof_shop          = 4.0724
a_roof_ter              = 85            # [m^2] square meters of roof surface per home >default 30.0
#PV_Amsterdam {Maarten Verkou}
```

```
beta_roof             = 25.              # [degrees] angle of the roof > used for app_new and app_reno
>default 45.0
beta_roof_ap          = 25.              # [degrees] angle of solar panels on a flat roof > used for terraced
house, ter   >default 36.0

# Electricity use households
name_elec_pattern      = 'Externe_Inputgegevens_model/profielen Elektriciteit 2018 versie 1.00.xlsx'
#source https://www.nedu.nl/documenten/verbruiksprofielen/
sheet_elec_pattern     = 'profielen Elektriciteit 2018 ve'
sheet_elec_leap        = 'E1A_leap'
sheet_elec_leap2       = 'E3B_leap'
sheet_elec_leap3       = 'E3C_leap'
e_elec_ap_new          = 3410.           # [kWh/year] electricity use (user related) for a detached home -
http://wetten.overheid.nl/BWBR0032503/2018-01-01   >default 1780
e_elec_ap_reno         = 1620.           # [kWh/year] electricity use (user related) for a detached home -
CBS data for label B appartment class I 1975-1991  >default 2400
e_elec_terraced        = 1910.           # [kWh/year] electricity use (user related) for a terraced home -
http://wetten.overheid.nl/BWBR0032503/2018-01-01    >default 3000
e_elec_shop            = 1630.          #  assumptie - appartement, 1929, label C
e_ligthing_ap_new      = 0               # [kWh/year] electricity use for lighting in a detached home  (stond
op 200 default)  > set to 0, bc already included in general electricity demand.
e_ligthing_ap_reno     = 0.              # [kWh/year] electricity use for lighting in a renovated appartment
e_ligthing_terraced    = 0.              # [kWh/year] electricity use for lighting in a new apartment
e_lighting_shop        = 0.

#Electric cooking households
name_cooking_pattern      = 'Externe_Inputgegevens_model/Elec_cooking.xlsx' # source
http://resolver.tudelft.nl/uuid:9d49b1d3-107b-4f49-a36c-b606786bc207 p.123
sheet_cooking_pattern     = 'Cooking'
if Ecooking == True:
   e_cooking_ap_new          = 175.          # [kWh/year] electricity use (user related) for a detached
home - https://www.milieucentraal.nl/energie-besparen/apparaten-en-verlichting/huishoudelijke-
apparaten/inductie-kookplaat/      #aanname voor 45 weken, 1x per week koken voor 10 mensen [10
per week]. Normaal appartement: 45 weken, 7x per week voor 2 mensen [14 per week]
   e_cooking_ap_reno         = 175.          # [kWh/year] electricity use (user related) for a detached
home - https://www.milieucentraal.nl/energie-besparen/apparaten-en-verlichting/huishoudelijke-
apparaten/inductie-kookplaat/
   e_cooking_terraced        = 175.          # [kWh/year] electricity use (user related) for a terraced home
- https://www.milieucentraal.nl/energie-besparen/apparaten-en-verlichting/huishoudelijke-
apparaten/inductie-kookplaat/
   e_cooking_shop            = 0.            #no cooking in shop
else:
   e_cooking_ap_new          = 0
   e_cooking_ap_reno         = 0
   e_cooking_terraced        = 0
   e_cooking_shop            = 0

#Electric car use in households
name_ev_pattern        = 'Externe_Inputgegevens_model/Elec_car_loadpattern.xlsx' #different sources,
see file
```

```
sheet_ev_pattern       = 'car_flex'
e_elec_car             = 2600.           # [kWh/year] electricity use for an electric car   >default 2600
f_elec_car             = 6               # [%] percentage of homes with an electric car  >default 70.  >max
parkeerplaatsen 303, als allemaal bezet met EV: 43.6 procent
f_car_homecharge       = 60.0            # [%] percentage of the total energy use of the car charged at
home    >default 60.0
eff_charge_bev         = 90.7            # [%] charging efficiency of electric car, from Farahani et al. (2020)

# battery in households
if curtailment == True:
   e_cap_battery      = 0                # [kWh] initial value of home battery
   e_cap_battery_other = 0               # [kWh] home battery for day care and wijkhuis: size of 5 Tesla
Powerwalls
else:
   e_cap_battery      = 13.5             # 10-14 [kWh] size of the home battery (Tesla Powerwall: 13.5)
   e_cap_battery_other = 68.5            # [kWh] home battery for day care and wijkhuis: size of 5 Tesla
Powerwalls
e_battery_ini          = 0.0             # [kWh] initial value of home battery
eff_battery            = 95              # [%] efficiency of battery storage one way (Tesla PW: two way 90%)

name_tapwater_pattern   = 'Externe_Inputgegevens_model/Tapwater_pattern.xlsx' #source
https://www.rvo.nl/sites/default/files/Definitief_Rapport Praktijkprestaties van warmtetechnieken bij
huishoudens.pdf p.27
sheet_tw_pattern       = 'Sheet2'
name_heatdemandaquifer  = 'Externe_Inputgegevens_model/Heat_demand_aquifer.xlsx'
sheet_heatdemandaq     = 'Sheet2'

### Heatloss in main district heating network ###
L_dhn          = 0.0                 # [m] length of district heating network
d_pipe         = 168.0               # [mm] pipe diameter of district heating network
L_seg          = 10.0                # [m] segment length
t_iso          = 0.0182              # [m] thickness of isulation layer

flag_plot      = False               # plot figures from heatloss_function

### Heatloss in loops from main DHN in the neighbourhood ###
L_dhn_loop     = 0.0                 # [m] length of district heating network
d_pipe_loop    = 50.0                # [mm] pipe diameter of district heating network
L_seg_loop     = 5.0                 # [m] segment length
t_iso_loop     = 0.055               # [m] thickness of isulation layer
n_loops        = 5.0                 # [-] amount of loops needed for houses (about one every 200 houses)

### Heatloss from main district heating network to house ###
L_tohouse             = 0.0          # [m] length of pipe from main DHN to home
d_pipe_house          = 25.0         # [mm] pipe diameter for the pipe between main network and
house
L_seg_house           = 0.1          # [m] segment length
t_iso_house           = 0.05         # [m] thickness of isulation layer
```

```
### Distribution network demiwater ###
d_pipe_water          = 100.0     # [mm] assumed average diameter of distribution network
l_pipe_dist           = L_dhn     # [m] length of distribution pipe
l_connect_pipe          = 11.0      # [m] length of pipes from distribution to connection
```

2. Parameter changes for the different simulations.

curtailment

```
name                ="curtailment"
startDate            = "20180901"      # Start date of the simulation in format "YYYYMMDD"
endDate              = "20200101"      # End date of the simulation in format "YYYYMMDD"
priority            = 1           # Priority of sustainable electricity, generating heat (1) or H2 (2)
saltcavern_stor        = 0           # [-] if 1.0, the system tries to fulfill all its needs from hydrogen storage before energ
curtailment           = True         # If True: max_cap_fuelcell, max_E_Electrolyser, hp_max, e_cap_battery_coll, e_cap_
Eheating             = False        #if True, spaceheat & tapwater are electric, if False they are 0 (natural gas demand)
Ecooking             = False        #if True, cooking is electric, if False, cooking is nat. gas.: demand = 0
H2boiler             = False        # if True hydrogen can be used for heating (spaceheat and tapwater), else not
max_cap_fuelcell   = 0
max_E_Electrolyser  = 0
max_v_h2tank          = 200           # [kg H2] [7.5 kg is 300 kWh, 200 kg = 8000 kWh] maximum volume of H2 storage
sell_v_h2tank         = 0          # [kg H2] [27.75 kg is 1110 kWh] amount of hydrogen sold per tube trailer when tank i
V0_H2sc              = 0.0          # [kg H2] initial volume of H2 storage tank
hp_max            = 0.0
heat_recovery         = 0.0           # [] set this parameter to 0.0 when you don't want heat recovery from fuel cell or e
e_cap_battery_coll  = 0.0
hp_hybrid           = False
f_elec_car            = 6            # [%] percentage of homes with an electric car  >default 70.  >max parkeerplaatsen 30
f_car_homecharge    = 60.0
e_cap_battery      = 0    # [kWh] initial value of home battery
e_cap_battery_other = 0   # [kWh] home battery for day care and wijkhuis: size of 5 Tesla Powerwalls
```

Load elec pattern [run_multiple_pm, 157-171]

Uitgezet: vanaf nu elke keer hetzelfde electriciteits patroon

Bh

```
name                ="Bh"
startDate            = "20180901"      # Start date of the simulation in format "YYYYMMDD"
endDate              = "20200101"      # End date of the simulation in format "YYYYMMDD"
priority            = 1           # Priority of sustainable electricity, generating heat (1) or H2 (2)
saltcavern_stor        = 0           # [-] if 1.0, the system tries to fulfill all its needs from hydrogen storage before energ
curtailment           = True         # If True: max_cap_fuelcell, max_E_Electrolyser, hp_max, e_cap_battery_coll, e_cap_
```

```
Eheating            = False         #if True, spaceheat & tapwater are electric, if False they are 0 (natural gas demand)
Ecooking            = False         #if True, cooking is electric, if False, cooking is nat. gas.: demand = 0
H2boiler            = False          # if True hydrogen can be used for heating (spaceheat and tapwater), else not
max_cap_fuelcell   = 0
max_E_Electrolyser  = 0
max_v_h2tank         = 200            # [kg H2] [7.5 kg is 300 kWh, 200 kg = 8000 kWh] maximum volume of H2 storage
sell_v_h2tank        = 0          # [kg H2] [27.75 kg is 1110 kWh] amount of hydrogen sold per tube trailer when tank is
V0_H2sc             = 0.0            # [kg H2] initial volume of H2 storage tank
hp_max           = 0.0
heat_recovery        = 0.0            # [] set this parameter to 0.0 when you don't want heat recovery from fuel cell or e
e_cap_battery_coll  = 0.0
hp_hybrid         = False
f_elec_car            = 6             # [%] percentage of homes with an electric car  >default 70.  >max parkeerplaatsen 30
f_car_homecharge    = 60.0
e_cap_battery      = 13.5# 0    # [kWh] initial value of home battery
e_cap_battery_other = 68.5 #0   # [kWh] home battery for day care and wijkhuis: size of 5 Tesla Powerwalls
```

Bc

```
name                ="Bc"
startDate            = "20180901"       # Start date of the simulation in format "YYYYMMDD"
endDate              = "20200101"        # End date of the simulation in format "YYYYMMDD"
priority             = 1              # Priority of sustainable electricity, generating heat (1) or H2 (2)
saltcavern_stor        = 0             # [-] if 1.0, the system tries to fulfill all its needs from hydrogen storage before energ
curtailment           = True          # If True: max_cap_fuelcell, max_E_Electrolyser, hp_max, e_cap_battery_coll, e_cap_
Eheating            = False         #if True, spaceheat & tapwater are electric, if False they are 0 (natural gas demand)
Ecooking            = False         #if True, cooking is electric, if False, cooking is nat. gas.: demand = 0
H2boiler            = False          # if True hydrogen can be used for heating (spaceheat and tapwater), else not
max_cap_fuelcell   = 0
max_E_Electrolyser  = 0
max_v_h2tank         = 200            # [kg H2] [7.5 kg is 300 kWh, 200 kg = 8000 kWh] maximum volume of H2 storage
sell_v_h2tank        = 0          # [kg H2] [27.75 kg is 1110 kWh] amount of hydrogen sold per tube trailer when tank is
V0_H2sc             = 0.0            # [kg H2] initial volume of H2 storage tank
hp_max           = 0.0
heat_recovery        = 0.0            # [] set this parameter to 0.0 when you don't want heat recovery from fuel cell or e
e_cap_battery_coll  = 4000 #0.0
hp_hybrid         = False
f_elec_car            = 6             # [%] percentage of homes with an electric car  >default 70.  >max parkeerplaatsen 30
f_car_homecharge    = 60.0
e_cap_battery      = 0    # [kWh] initial value of home battery
e_cap_battery_other = 0   # [kWh] home battery for day care and wijkhuis: size of 5 Tesla Powerwalls
```

Cook

```
name                ="Cook"
startDate            = "20180901"       # Start date of the simulation in format "YYYYMMDD"
endDate              = "20200101"        # End date of the simulation in format "YYYYMMDD"
priority             = 1              # Priority of sustainable electricity, generating heat (1) or H2 (2)
saltcavern_stor        = 0.0             # [-] if 1.0, the system tries to fulfill all its needs from hydrogen storage before ener
```

```
curtailment          = True          # If True: max_cap_fuelcell, max_E_Electrolyser, hp_max, e_cap_battery_coll, e_cap
Eheating             = False         #if True, spaceheat & tapwater are electric, if False they are 0 (natural gas demand)
Ecooking             = True          #if True, cooking is electric, if False, cooking is nat. gas.: demand = 0
H2boiler             = False          # if True hydrogen can be used for heating (spaceheat and tapwater), else not
max_cap_fuelcell   =  0
max_E_Electrolyser  = 0
max_v_h2tank         = 200            # [kg H2] [7.5 kg is 300 kWh, 200 kg = 8000 kWh] maximum volume of H2 storage
sell_v_h2tank        = 0           # [kg H2] [27.75 kg is 1110 kWh] amount of hydrogen sold per tube trailer when tank i
V0_H2sc              = 0.0            # [kg H2] initial volume of H2 storage tank
hp_max          = 0.0
heat_recovery        = 0.0            # [] set this parameter to 0.0 when you don't want heat recovery from fuel cell or e
e_cap_battery_coll  = 0.0
hp_hybrid         = False
f_elec_car           = 6             # [%] percentage of homes with an electric car  >default 70.  >max parkeerplaatsen 30
f_car_homecharge   = 60.0
e_cap_battery      = 0    # [kWh] initial value of home battery
e_cap_battery_other = 0   # [kWh] home battery for day care and wijkhuis: size of 5 Tesla Powerwalls
```

EVmax

```
name                ="EVmax"
startDate            = "20180901"       # Start date of the simulation in format "YYYYMMDD"
endDate              = "20200101"        # End date of the simulation in format "YYYYMMDD"
priority             = 1             # Priority of sustainable electricity, generating heat (1) or H2 (2)
saltcavern_stor       = 0.0            # [-] if 1.0, the system tries to fulfill all its needs from hydrogen storage before ener
curtailment          = True          # If True: max_cap_fuelcell, max_E_Electrolyser, hp_max, e_cap_battery_coll, e_cap
Eheating             = False         #if True, spaceheat & tapwater are electric, if False they are 0 (natural gas demand)
Ecooking             = False          #if True, cooking is electric, if False, cooking is nat. gas.: demand = 0
H2boiler             = False          # if True hydrogen can be used for heating (spaceheat and tapwater), else not
max_cap_fuelcell   =  0
max_E_Electrolyser  = 0
max_v_h2tank         = 200            # [kg H2] [7.5 kg is 300 kWh, 200 kg = 8000 kWh] maximum volume of H2 storage
sell_v_h2tank        = 0           # [kg H2] [27.75 kg is 1110 kWh] amount of hydrogen sold per tube trailer when tank is
V0_H2sc              = 0.0            # [kg H2] initial volume of H2 storage tank
hp_max          = 0.0
heat_recovery        = 0.0            # [] set this parameter to 0.0 when you don't want heat recovery from fuel cell or e
e_cap_battery_coll  = 0.0
hp_hybrid         = False
f_elec_car           = 43.6             # [%] percentage of homes with an electric car  >default 70.  >max parkeerplaatsen
f_car_homecharge   = 60.0
e_cap_battery      = 0    # [kWh] initial value of home battery
e_cap_battery_other = 0   # [kWh] home battery for day care and wijkhuis: size of 5 Tesla Powerwalls
```

CookEVmax

name   ="CookEVmax"

```
startDate            = "20180901"       # Start date of the simulation in format "YYYYMMDD"
endDate              = "20200101"        # End date of the simulation in format "YYYYMMDD"
priority             = 1             # Priority of sustainable electricity, generating heat (1) or H2 (2)
saltcavern_stor       = 0.0            # [-] if 1.0, the system tries to fulfill all its needs from hydrogen storage before ener
```

```
curtailment          = True         # If True: max_cap_fuelcell, max_E_Electrolyser, hp_max, e_cap_battery_coll, e_cap_
Eheating             = False        #if True, spaceheat & tapwater are electric, if False they are 0 (natural gas demand)
Ecooking             = True         #if True, cooking is electric, if False, cooking is nat. gas.: demand = 0
H2boiler             = False        # if True hydrogen can be used for heating (spaceheat and tapwater), else not
max_cap_fuelcell  =  0
max_E_Electrolyser  = 0
max_v_h2tank         = 200          # [kg H2] [7.5 kg is 300 kWh, 200 kg = 8000 kWh] maximum volume of H2 storage
sell_v_h2tank        = 0          # [kg H2] [27.75 kg is 1110 kWh] amount of hydrogen sold per tube trailer when tank is
V0_H2sc              = 0.0          # [kg H2] initial volume of H2 storage tank
hp_max            = 0.0
heat_recovery        = 0.0          # [] set this parameter to 0.0 when you don't want heat recovery from fuel cell or e
e_cap_battery_coll  = 0.0
hp_hybrid          = False
f_elec_car           = 43.6         # [%] percentage of homes with an electric car  >default 70.  >max parkeerplaatsen
f_car_homecharge   = 60.0
e_cap_battery      = 0   # [kWh] initial value of home battery
e_cap_battery_other = 0   # [kWh] home battery for day care and wijkhuis: size of 5 Tesla Powerwalls
```

Hy

```
name                ="HyBoilTapHeat"
startDate            = "20180901"     # Start date of the simulation in format "YYYYMMDD"
endDate              = "20200101"     # End date of the simulation in format "YYYYMMDD"
priority            = 1          # Priority of sustainable electricity, generating heat (1) or H2 (2)
saltcavern_stor       = 1.0          # [-] if 1.0, the system tries to fulfill all its needs from hydrogen storage before ener
curtailment          = True         # If True: max_cap_fuelcell, max_E_Electrolyser, hp_max, e_cap_battery_coll, e_cap_
Eheating             = True         #if True, spaceheat & tapwater are electric, if False they are 0 (natural gas demand)
Ecooking             = False        #if True, cooking is electric, if False, cooking is nat. gas.: demand = 0
H2boiler             = True         # if True hydrogen can be used for heating (spaceheat and tapwater), else not
max_cap_fuelcell  =  150 #0
h2_target            = 0            # [kg h2/year] target of yearly h2 production, if 0, there is no cap on the production
max_E_Electrolyser  = 150 #0
max_v_h2tank         = 200          # [kg H2] [7.5 kg is 300 kWh, 200 kg = 8000 kWh] maximum volume of H2 storage
sell_v_h2tank        = 0          # [kg H2] [27.75 kg is 1110 kWh] amount of hydrogen sold per tube trailer when tank is
V0_H2sc              = 1000000 # 0.0          # [kg H2] initial volume of H2 storage tank
hp_max            = 0.0
heat_recovery        = 0.0          # [] set this parameter to 0.0 when you don't want heat recovery from fuel cell or e
e_cap_battery_coll  = 0.0
hp_hybrid          = True
f_elec_car           = 6          # [%] percentage of homes with an electric car  >default 70.  >max parkeerplaatsen 30
f_car_homecharge   = 60.0
e_cap_battery      = 0   # [kWh] initial value of home battery
e_cap_battery_other = 0   # [kWh] home battery for day care and wijkhuis: size of 5 Tesla Powerwalls
```

HyCook

```
name                ="HyBoilTapHeatCook"
startDate            = "20180901"     # Start date of the simulation in format "YYYYMMDD"
endDate              = "20200101"     # End date of the simulation in format "YYYYMMDD"
priority            = 1          # Priority of sustainable electricity, generating heat (1) or H2 (2)
```

```
saltcavern_stor       = 1.0           # [-] if 1.0, the system tries to fulfill all its needs from hydrogen storage before ener
curtailment          = True         # If True: max_cap_fuelcell, max_E_Electrolyser, hp_max, e_cap_battery_coll, e_cap_
Eheating             = True         #if True, spaceheat & tapwater are electric, if False they are 0 (natural gas demand)
Ecooking             = True         #if True, cooking is electric, if False, cooking is nat. gas.: demand = 0
H2boiler             = True         # if True hydrogen can be used for heating (spaceheat and tapwater), else not
max_cap_fuelcell   =  150 #0
h2_target           = 0            # [kg h2/year] target of yearly h2 production, if 0, there is no cap on the production
max_E_Electrolyser  = 150 #0
max_v_h2tank         = 200           # [kg H2] [7.5 kg is 300 kWh, 200 kg = 8000 kWh] maximum volume of H2 storage
sell_v_h2tank        = 0           # [kg H2] [27.75 kg is 1110 kWh] amount of hydrogen sold per tube trailer when tank is
V0_H2sc              = 1000000 #0.0           # [kg H2] initial volume of H2 storage tank
hp_max           = 0.0
heat_recovery        = 0.0           # [] set this parameter to 0.0 when you don't want heat recovery from fuel cell or e
e_cap_battery_coll  = 0.0
hp_hybrid          = True
f_elec_car           = 6             # [%] percentage of homes with an electric car  >default 70.  >max parkeerplaatsen 303
f_car_homecharge    = 60.0
e_cap_battery      = 0   # [kWh] initial value of home battery
e_cap_battery_other = 0   # [kWh] home battery for day care and wijkhuis: size of 5 Tesla Powerwalls
```

HyEVmax

```
name                ="HyBoilTapHeatEVmax"
startDate            = "20180901"      # Start date of the simulation in format "YYYYMMDD"
endDate              = "20200101"       # End date of the simulation in format "YYYYMMDD"
priority           = 1           # Priority of sustainable electricity, generating heat (1) or H2 (2)
saltcavern_stor       = 1.0           # [-] if 1.0, the system tries to fulfill all its needs from hydrogen storage before ener
curtailment          = True         # If True: max_cap_fuelcell, max_E_Electrolyser, hp_max, e_cap_battery_coll, e_cap_
Eheating             = True         #if True, spaceheat & tapwater are electric, if False they are 0 (natural gas demand)
Ecooking             = False         #if True, cooking is electric, if False, cooking is nat. gas.: demand = 0
H2boiler             = True         # if True hydrogen can be used for heating (spaceheat and tapwater), else not
max_cap_fuelcell   =  150 #0
h2_target           = 0            # [kg h2/year] target of yearly h2 production, if 0, there is no cap on the production
max_E_Electrolyser  = 150 #0
max_v_h2tank         = 200           # [kg H2] [7.5 kg is 300 kWh, 200 kg = 8000 kWh] maximum volume of H2 storage
sell_v_h2tank        = 0           # [kg H2] [27.75 kg is 1110 kWh] amount of hydrogen sold per tube trailer when tank is
V0_H2sc              = 1000000           # [kg H2] initial volume of H2 storage tank
hp_max           = 0.0
heat_recovery        = 0.0           # [] set this parameter to 0.0 when you don't want heat recovery from fuel cell or e
e_cap_battery_coll  = 0.0
hp_hybrid          = True
f_elec_car           = 43.6           # [%] percentage of homes with an electric car  >default 70.  >max parkeerplaatsen
f_car_homecharge    = 60.0
e_cap_battery      = 0   # [kWh] initial value of home battery
e_cap_battery_other = 0   # [kWh] home battery for day care and wijkhuis: size of 5 Tesla Powerwalls
```

HyBoilTapHeatCookEVmax

```
name                ="HyBoilTapHeatCookEVmax"
startDate            = "20180901"      # Start date of the simulation in format "YYYYMMDD"
```

```
endDate             = "20200101"       # End date of the simulation in format "YYYYMMDD"
priority            = 1            # Priority of sustainable electricity, generating heat (1) or H2 (2)
saltcavern_stor       = 1.0           # [-] if 1.0, the system tries to fulfill all its needs from hydrogen storage before ener
curtailment          = True         # If True: max_cap_fuelcell, max_E_Electrolyser, hp_max, e_cap_battery_coll, e_cap_
Eheating            = True         #if True, spaceheat & tapwater are electric, if False they are 0 (natural gas demand)
Ecooking            = True         #if True, cooking is electric, if False, cooking is nat. gas.: demand = 0
H2boiler            = True         # if True hydrogen can be used for heating (spaceheat and tapwater), else not
max_cap_fuelcell  =  150 #0
h2_target           = 0           # [kg h2/year] target of yearly h2 production, if 0, there is no cap on the production
max_E_Electrolyser  = 150 #0
max_v_h2tank         = 200           # [kg H2] [7.5 kg is 300 kWh, 200 kg = 8000 kWh] maximum volume of H2 storage
sell_v_h2tank        = 0          # [kg H2] [27.75 kg is 1110 kWh] amount of hydrogen sold per tube trailer when tank is
V0_H2sc             = 1000000           # [kg H2] initial volume of H2 storage tank
hp_max            = 0.0
heat_recovery         = 0.0           # [] set this parameter to 0.0 when you don't want heat recovery from fuel cell or e
e_cap_battery_coll  = 0.0
hp_hybrid           = True
f_elec_car            = 43.6           # [%] percentage of homes with an electric car  >default 70.  >max parkeerplaatsen
f_car_homecharge    = 60.0
e_cap_battery       = 0    # [kWh] initial value of home battery
e_cap_battery_other = 0   # [kWh] home battery for day care and wijkhuis: size of 5 Tesla Powerwalls
```

BhCook

```
name                ="BhCook"
startDate           = "20180901"       # Start date of the simulation in format "YYYYMMDD"
endDate             = "20200101"       # End date of the simulation in format "YYYYMMDD"
priority            = 1            # Priority of sustainable electricity, generating heat (1) or H2 (2)
saltcavern_stor       = 0.0           # [-] if 1.0, the system tries to fulfill all its needs from hydrogen storage before ener
curtailment          = True         # If True: max_cap_fuelcell, max_E_Electrolyser, hp_max, e_cap_battery_coll, e_cap_
Eheating            = False         #if True, spaceheat & tapwater are electric, if False they are 0 (natural gas demand)
Ecooking            = True         #if True, cooking is electric, if False, cooking is nat. gas.: demand = 0
H2boiler            = False         # if True hydrogen can be used for heating (spaceheat and tapwater), else not
max_cap_fuelcell  =  0
max_E_Electrolyser  = 0
max_v_h2tank         = 200           # [kg H2] [7.5 kg is 300 kWh, 200 kg = 8000 kWh] maximum volume of H2 storage
sell_v_h2tank        = 0          # [kg H2] [27.75 kg is 1110 kWh] amount of hydrogen sold per tube trailer when tank is
V0_H2sc             = 0.0          # [kg H2] initial volume of H2 storage tank
hp_max            = 0.0
heat_recovery         = 0.0           # [] set this parameter to 0.0 when you don't want heat recovery from fuel cell or e
e_cap_battery_coll  = 0.0
hp_hybrid           = False
f_elec_car            = 6           # [%] percentage of homes with an electric car  >default 70.  >max parkeerplaatsen 30
f_car_homecharge    = 60.0
e_cap_battery       = 13.5   # [kWh] initial value of home battery
e_cap_battery_other = 68.5   # [kWh] home battery for day care and wijkhuis: size of 5 Tesla Powerwalls
```

BhEVmax

```
name                ="BhEVmax"
```

```
startDate            = "20180901"      # Start date of the simulation in format "YYYYMMDD"
endDate              = "20200101"       # End date of the simulation in format "YYYYMMDD"
priority             = 1            # Priority of sustainable electricity, generating heat (1) or H2 (2)
saltcavern_stor        = 0.0            # [-] if 1.0, the system tries to fulfill all its needs from hydrogen storage before ener
curtailment           = True          # If True: max_cap_fuelcell, max_E_Electrolyser, hp_max, e_cap_battery_coll, e_cap_
Eheating             = False          #if True, spaceheat & tapwater are electric, if False they are 0 (natural gas demand)
Ecooking             = False          #if True, cooking is electric, if False, cooking is nat. gas.: demand = 0
H2boiler             = False           # if True hydrogen can be used for heating (spaceheat and tapwater), else not
max_cap_fuelcell   =  0
max_E_Electrolyser  = 0
max_v_h2tank          = 200            # [kg H2] [7.5 kg is 300 kWh, 200 kg = 8000 kWh] maximum volume of H2 storage
sell_v_h2tank         = 0          # [kg H2] [27.75 kg is 1110 kWh] amount of hydrogen sold per tube trailer when tank is
V0_H2sc              = 0.0            # [kg H2] initial volume of H2 storage tank
hp_max           = 0.0
heat_recovery         = 0.0            # [] set this parameter to 0.0 when you don't want heat recovery from fuel cell or e
e_cap_battery_coll  = 0.0
hp_hybrid          = False
f_elec_car           = 43.6             # [%] percentage of homes with an electric car  >default 70.  >max parkeerplaatsen
f_car_homecharge    = 60.0
e_cap_battery      = 13.5    # [kWh] initial value of home battery
e_cap_battery_other = 68.5   # [kWh] home battery for day care and wijkhuis: size of 5 Tesla Powerwalls
```

BhCookEVmax

```
name                ="BhCookEVmax"
startDate            = "20180901"      # Start date of the simulation in format "YYYYMMDD"
endDate              = "20200101"       # End date of the simulation in format "YYYYMMDD"
priority             = 1            # Priority of sustainable electricity, generating heat (1) or H2 (2)
saltcavern_stor        = 0.0            # [-] if 1.0, the system tries to fulfill all its needs from hydrogen storage before ener
curtailment           = True          # If True: max_cap_fuelcell, max_E_Electrolyser, hp_max, e_cap_battery_coll, e_cap_
Eheating             = False          #if True, spaceheat & tapwater are electric, if False they are 0 (natural gas demand)
Ecooking             = True          #if True, cooking is electric, if False, cooking is nat. gas.: demand = 0
H2boiler             = False           # if True hydrogen can be used for heating (spaceheat and tapwater), else not
max_cap_fuelcell   =  0
max_E_Electrolyser  = 0
max_v_h2tank          = 200            # [kg H2] [7.5 kg is 300 kWh, 200 kg = 8000 kWh] maximum volume of H2 storage
sell_v_h2tank         = 0          # [kg H2] [27.75 kg is 1110 kWh] amount of hydrogen sold per tube trailer when tank is
V0_H2sc              = 0.0            # [kg H2] initial volume of H2 storage tank
hp_max           = 0.0
heat_recovery         = 0.0            # [] set this parameter to 0.0 when you don't want heat recovery from fuel cell or e
e_cap_battery_coll  = 0.0
hp_hybrid          = False
f_elec_car           = 43.6             # [%] percentage of homes with an electric car  >default 70.  >max parkeerplaatsen
f_car_homecharge    = 60.0
e_cap_battery      = 13.5    # [kWh] initial value of home battery
e_cap_battery_other = 68.5   # [kWh] home battery for day care and wijkhuis: size of 5 Tesla Powerwalls
```

HyBh

```
name               ="HyBoilBhTapHeat"
startDate            = "20180901"      # Start date of the simulation in format "YYYYMMDD"
endDate              = "20200101"      # End date of the simulation in format "YYYYMMDD"
priority           = 1            # Priority of sustainable electricity, generating heat (1) or H2 (2)
saltcavern_stor       = 1.0           # [-] if 1.0, the system tries to fulfill all its needs from hydrogen storage before ener
curtailment          = True         # If True: max_cap_fuelcell, max_E_Electrolyser, hp_max, e_cap_battery_coll, e_cap
Eheating             = True         #if True, spaceheat & tapwater are electric, if False they are 0 (natural gas demand)
Ecooking             = False         #if True, cooking is electric, if False, cooking is nat. gas.: demand = 0
H2boiler             = True         # if True hydrogen can be used for heating (spaceheat and tapwater), else not
max_cap_fuelcell   =  150 #0
h2_target           = 0            # [kg h2/year] target of yearly h2 production, if 0, there is no cap on the production
max_E_Electrolyser  = 150 #0
max_v_h2tank         = 200           # [kg H2] [7.5 kg is 300 kWh, 200 kg = 8000 kWh] maximum volume of H2 storage
sell_v_h2tank        = 0          # [kg H2] [27.75 kg is 1110 kWh] amount of hydrogen sold per tube trailer when tank is
V0_H2sc             = 1000000           # [kg H2] initial volume of H2 storage tank
hp_max           = 0.0
heat_recovery        = 0.0           # [] set this parameter to 0.0 when you don't want heat recovery from fuel cell or e
e_cap_battery_coll  = 0.0
hp_hybrid          = True
f_elec_car           = 6          # [%] percentage of homes with an electric car  >default 70.  >max parkeerplaatsen 30
f_car_homecharge    = 60.0
e_cap_battery       = 13.5    # [kWh] initial value of home battery
e_cap_battery_other = 68.5   # [kWh] home battery for day care and wijkhuis: size of 5 Tesla Powerwalls
```

HyBhCook

```
name               ="HyBoilBhTapHeatCook"
startDate            = "20180901"      # Start date of the simulation in format "YYYYMMDD"
endDate              = "20200101"      # End date of the simulation in format "YYYYMMDD"
priority           = 1            # Priority of sustainable electricity, generating heat (1) or H2 (2)
saltcavern_stor       = 1.0           # [-] if 1.0, the system tries to fulfill all its needs from hydrogen storage before ener
curtailment          = True         # If True: max_cap_fuelcell, max_E_Electrolyser, hp_max, e_cap_battery_coll, e_cap
Eheating             = True         #if True, spaceheat & tapwater are electric, if False they are 0 (natural gas demand)
Ecooking             = True         #if True, cooking is electric, if False, cooking is nat. gas.: demand = 0
H2boiler             = True         # if True hydrogen can be used for heating (spaceheat and tapwater), else not
max_cap_fuelcell   =  150 #0
h2_target           = 0            # [kg h2/year] target of yearly h2 production, if 0, there is no cap on the production
max_E_Electrolyser  = 150 #0
max_v_h2tank         = 200           # [kg H2] [7.5 kg is 300 kWh, 200 kg = 8000 kWh] maximum volume of H2 storage
sell_v_h2tank        = 0          # [kg H2] [27.75 kg is 1110 kWh] amount of hydrogen sold per tube trailer when tank is
V0_H2sc             = 1000000           # [kg H2] initial volume of H2 storage tank
hp_max           = 0.0
heat_recovery        = 0.0           # [] set this parameter to 0.0 when you don't want heat recovery from fuel cell or e
e_cap_battery_coll  = 0.0
hp_hybrid          = True
f_elec_car           = 6          # [%] percentage of homes with an electric car  >default 70.  >max parkeerplaatsen 30
f_car_homecharge    = 60.0
e_cap_battery       = 13.5    # [kWh] initial value of home battery
e_cap_battery_other = 68.5   # [kWh] home battery for day care and wijkhuis: size of 5 Tesla Powerwalls
```

HyBhEVmax

```
name
="HyBoilBhTapHeatEVmax"
startDate          = "20180901"      # Start date of the simulation in format "YYYYMMDD"
endDate            = "20200101"      # End date of the simulation in format "YYYYMMDD"
priority          = 1           # Priority of sustainable electricity, generating heat (1) or H2 (2)
saltcavern_stor      = 1.0          # [-] if 1.0, the system tries to fulfill all its needs from hydrogen storage before ener
curtailment         = True         # If True: max_cap_fuelcell, max_E_Electrolyser, hp_max, e_cap_battery_coll, e_cap
Eheating           = True         #if True, spaceheat & tapwater are electric, if False they are 0 (natural gas demand)
Ecooking           = False         #if True, cooking is electric, if False, cooking is nat. gas.: demand = 0
H2boiler           = True         # if True hydrogen can be used for heating (spaceheat and tapwater), else not
max_cap_fuelcell  =  150 #0
h2_target          = 0           # [kg h2/year] target of yearly h2 production, if 0, there is no cap on the production
max_E_Electrolyser  = 150 #0
max_v_h2tank        = 200          # [kg H2] [7.5 kg is 300 kWh, 200 kg = 8000 kWh] maximum volume of H2 storage
sell_v_h2tank        = 0          # [kg H2] [27.75 kg is 1110 kWh] amount of hydrogen sold per tube trailer when tank is
V0_H2sc             = 1000000           # [kg H2] initial volume of H2 storage tank
hp_max           = 0.0
heat_recovery        = 0.0          # [] set this parameter to 0.0 when you don't want heat recovery from fuel cell or e
e_cap_battery_coll  = 0.0
hp_hybrid          = True
f_elec_car           = 43.6           # [%] percentage of homes with an electric car  >default 70.  >max parkeerplaatsen
f_car_homecharge    = 60.0
e_cap_battery       = 13.5    # [kWh] initial value of home battery
e_cap_battery_other = 68.5   # [kWh] home battery for day care and wijkhuis: size of 5 Tesla Powerwalls
```

HyBhCookEVmax

```
name                ="HyBoilBhTapHeatCookEVmax"
startDate          = "20180901"      # Start date of the simulation in format "YYYYMMDD"
endDate            = "20200101"      # End date of the simulation in format "YYYYMMDD"
priority          = 1           # Priority of sustainable electricity, generating heat (1) or H2 (2)
saltcavern_stor      = 1.0          # [-] if 1.0, the system tries to fulfill all its needs from hydrogen storage before ener
curtailment         = True         # If True: max_cap_fuelcell, max_E_Electrolyser, hp_max, e_cap_battery_coll, e_cap
Eheating           = True         #if True, spaceheat & tapwater are electric, if False they are 0 (natural gas demand)
Ecooking           = True         #if True, cooking is electric, if False, cooking is nat. gas.: demand = 0
H2boiler           = True         # if True hydrogen can be used for heating (spaceheat and tapwater), else not
max_cap_fuelcell  =  150 #0
h2_target          = 0           # [kg h2/year] target of yearly h2 production, if 0, there is no cap on the production
max_E_Electrolyser  = 150 #0
max_v_h2tank        = 200          # [kg H2] [7.5 kg is 300 kWh, 200 kg = 8000 kWh] maximum volume of H2 storage
sell_v_h2tank        = 0          # [kg H2] [27.75 kg is 1110 kWh] amount of hydrogen sold per tube trailer when tank is
V0_H2sc             = 1000000           # [kg H2] initial volume of H2 storage tank
hp_max           = 0.0
heat_recovery        = 0.0          # [] set this parameter to 0.0 when you don't want heat recovery from fuel cell or e
e_cap_battery_coll  = 0.0
hp_hybrid          = True
f_elec_car           = 43.6           # [%] percentage of homes with an electric car  >default 70.  >max parkeerplaatsen
```

```
f_car_homecharge    = 60.0
e_cap_battery       = 13.5    # [kWh] initial value of home battery
e_cap_battery_other = 68.5   # [kWh] home battery for day care and wijkhuis: size of 5 Tesla Powerwalls
```

GridReinforcement

```
name                ="GridReinforcement"
startDate            = "20180901"      # Start date of the simulation in format "YYYYMMDD"
endDate              = "20200101"       # End date of the simulation in format "YYYYMMDD"
priority            = 1            # Priority of sustainable electricity, generating heat (1) or H2 (2)
saltcavern_stor       = 0           # [-] if 1.0, the system tries to fulfill all its needs from hydrogen storage before energ
curtailment          = True         # If True: max_cap_fuelcell, max_E_Electrolyser, hp_max, e_cap_battery_coll, e_cap
Eheating             = False         #if True, spaceheat & tapwater are electric, if False they are 0 (natural gas demand)
Ecooking             = False         #if True, cooking is electric, if False, cooking is nat. gas.: demand = 0
H2boiler             = False          # if True hydrogen can be used for heating (spaceheat and tapwater), else not
max_cap_fuelcell   = 0
max_E_Electrolyser  = 0
max_v_h2tank          = 200            # [kg H2] [7.5 kg is 300 kWh, 200 kg = 8000 kWh] maximum volume of H2 storage
sell_v_h2tank         = 0          # [kg H2] [27.75 kg is 1110 kWh] amount of hydrogen sold per tube trailer when tank i
V0_H2sc              = 0.0          # [kg H2] initial volume of H2 storage tank
grid_cap               = 1000       # [kW] grid capacity for a certain location - > default 750 kW for neighbourhood w
ms_ls               = 1.0          # [MW] capacity of a medium to low power transformator building (10-23 - 0.4 kV, 0.1
hp_max           = 0.0
heat_recovery         = 0.0           # [] set this parameter to 0.0 when you don't want heat recovery from fuel cell or e
e_cap_battery_coll  = 0.0
hp_hybrid          = False
f_elec_car           = 6            # [%] percentage of homes with an electric car  >default 70.  >max parkeerplaatsen 30
f_car_homecharge    = 60.0
e_cap_battery       = 0    # [kWh] initial value of home battery
e_cap_battery_other = 0   # [kWh] home battery for day care and wijkhuis: size of 5 Tesla Powerwalls
```

GridReinforcementCook

```
name                ="GridReinforcement"
startDate            = "20180901"      # Start date of the simulation in format "YYYYMMDD"
endDate              = "20200101"       # End date of the simulation in format "YYYYMMDD"
priority            = 1            # Priority of sustainable electricity, generating heat (1) or H2 (2)
saltcavern_stor       = 0           # [-] if 1.0, the system tries to fulfill all its needs from hydrogen storage before energ
curtailment          = True         # If True: max_cap_fuelcell, max_E_Electrolyser, hp_max, e_cap_battery_coll, e_cap
Eheating             = False         #if True, spaceheat & tapwater are electric, if False they are 0 (natural gas demand)
Ecooking             = True         #if True, cooking is electric, if False, cooking is nat. gas.: demand = 0
H2boiler             = False          # if True hydrogen can be used for heating (spaceheat and tapwater), else not
max_cap_fuelcell   = 0
max_E_Electrolyser  = 0
max_v_h2tank          = 200            # [kg H2] [7.5 kg is 300 kWh, 200 kg = 8000 kWh] maximum volume of H2 storage
sell_v_h2tank         = 0          # [kg H2] [27.75 kg is 1110 kWh] amount of hydrogen sold per tube trailer when tank i
V0_H2sc              = 0.0          # [kg H2] initial volume of H2 storage tank
grid_cap               = 1000       # [kW] grid capacity for a certain location - > default 750 kW for neighbourhood w
ms_ls               = 1.0          # [MW] capacity of a medium to low power transformator building (10-23 - 0.4 kV, 0.1
hp_max           = 0.0
```

```
heat_recovery        = 0.0           # [] set this parameter to 0.0 when you don't want heat recovery from fuel cell or e
e_cap_battery_coll  = 0.0
hp_hybrid          = False
f_elec_car           = 6             # [%] percentage of homes with an electric car  >default 70.  >max parkeerplaatsen 30
f_car_homecharge   = 60.0
e_cap_battery      = 0    # [kWh] initial value of home battery
e_cap_battery_other = 0   # [kWh] home battery for day care and wijkhuis: size of 5 Tesla Powerwalls
```

GridReinforcementEVmax

```
name               ="GridReinforcement"
startDate           = "20180901"      # Start date of the simulation in format "YYYYMMDD"
endDate             = "20200101"       # End date of the simulation in format "YYYYMMDD"
priority           = 1            # Priority of sustainable electricity, generating heat (1) or H2 (2)
saltcavern_stor       = 0           # [-] if 1.0, the system tries to fulfill all its needs from hydrogen storage before energ
curtailment          = True          # If True: max_cap_fuelcell, max_E_Electrolyser, hp_max, e_cap_battery_coll, e_cap
Eheating            = False         #if True, spaceheat & tapwater are electric, if False they are 0 (natural gas demand)
Ecooking            = False         #if True, cooking is electric, if False, cooking is nat. gas.: demand = 0
H2boiler            = False         # if True hydrogen can be used for heating (spaceheat and tapwater), else not
max_cap_fuelcell   = 0
max_E_Electrolyser  = 0
max_v_h2tank         = 200           # [kg H2] [7.5 kg is 300 kWh, 200 kg = 8000 kWh] maximum volume of H2 storage
sell_v_h2tank        = 0           # [kg H2] [27.75 kg is 1110 kWh] amount of hydrogen sold per tube trailer when tank i
V0_H2sc             = 0.0          # [kg H2] initial volume of H2 storage tank
grid_cap             = 1000        # [kW] grid capacity for a certain location - > default 750 kW for neighbourhood w
ms_ls              = 1.0          # [MW] capacity of a medium to low power transformator building (10-23 - 0.4 kV, 0.1
hp_max            = 0.0
heat_recovery        = 0.0           # [] set this parameter to 0.0 when you don't want heat recovery from fuel cell or e
e_cap_battery_coll  = 0.0
hp_hybrid          = False
f_elec_car           = 43.6          # [%] percentage of homes with an electric car  >default 70.  >max parkeerplaatse
f_car_homecharge   = 60.0
e_cap_battery      = 0    # [kWh] initial value of home battery
e_cap_battery_other = 0   # [kWh] home battery for day care and wijkhuis: size of 5 Tesla Powerwalls
```

GridReinforcementCookEVmax

```
name               ="GridReinforcement"
startDate           = "20180901"      # Start date of the simulation in format "YYYYMMDD"
endDate             = "20200101"       # End date of the simulation in format "YYYYMMDD"
priority           = 1            # Priority of sustainable electricity, generating heat (1) or H2 (2)
saltcavern_stor       = 0           # [-] if 1.0, the system tries to fulfill all its needs from hydrogen storage before energ
curtailment          = True          # If True: max_cap_fuelcell, max_E_Electrolyser, hp_max, e_cap_battery_coll, e_cap
Eheating            = False         #if True, spaceheat & tapwater are electric, if False they are 0 (natural gas demand)
Ecooking            = True          #if True, cooking is electric, if False, cooking is nat. gas.: demand = 0
H2boiler            = False         # if True hydrogen can be used for heating (spaceheat and tapwater), else not
max_cap_fuelcell   = 0
max_E_Electrolyser  = 0
max_v_h2tank         = 200           # [kg H2] [7.5 kg is 300 kWh, 200 kg = 8000 kWh] maximum volume of H2 storage
sell_v_h2tank        = 0           # [kg H2] [27.75 kg is 1110 kWh] amount of hydrogen sold per tube trailer when tank i
```

```
V0_H2sc             = 0.0           # [kg H2] initial volume of H2 storage tank
grid_cap              = 1000        # [kW] grid capacity for a certain location - > default 750 kW for neighbourhood w
ms_ls               = 1.0           # [MW] capacity of a medium to low power transformator building (10-23 - 0.4 kV, 0.1
hp_max          = 0.0
heat_recovery         = 0.0             # [] set this parameter to 0.0 when you don't want heat recovery from fuel cell or e
e_cap_battery_coll  = 0.0
hp_hybrid         = False
f_elec_car            = 43.6            # [%] percentage of homes with an electric car  >default 70.  >max parkeerplaatse
f_car_homecharge    = 60.0
e_cap_battery      = 0    # [kWh] initial value of home battery
e_cap_battery_other = 0   # [kWh] home battery for day care and wijkhuis: size of 5 Tesla Powerwalls
```