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Reconfiguring the power grid

Assessing the benefits of making Utrecht Science Park's power grid dynamically reconfigurable

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Abstract

Increasing implementation of renewable energy as well as increasing electrification of formerly fossil forms of energy consumption, is leading to increasing problems with congestion in both transmission and distribution grids. There are several possible ways in which this problem can be mitigated, one of which is by implementing dynamic grid reconfiguration. In this study the effects of dynamic grid reconfiguration on local distribution grids were studied. This was done by creating several scenarios of what the distribution grid at Utrecht Science Park (USP) would be subjected to in the future, and modelling the effects that reconfigurability would have on this grid. It was found that in several possible future scenarios USP's distribution grid would be severely congested in the future, and that most of that congestion could be mitigated by the introduction of dynamic reconfigurability.

This work could not have been completed without the help of many people, several of whom I'd like to thank here. Madeleine and Bart, thank you for your guidance, wisdom, and inspiration. Olivia, thank you for the continued support and for keeping me sane. Ellen, thank you for your help with the final touches.

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1 Introduction

Humanity's ongoing practice of generating energy from fossilised carbon resources and the ensuing release of carbon dioxide into the atmosphere is contributing to the shift in climatic conditions that will make our Earth significantly less livable in the near future [1]. Reforming our energy systems is therefore a vital priority in safeguarding our planet's ability to sustain life.

This reform will largely occur along two fronts: First of all, equipment and processes that currently use fossil energy resources to perform useful work, such as heating or transport, will be replaced with alternatives that can perform these tasks while consuming electrical energy. Secondly, the task of electricity generation will in an increasingly larger part be performed by renewable energy generation assets such as solar photovoltaics (PV) and wind.

This far reaching electrification of energy systems, as part of a wider societal energy transition, will place a significant additional load on existing electrical power infrastructure. In addition to that, there is the fact that renewable energy resources are typically implemented in a more distributed and decentralised nature than classical power infrastructure, or are simply located in different locations than the current power grid was designed for. This change, from a centralised system structure to a more decentralised one, will result in a shift of electricity flow patterns, sometimes possibly even including reverse power flow situations.

This increase in load, and shifting of power flow patterns will in many cases mean that the existing power grid has insufficient capacity in places, and that capacity upgrades are necessary. The severity of these problems can already be felt in certain places, for example in the Netherlands, as can be seen in [2]. Given the cost and complexity of such upgrades it is desirable if this congestion in the power grid can be resolved in a manner that reduces the necessity of these expensive capacity upgrades.

Grid congestion occurs when the demand for electrical transport capacity outstrips the available capacity. This can lead to thermal overloads of components in the system, as well as deviating voltages across the system, possibly causing damage [3]. In the rest of this study, congestion is taken to mean loading of a component above 100% of its rated capacity.

There are multiple ways of dealing with grid congestion. Good overviews of these can be found in [4] and [5]. A high level taxonomy of different methods for handling grid congestion can be seen below in Figure 1. The specific method that this study focuses on is reconfiguration, the reason for this is further explained below.

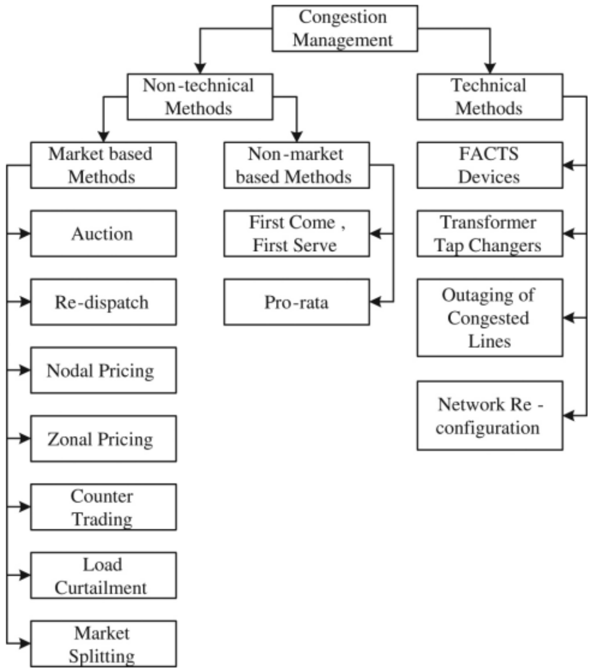

Figure 1: High level taxonomy of congestion management methods.
[5]

Reconfigurability in the power grid, generally speaking, is the idea that through opening and closing specific breakers it becomes possible to dynamically shift the bays and corresponding grid segments from which certain loads and generation sources are fed. Loading of the grid that exceeds the capacity of a single segment may thus be averted by distributing an excessive net load over multiple segments. This means that existing grid capacity may be used more efficiently [6]. In a simple sense this means that the normally open position in a radially operated grid 'shifts place' allowing one branch of the circle to take on part of the load of the other branch. Application of this idea in medium voltage distribution grids will be the main focus of this study, specifically, 10kV distribution grids, as the grid examined in the case study is such a grid.

The idea of grid reconfiguration is not new, already in the 1980s did engineers and researchers consider ways of performing switching operations in order to improve electrical systems performance [7]. Back then, congestion management was also considered one of the problems that reconfiguration could solve [8], however, the focus of this early research was mostly on minimising line losses and solving other problems related to energy management [9] [10].

In recent times reconfiguration has once again come into focus, however, now mostly as a way of handling the impact on power grids from ongoing implementation of decentralised generation systems and increasingly intermittent energy demand [11] [12] [13].

Most of the more recently published studies can be characterised by two factors. Firstly, they approach questions of reconfiguration by analysing fictional, or standardised 'example' grids, and looking whether reconfigurability improves performance, without trying to accurately model the changes that can be expected as a result of the energy transition (that is, integration of more intermittent generation capacity, and electrification of heat and transport). Secondly, the aim of these studies appears mostly to be finding fast and accurate methods for solving the combinatorial optimisation problem that is grid reconfiguration, whether by heuristic methods such as [14] and [15], or by algorithmic means such as [6] and [16].

Almost no studies have been done that combine analysis of the effects of reconfigurability on a medium voltage distribution grid, with a model of an existing distribution grid where reconfiguration is used to optimise for minimal congestion, and an analysis of how the energy transition will affect congestion in that power grid. This study aims to fill that gap in literature.

The aim of this study is therefore, to investigate whether making a local distribution grid dynamically reconfigurable would yield any benefit with regard to expected grid capacity resulting from electrification of currently non electrified services. Dynamic reconfigurability is used as a term to refer to the reconfiguration of the grid happening in real time, with little to no service interruption, as a response to the needs of the power grid that is being reconfigured. Benefit in this context would consist of the ability to carry out the planned electrification and other changes as part of the wider societal energy transition without having to carry out costly and time consuming capacity upgrades to the local power grid, or, at minimum, being able to defer these upgrades.

From the above we can formulate the following research question:

- *"What is the possible technical benefit that distribution system operators can achieve by making a local power grid dynamically reconfigurable?"*

This question can be answered by first answering the following sub questions:

1. *"What will local distribution grids look like in the year 2035, given the further electrification and reorganisation of energy systems as a result of the energy transition?"*
2. *"To what extent, if any, will these distribution grids experience congestion, and will the maximum rated capacity of electrical components be exceeded, as a result of these changes?"*
3. *"To what extent does making these grids dynamically reconfigurable result in reducing congestion and exceeding of capacity limits, that may occur?"*

The structure of this thesis is as follows: first, there will be a section outlining the specifics of the case study that will be used to answer the research questions. Secondly, a section going into more detail on the methodology used to answer the research question. Thirdly, a section setting out the results of the study. And finally sections discussing these results and any possible conclusions that can be drawn.

2 Case Study and Assumptions

2.1 Case Study

In order to find a more concrete answer to the research questions a case study will be performed on the Utrecht Science Park (USP). The decision to perform a case study was made in order to better align the available time and means with the research questions that are to be answered. Performing this case study simplifies the process of estimating the changes happening to a local grid as a result of the energy transition, as USP's Facility Management [17] have relatively detailed plans available concerning the transition of their energy system to a more electrified and less fossil fuel dependent one over the years leading up to 2035. This significantly reduces the amount of assumptions that need to be made and greatly simplifies data collection. Additionally, performing a case study allows the application of theory on reconfiguration in a more realistic setting with real world data, thus producing more realistic and verifiable results.

USP is the campus shared by Utrecht University (UU), Utrecht University of Applied Sciences (HU), the Academic hospital of Utrecht (UMC Utrecht), and several other commercial and research organisations. Plans to make the campus more sustainable involve installing large heat pumps and peaking boilers, a significant number of EV charging locations, substantial amounts of distributed generation capacity, and possibly large storage systems for both electrical and thermal energy [18] [19]. The additional load that this places on the existing power grid will likely, at times, exceed the designed maximum capacity of certain components in this system and therefore, USP may benefit from the introduction of reconfigurability in their energy system besides other, software-oriented solutions such as smart charging of EVs or demand response from heat pumps.

The distribution grid on the USP consists of a 10 kV grid that runs across campus, and more localised low voltage systems that feed individual buildings. This 10 kV grid will be the main focus of this study. It is this layer of the grid that feeds the entire USP and it is this layer that, ultimately, all power sources and loads on the USP are connected to.

2.2 Assumptions

In order to keep the scope of this study manageable this case study will limit itself to the 10 kV medium voltage grid on the USP. When generation or load is increased or decreased in the low voltage parts of the grid this will be modelled at the level of the 10kV/LV transformers. It will be assumed that the 50kV/10kV transforming substation has ample capacity. While this is not true, it falls outside of the scope of this study. Additionally it will be assumed that the contractual limitations that exist currently, regarding the amount of energy that can be delivered back into the grid, will not apply. This is done not only to simplify the problem to be modelled, but also because it exacerbates grid congestion in a reverse power flow situation at the distribution grid level, thus making any effects of reconfiguration more visible.

Given the fact that the structure of the internal power grid within and between the UMC buildings is not publicly available, and that no or very little renewable energy generation capacity is likely to be brought online there, the UMC will be left out of consideration in this study.

This study will also assume that all switches/breakers in the grid are fully remotely operable, and are fully capable of current interruption, hence they will simply be referred to as breakers in the rest of the study. This also entails assuming the appropriate sensing and signals transfer and processing systems are in place. Assuming this is an inaccuracy and will be discussed at a later time, in reality there are a variety of reasons, such as limitations resulting from protection systems, and increased wear and tear on breaker equipment, that limit frequent switching operations. Modelling these, however, would complicate the study significantly without adding to the ability of answering the research questions.

Similarly, the lower voltage parts of the power grid are not included in this study, but simply modelled as loads. While these parts of the grid can also experience congestion, this congestion can typically not be resolved by grid reconfiguration, and thus modeling them does not contribute to answering the research questions.

Likewise the effects that the energy transition or grid reconfiguration may have on voltages throughout the network is left out of scope. The study aims to focus on grid congestion, and hence, only line loading, and derived metrics, will be used in evaluation.

The power grid on the USP was itself somewhat simplified. This was done because in its current state, and with the method outlined in 3, the amount of breakers in the USP's power grid (164) would lead to computation times in the order of millions of years. This is because the method chosen essentially solves the problem in a 'brute force' way, amounting to a combinatorial problem in which the number of breakers in the grid is the main driver of a combinatorial explosion leading to awe inspiring computational requirements. Two assumptions specifically were made in order to facilitate this simplification: Firstly, when a line between two nodes in the grid has a breaker on either end of it, electrically, the effect of one or the other breaker being open is negligible, hence one of them may be removed. And secondly, that a breaker at a switching installation near the Princetonlaan (Stedin ID 2453_103), which is normally open, always remains open. This effectively splits the USP's power grid into a North and South grid, and treating these as separate grids brings the number of breakers in each sub grid to such a level that it becomes possible to perform this study.

For several data sources used during this study 2019 was the latest year for which reliable data is available, hence, whenever possible 2019 was chosen as the year from which to source input data, if this was not possible the closest suitable year was chosen.

3 Methodology

The way to answer the research questions above can roughly be described as follows: First, an overview of all energy consumption and generation at USP in 2035 will be created across several scenarios. Then, that data will be combined with a model of the physical energy infrastructure that will be present at that time. The resulting model constitutes an answer to sub question 1. These scenario models are then subjected to load flow simulation, the results of this simulation will tell if the grid is likely to experience congestion and thus, 2 is answered. These modelled scenarios are then built into a model that tests the effects of reconfiguration, the results of this model will include the effects that reconfiguration would have on any congestion that may occur, thus answering 3. All sub questions stated in Chapter 1 are then answered and it should be possible to answer the main research question. A schematic representation of this can be seen below in Figure 2.

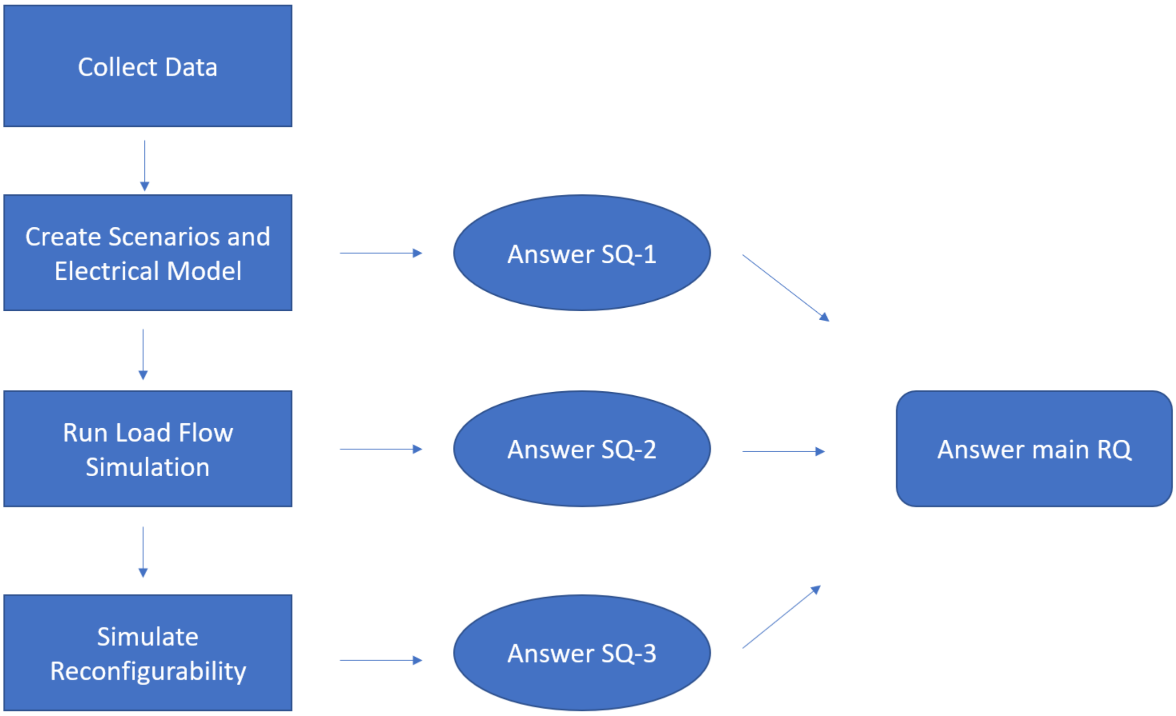

Figure 2: Schematic overview of the contribution of each methodological step to answering the main Research Question

In order to accurately assess whether reconfigurability would be useful to introduce into the USP's power grid it is first necessary to know what the USP's power grid will look like when the expected upgrades resulting from the energy transition have been completed. Naturally, it is not possible to know the future, and there is significant uncertainty concerning the precise way the energy transition will take shape, hence the best option available is to make multiple scenarios based on data and plans available, and for each, compare the effects of dynamic reconfiguration on grid congestion in the North and South grid. That is not to say that upgrades resulting from the energy transition can be just anything; for this study, specifically upgrades that do not concern the electricity grid itself are of interest. That means upgrades on the energy consumption and demand side, such as introduction of solar PV installations or electrical heating systems are included, but upgrades to the grid itself, such as extra or higher capacity power cables are not included. Dynamic reconfiguration is the reconfiguration of the grid while it is in operation.

Because the additional loads resulting from the energy transition are not distributed evenly across the grid, either geographically or temporally, it is interesting to model the effects of reconfigurability over the course of a year. For this reason the South grid will be modelled over the course of a year, with a resolution of one hour. The North grid is larger than the South grid and, in order to contain computation times to manageable levels, the North grid will only be modelled over the course of four representative weeks throughout the year, these will be the first weeks of each quarter.

The plans that the stakeholders of the USP have for the energy transition are documented in a quite detailed manner in several reports that have been written on this topic [18] [19] [20] [21] [22]. When combining this with publicly available data that can be argued to be representative for the USP as well, it becomes possible to create energy transition scenarios that are accurate enough for the purposes of this study.

These scenarios can be constructed by considering the USP as it is currently, and then factoring in changes to energy generation and changes to energy consumption.

Energy generation will change in two key ways: Firstly, fossil fuel based generating capacity will be phased out. This will include both electricity, and heat generating installations. Secondly, more renewable generating capacity will be brought online. This will mainly consist of PV installations but wind turbines are under consideration as well.

Energy consumption on the USP will change mostly as a result of heating demand being electrified, a share of transportation demand being electrified, and increases in building efficiencies. Estimated total future heating demand, as well as the amount of planned EV charging stations have been researched and documented already [18] [19], and for both of these typical demand profiles are known.

3.1 Scenarios

In order to deal with the uncertainty of future developments, and in order to assess how the USP power grid would behave under different possible future circumstances, several possible future scenarios will be created. The first scenario will include USP's plans for wind and PV energy generation systems, future power consumption of buildings, and the inclusion of energy consumption for EV charging. The second scenario will include everything in scenario 1, as well as the energy consumption of electrical heating systems. And the third scenario will include everything in scenario 2, but the EV energy consumption, instead of the 'dumb' model from scenarios 1 and 2, will be modelled as if happening through a green charging regime.

3.1.1 Scenario 1

Generation Modelling the new energy generation capacity will require knowing their location and their behaviour. While no certain plans exist yet, intentions on where to place which generation capacity are laid out in [18] and [19] and the behaviour of these installations is unlikely to differ significantly from comparable installations, hence energy generation data generated by [23] and [24] was accessed through [25] in order to generate typical production profiles for wind and PV generation assets located at the USP.

In the case of wind generation, USP plans for two turbines with three MW capacity each. In order to reflect this, an hourly energy generation profile for a Siemens swt 3.0-101 turbine (a 3 MW model) was generated using [25]. This way the model can draw the energy each turbine generates directly from the given time series.

In the case of solar PV generation, the energy production time series from a one MW solar farm located at USP was generated using [25]. The actual energy production of each PV installation on the USP, at each timestep is then modelled as:

$$\mathrm{P_t} = \mathrm{Q_t} * \mathrm{C} \tag{1}$$

With $\mathrm{P_t}$ as actual energy production at that timestep, $\mathrm{Q_t}$ as energy production of a one MW solar farm (both in MWh), and C being a dimensionless number equal to the installed capacity of the specific PV installation being modelled in MW.

Non Residential Building Consumption On the energy consumption side there are four aspects that need to be modelled: non-residential building energy consumption, residential building energy consumption, EV energy consumption, and building heat consumption.

The non residential buildings at USP are broadly varied in their size, age, and function. While it would have been ideal to know the exact energy consumption of each building individually, that is regrettably not in the realm of possibility. What was possible was obtaining hourly energy consumption data from four specific buildings, these are: the Androclus building, Vening-Meinesz building, Ruppert building, and Koningsberger building. The first two buildings are an old and a new building, respectively, that contain laboratories. Whereas, the other two buildings are an old and a new building, respectively, that solely contain educational and office facilities. All buildings on the USP are supplied from one or more MV/LV transformers, the installed transformer capacity is taken to be indicative of a buildings size and energy consumption. The energy consumption data of these reference buildings was then standardised to be the consumption these buildings would have had, if they had one MW of transformer capacity. This makes it easy to scale the energy consumption of all other buildings off of their installed transformer capacity. Thus, the load of a building x, for which load profile similar to that of building y is appropriate (e.g. a building that is old and has laboratory facilities), at timestep t would be:

$$\mathrm{P_{x,t}} = \frac{\mathrm{P_{y,t}}}{\mathrm{C_y}} * \mathrm{C_x} \tag{2}$$

With P being the load of buildings x and y at timestep t in MWh, and with C being a dimensionless number equal to the installed transformers capacities of buildings x and y in MW.

Residential Building Consumption In the case of the energy consumption of student residential buildings, the most accessible data source was [26], sourced from [27]. This dataset contains the energy consumption profiles of three German households in an urban environment, this data can be considered representative, as (student) housing on the USP also takes the form of households living in apartment buildings. These were then standardised the same way as described above, and then each residential building was assigned one of the three profiles. This was done somewhat arbitrarily to introduce some variability into the residential buildings energy consumption. The energy consumption of a residential building x that has been assigned load profile y at timestep t can then be described using equation 2.

EV Consumption Like buildings, EV energy consumption is also heavily dependent on the load profile that is associated with it. In scenario one and two it will be assumed that EVs are charged with a very basic smart charging regime that charges cars gradually over the course of an eight hour workday. In [18] it was found that, given the average daily travel distance of Dutch cars, and the average efficiency of EVs, that EVs at USP would charge approximately 7-8 kWh per day. It is likely that EV size will increase slightly over the coming years, hence 8 kWh per day was chosen as the amount of energy that each EV charges per day [28]. Such a charging regime would then yield a load of one kW per vehicle per charging hour, that is only active between nine in the morning and five in the afternoon.

3.1.2 Scenario 2

Energy consumption from heat generation is based on heating regime and heating degree days (or hours). A timeseries of the heating degree hours at USP in 2019 is sourced from [25]. A simple but, given the thermal mass of many buildings at USP, not invalid heating regime would be to keep all buildings at a constant temperature. The amount of energy used for heating on the USP is derived in [18], there it is assumed that each building is individually heated with a mix of heat pumps for general use, and electrical boilers for peaking use. Given the rather significant size centralised heating installations would have and the fact that in building installations are likely more efficient, this assumption was adopted. Given then, standard heat pump coefficients of performance, and historical heat demand, the report finds 11 826 MWh of electricity is needed for heating over the course of a year. It is then possible to express the amount of energy needed to keep a building with transformer capacity x heated at timestep t.

$$P_{x,t} = \left(\frac{\frac{E_{tot}}{H_{tot}}}{C_{tot}} \right) * C_x * H_t \tag{3}$$

With P being the amount of energy needed to keep the building heated for a given capacity and number of heating degree hours in MWh, E_{tot} being the total amount of energy used in a year for heating all buildings on the USP in MWh, H_{tot} being the total amount of heating degree hours in that same year, C_{tot} being the total installed transformer capacity at USP in MW, C_x being the transformer capacity of building x in MW, and H_t being the heating degree hours at timestep t for that particular building.

This amount of energy that would be needed to keep a building heated at a given timestep was then simply added to the regular energy use of the building.

3.1.3 Scenario 3

In scenario 3 the way EVs are charged is changed. Whereas in scenarios 1 and 2 this was done by letting the EVs charge gradually over the course of a day. Here in scenario 3 it is assumed that EVs will be charged according to a 'green' charging regime. This means that EVs will be charged at the moment when the greatest amount of renewable energy is available. This is done by letting EVs be charged during a three hour long charging peak with a first second and third hour during which EVs charge 2 MWh, 4 MWh, and 2 MWh respectively, for a total charge of 8 MWh. This peak is then centered around, i.e. the middle hour is located at, the hour during office hours that has the highest renewable energy production.

3.1.4 Electrical Model

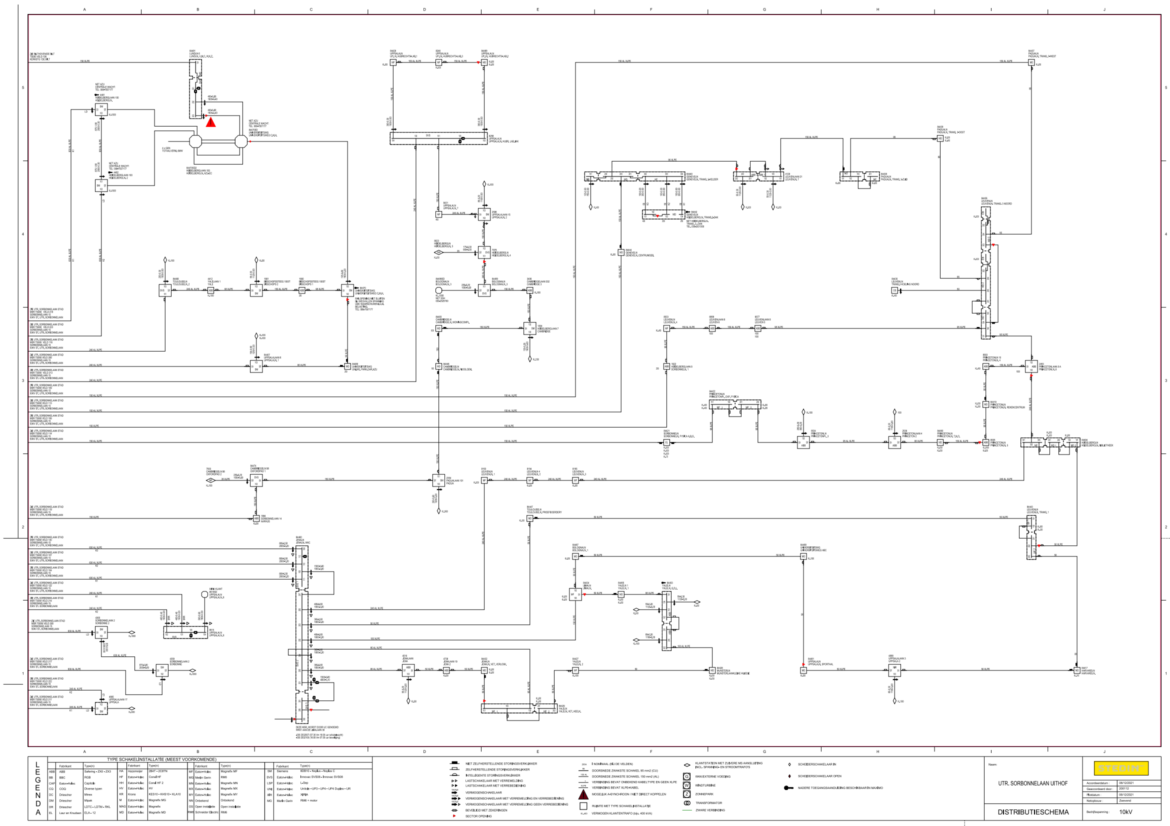

Figure 3: Schematic overview of the 10 kV power grid at USP

With these scenarios fully developed they can be mapped onto the currently existing power grid and be modelled. Data concerning the currently existing power grid was obtained from UU and the grid operator Stedin [29], this includes data concerning grid topology and the position of all breakers in the grid, for a general impression of what the grid looks like see Figure 4. For a more detailed view, please see Appendix A.1.

As can be seen in Appendix A.1, cable types were given for every cable on the USP. However, the precise electrical properties of these are unknown. As the cable types are known though, it was possible to source the electrical properties, such as the resistance and reactance from reference cables of the same type. For this a brochure by the Dutch cable manufacturer TKF (Twentse Kabel Fabriek) was used [30].

Cable lengths could be estimated using [29].

All this data was used to create a python model of the USP's power grid. This model, if given a set of power generation and power consumption values can run a full power flow, or load flow, simulation calculating exactly how this grid would behave in real life. If this load flow simulation is then iterated 8 760 times, while each time different values for hourly energy generation and consumption from the profiles discussed above are supplied, it effectively models the behaviour of the power grid over the course of a year. The exact model can be found at [31].

In creating this model it is important to assign each generation asset to a correct place in the grid. In [18] a comprehensive vision can be found of where generation assets are located or will likely be located. Using these locations all generation assets that were not directly building-bound were assumed to be connected to the nearest switching installation. An overview of this can be found in Appendix A.2.

As can be read in Subsection ??, most sources of load on the USP were modelled by selecting a load profile, and scaling it with the transformer capacity that was installed at that location. There are several cases where this was impractical, buildings that were scheduled for demolition were not modelled, buildings that were scheduled to be replaced were assumed to be replaced by buildings with similar transformer capacity (but were assigned the load profile of a new building naturally), and EV charging locations were spread out based on plans for installing solar carports, and across several of the larger parking garages that exist at USP. Energy use for heating was simply added to the buildings regular energy use.

When this step is completed, ideally, several models are available, four for each scenario (both the North and South grid modelled with and without reconfiguration) of the USP distribution grid with production and load at each bus specified with a resolution of one hour. These models are the answer to sub question 1. Running a power flow analysis for the models without reconfiguration, and assessing the results will answer sub question 2.

3.2 Analysis

With an electrical model of what the USP will look like after a completed energy transition, it becomes possible to simulate grid congestion without reconfiguration. This is done by running a load flow simulation for each timestep, after updating load and generation data for that timestep. From this analysis the number of congested hours in a year was calculated as well as the total overloading, this being the summed total of every line loading that is above 100% over all timesteps. This was chosen as a metric as it gives insight into the total magnitude of the congestion occurring. In addition to that the average load on all lines across all timesteps was also calculated to8 give a better idea of the loading occuring in the grid in general.

Next, it is time to model how reconfiguration will affect this system. The method chosen for this resembles what can be read in [32] and will be explained in the paragraphs below, however, in this study transformer tap changes and short circuit current analysis were discarded as they are not relevant for assessing the effects of dynamic reconfiguration.

3.2.1 Switch Configurations

First of all it was necessary to know which combinations of open and closed breakers would lead to states that were worth considering. For example a state where two breakers on the same line are in the open position would leave whatever load lies between those breakers unsupplied, and thus not be a state worth considering. Similarly, a state where too many breakers are closed would lead to loops being created in the grid. This is undesirable as the protection systems on the grid were not designed for it to be operated in such a configuration [33].

Luckily, the amount of breakers that need to be open for the grid to be in radial configuration is fixed, four in the South grid, and seven in the North grid. This means that in order to find all 'valid' states, a list needs to be generated of all the possible combinations in which that number of switches can be opened with all others closed. Then, for each combination, one will need to check whether all loads are supplied, and test for radiality by generating a graph of the grid and checking if loops exist in the graph. With the resulting list of 'valid' switching combinations, actual reconfiguration can be tested.

3.2.2 Reconfiguration

Actually testing reconfiguration is simple enough. For a given timestep in a given scenario, first all loads and energy generation are assigned, then, for each 'valid' state, all breakers are closed, then, the breakers that need to be open for that state are opened and a load flow simulation is run. Among the results of this load flow simulation is a list with the loading of all cables in the grid, expressed as a percentage of total capacity. From this list, the cable that has the highest loading is selected, and this cable's number and the associated loading are stored.

After all of the valid states have been analysed in this way a timestep is concluded. At this point there is a table that contains the highest line loading that exists for each valid state. From this list of highest line loadings, the lowest line loading is selected, and the switching state that produced that lowest line loading is selected as the best, or least congested, state. At this point the next timestep starts and the whole process starts again.

3.3 Post Processing

The above process yields a list of the optimal switching states for each timestep and the highest line loading that exists in the grid during that timestep. From this list the amount of congested hours can be derived but in order to learn more some post-processing was required.

Re-running power flow analyses for all timesteps, but with the switch configurations that were earlier found to be optimal, it was possible to compute the average line loadings across all lines and all timesteps. Further analysis required looking at the specific timesteps during which congestion occurred. For this some code was written that isolated the timesteps during which congestion existed, and then recreated those timesteps. It set load and generation data to the appropriate values, opened the relevant breakers and closed all others, and then reran a load flow simulation. From this the total overloading could also be computed.

The model for this study was created in python using the open source PandaPower library [32]. This library was chosen because it combines a well known and proven power flow analysis tool, PyPower (a python port of MatPower) with the Pandas data science library. This modelling tool was chosen because of accessibility and because the Pandas datastructures used to handle almost all data in the model allow the state of the model to be easily and automatically altered. This greatly increased the ease with which different energy production and consumption values, as well as switching states could be put into the model.

4 Results

The results of the simulations of the Southern half of USP's power grid can be seen below in Table 1. Several interesting things can be observed. First of all, the effect that introducing reconfiguration appears to have on reducing congestion across all metrics is significant. Secondly, the amount of congested hours in scenario 2, with and without reconfiguration, is slightly lower than in scenario 1, whereas that amount in scenario 3 is the highest, despite the total sum of squares of line overloading being the lowest of all unreconfigured scenarios.

Post processing also indicated an interesting difference between the scenarios; while in scenario 1 after reconfiguration it was lines 17, 18, and 19 that were oft overloaded. In scenario 3 it was line 4 as well as on one occasion line 3 where loads higher than 100% of line capacity occurred (for a detailed overview of which lines these are exactly, please see Appendix A.3).

Table 1: Results table detailing the simulation results from the Southern grid.

	Scenario 1		Scenario 2		Scenario 3	
	unreconfigured	reconfigured	unreconfigured	reconfigured	unreconfigured	reconfigured
Total Congested Hours	868	4	858	0	920	7
Total Overloading	70 338	926	67 355	0	67 361	824
Average Line load	15.06 %	13.43 %	16.00 %	13.96 %	16.01 %	13.96 %
Highest Line Load	166 %	107 %	166 %	98 %	166 %	106 %

The results of the simulations of the Northern half of USP's power grid can be seen below in Table 2. Given that no congestion is occurring at any time in this section of the grid it is only of marginal utility to discuss these results. One interesting aspect is the fact that in scenarios 2 and 3 the average line loadings were higher if reconfiguration was applied than if not. However, the highest line loading that did occur in these scenarios was still significantly lower if reconfiguration was applied.

Table 2: Results table detailing the simulation results from the Northern grid.

	Scenario 1		Scenario 2		Scenario 3	
	unreconfigured	reconfigured	unreconfigured	reconfigured	unreconfigured	reconfigured
Total Congested Hours	0	0	0	0	0	0
Total Overloading	0	0	0	0	0	0
Average Line load	7.43 %	6.43 %	8.72 %	10.01 %	8.73 %	10.01 %
Highest Line Load	70 %	47 %	81 %	50 %	95 %	50 %

First of all, the results seem to indicate that introducing reconfigurability into the grid has a significant effect on reducing grid congestion. Furthermore, there are several other things that can be observed: First, in all three scenarios in the Southern grid, the highest occurring line loading when reconfiguration is not applied, is 166%. This implies that this specific overload is caused by something that is the same across scenarios. Given that demand changes across scenarios, this can realistically only be a spike in renewable energy generation. It is then interesting to notice that the changes brought in in the second and third scenario do not affect this specific overloading. Secondly, what is also interesting, is the effect that introducing the extra load due to heat generation has on where and how congestion manifests. Despite heat generation placing extra demand on the power grid, congested hours as well as the total magnitude of congestion, as seen in the total overloading figure, are going down. A possible explanation for this could be that the increase in energy consumption for heat generation means that more energy generated from distributed generation sources is being consumed locally. This decreased severity of congestion in scenario 2 is also reflected in the fact that applying reconfiguration to the Southern grid solves all congestion in this scenario. Thirdly, in scenario 3 the amount of congested hours increases again, while the total magnitude of this congestion does not significantly change in regards to scenario 2. The increased spiking behaviour in the energy demand from EV charging may cause additional congestion in two distinct ways. First, spiking energy demand during certain hours may increase load on the grid. Second, reduction of energy demand during non spike hours may mean that less renewably generated energy is consumed locally, and thus has to go through the grid, increasing the load. Given that the total magnitude of congestion has not significantly changed, it would appear that the overloading that takes place during the extra congested hours of peak EV charging is not very severe, and not caused by significant spikes of some sort. This would indicate that the latter of the two causes is more likely to apply here.

Finally, given that no congestion occurs in the Northern grid, it is of marginal utility to discuss it here. That being said it is interesting that in scenarios 2 and 3 the average line load throughout the grid over all timesteps increases when reconfiguration is applied. This may suggest that in the Northern grid reconfiguration increases overall line loadings slightly while decreasing peaks in energy flow through the grid, as can be seen in the highest line load figures for these scenarios.

5 Discussion

There are, however, several limitations on the execution of this study, as well as what could be included and what not. These can roughly be divided in two subcategories: limitations in the method with which this study was executed, and limitations imposed by the reality that not every possible factor could be included in the study. Below, these are further elaborated, in that order.

5.1 Methodology

There are several places where the methodology of this study and reality somewhat diverge. While these occurrences of divergence are justifiable, their possible impact on the results should be discussed nonetheless.

First of all, the method by which energy consumption is modelled leads to rather uniform consumption patterns at USP. In reality of course, every building is different, has different energy requirements, and is operated in a unique manner. If one were to model building energy use perfectly, one would likely see a more distributed energy consumption patterns across the USP, meaning that certain peaks would likely not occur as significantly as they would now, when many buildings are sharing the same load profiles. Thus, more precisely modelling building power consumption would mean that congestion would likely be somewhat diminished.

Secondly, the specific way energy generation installations are connected in the grid, and to which switching installations they are connected was done without being burdened by large amounts of electrical engineering expertise. It is entirely possible that, were these installations to be built, they would be connected to the grid in a different manner, or even given their own connections to the Sorbonnelaan substation, which would likely reduce grid congestion.

Thirdly, heat generation was modelled assuming that all buildings would be kept at a constant temperature, and that all buildings heat requirements scaled solely off of their transformer capacity. In reality a different heating regime may be applied, for example, one where buildings are only heated for the hours they are in use. This would lead to peaks in heat demand when buildings need to be heated up, and likely increase congestion. Additionally, the heat demand of a building depends on many more factors than solely transformer capacity, chief among which is the building envelope's thermal properties. This means that several, likely older, buildings heat demands may be significantly higher than modelled here, thus also possibly increasing congestion. This is of course counteracted by the possibility of renovation actions which aim to insulate buildings better. Or by the possibility of installing smarter building energy management systems, which would implement demand response in a way that takes grid congestion into account.

5.2 Omissions

There are several important factors relating to the problem of reconfiguration as a method of congestion management that have not been addressed in this report. These are factors that may significantly alter the outcome of the study were they to be included and therefore, it is important to discuss them and their possible impacts.

Energy storage is likely to play a significant role in the future of energy systems, also on the USP [19]. The effect that the inclusion of energy storage installations may have on the outcome of the study could vary wildly based on the type of storage and the way it is utilised. If an electrical energy storage system were programmed to contribute to system balancing the national power grid, its charging and discharging cycle would be determined in part by conditions away from the USP and charging and discharging may not align optimally with local conditions. This way an energy storage system could actually increase local grid congestion similar to EV charging or any other kind of price-driven demand response. If however, a storage system was set to balance the local grid, peaks in energy production could, depending on how much storage is installed where in the grid, be smoothed out and congestion could be mitigated.

Another matter that has not been discussed so far is the economical viability of making a grid dynamically reconfigurable. Dynamic reconfigurability requires all switching installations in the grid be remotely operable. It is entirely the question whether making all breakers in a grid remotely operable, including installing the prerequisite signals transfer and processing systems, is actually cheaper to do than to simply increase grid capacity.

6 Conclusion

As can be read in Section 3.1 there is a degree of uncertainty as to what the future energy system of the USP will look like. Because of this uncertainty several possible scenarios have been created in Section 3.1. When these scenarios are mapped onto an electrical model of the USP, a complete model emerges of what the USP's local distribution grid will look like around 2035, thus answering Subquestion 1. Please also see [31].

When load flow simulations are run in each of these scenarios, it is evident that the Southern half of the grid will likely experience congestion, and it is likely that at times the maximum allowable capacity of electrical components will be violated. In the Northern grid, under the assumptions in this study, no congestion is likely to occur. With this information, and the more detailed data from Appendix A.3, Subquestion 2 is answered.

As can be read in section 4 the effects of introducing reconfigurability to a local power grid are not insignificant, to the extent that congestion almost completely ceases to be a problem. There are several sources of inaccuracy in the model used for this study, as detailed in section 5.1. But none of these introduce such inaccuracy into the study that it would become impossible to state that, also in a real power grid under several scenarios that may result from the energy transition, reconfiguration is a very effective way of resolving grid congestion. This, as is most clearly seen in Table 1, answers Subquestion 3.

The above answers to Subquestions make it clear that in local distribution grids, despite the various ways in which the energy transition can take place, introducing reconfigurability may provide significant mitigation for congestion problems that may occur as a result of said energy transition.

For future research two main avenues of approach can be considered: Firstly, future research could focus on perfecting the simulation of a power grid under a completed energy transition. As laid out in Section 5, there are several points where the simulation was simplified, and making the model more exact in these areas would yield results that more closely align with reality. This would allow USP's management as well as Stedin to better estimate the extent to which grid congestion will be a problem in the future, and the role grid reconfiguration may play in that future.

Secondly, research should focus on whether grid reconfiguration is a technology that can be implemented cost effectively. As pointed out in Section 5.2, it is by no means a foregone conclusion that this technology presents an economical solution to the problems of grid congestion, and more research is definitely needed in this area.

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A Appendices

A.1 USP Power Grid

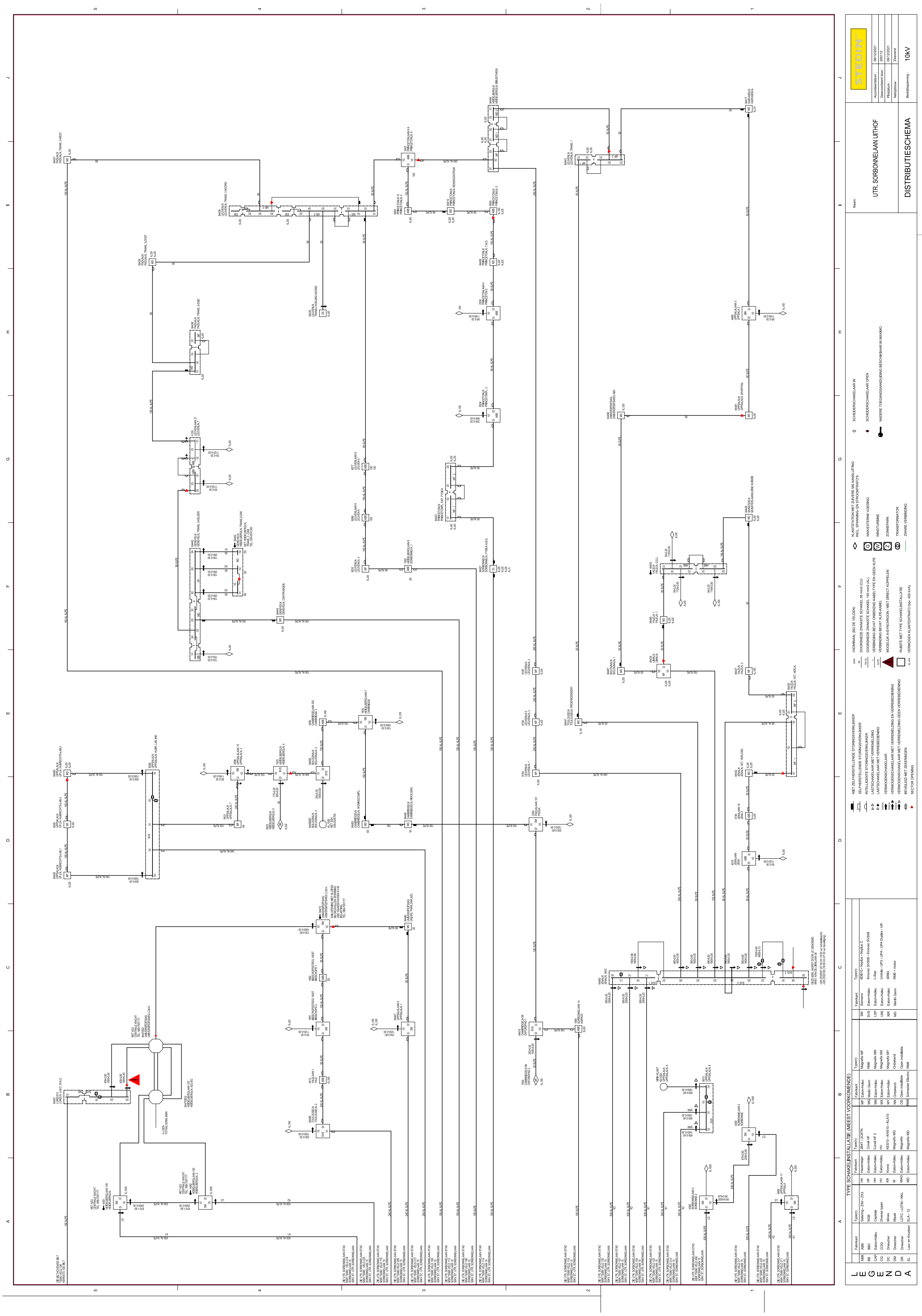

Figure 4: Schematic overview of the 10 kV power grid at USP

A.2 List of generation assets

Table 3: Table detailing which generation assets are connected to which busses in the grid (horizontal line in the middle is used to differentiate the South from the North grid, South being the upper part).

Name	Location	Installed capacity [MW]	Connected to [Bus ID or Stedin ID]
pv_4738	Tolakker, jongveestal	0.1312	4738
pv_84432	Roof M.G. de Bruin building	0.2862	84432
pv_84432_2	PV carport adjacent to de Bruin building	0.0499	84432
pv_dak+carports_zuidoost	South East solar carports	2	zonpv_zuidoost
pv_4738_2	Tolakker, rundveestal	0.1576	4738
pv_9mwweide_zuidoost	Fields East of Tolakker	9	zonpv_zuidoost
pv_84429_1	Roof W.C. Schimmel building	0.2333	84429
pv_84427	Roof J.D-V building	0.107	84427
windmolen_1	Near Olympos	3	84417
windmolen_2	Near Vening-Meinesz building	3	84417
pv_84443_1	Roof Ruppert building	0.2113	84443
pv_4898	Parking garage Olympos	0.3368	4898
pv_8193	Roof D. de Wied building	0.1231	8193
pv_84494_1	Roof Library	0.2322	84494
zonpv_rivmoost	Field east of RIVM building	3.5	84474
pv_rivmnoord	Field North of RIVM building	2.5	84437
pv_84421	Roof C. Bleeker building	0.1323	84421
pv_84490	Roof TNO	0.136	84490
pv_2536	Roof Earth Simulations Lab	0.0405	2536
pv_84444	Roof Langeveld building	0.0288	84444
pv_4412	Field South of Androclus gebouw	0.12	4412
pv_6999	Roof KBG building	0.034	6999
pv_1922	South West solar carports	0.4	1922
pv_zonpv_schapenveld	Field North of Vening-Meinesz building	2.5	2453
pv_8563	Nort West solar carports	0.3	8563

A.3 Overloaded lines

Post processing also indicated an interesting difference between the scenarios; while in scenario 1 after reconfiguration it was lines 17 and 18 (those running to and from the old farm on the Toulouselaan, Stedin object ID 84447), as well as line 19 (running between the 'bestuursgebouw', and the botanical gardens, Stedin IDs 84443 and 84417, respectively) that were oft overloaded. In scenario 3 it was line number 4 running between a switching installation on the Jenalaan (Stedin ID 4516) to the Tolakker farm buildings (Stedin ID 4738) that got overloaded.