Relocatable Energy Storage Systems for Congestion Management

by

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Preface

In front of you lies the report of my Master thesis project. It was a challenging and above all interesting topic. I have learned many new things, about the topic and about myself.

I am very pleased I have chosen my Master thesis topic within the Intelligent Electrical Power Grids (IEPG) group. A special thanks to the IEPG group members for their involvement and input on the topic. Especially Milos Cvetkovic for guiding me along the way and the many interesting brainstorm sessions. Aihui Fu for her coaching and helping me to stay focussed. Peter Palensky for his effort in defining the topic and his advice that I cannot solve every problem in the world.

Also, I would like to thank my friends and family for being supportive. They were always there to listen when I needed to clear my mind. And they have taken the time to give me feedback when I was writing the thesis.

Doing my Master thesis has been a ride! Even though there were some obstacles I had to face, my interest for this topic never disappeared. It has been a turbulent year on which I look back with a smile!

Suzanne Janssen
Delft, December 2019

Contents

Chapter 1

Introduction

1.1 Background

In 2018 the Dutch government, businesses and other stakeholders started negotiating an agreement to combat climate change (het Klimaatakkoord [1]). One of the chapters in het Klimaatakkoord focuses on electricity [2]. The main agreement in this chapter is the use of electricity in the Netherlands should rely for 70% on renewable generation in 2030. This is achieved by having more Renewable Energy Sources (RES) implemented in the coming years, making residents collaborate in the energy transition and making sure energy is always available. Het Klimaatakkoord is an ambitious agreement both for production and demand of energy.

The electricity produced by RES has to increase in the coming years. The aim is to produce 49 billion kWh a year in 2030 by wind parks on sea and 35 billion kWh of solar and wind energy on land. This is at least 84 billion kWh of renewable energy in total, to be produced in 2030 by RES. In 2017 the total of renewable energy was 17 billion kWh. This means within 13 years the amount of energy produced by RES has to increase with 67 billion kWh. In a time span of 10 years the amount of RES has grown with approximately 9 billion kWh as Figure 1.1 shows. It can be concluded that the implementation of RES needs to speed up rapidly, in order for the agreements to be met.

Residents also have to participate, which is organised on a regional level. By the end of 2021, each region will need to have a Regional Energy Strategy. The approach can vary per region. Each region develops its own goals and the deadline in which they have to be achieved.

Consumers of electricity are changing their behaviour regarding electrical energy consumption. The amount of full Electric Vehicles (EVs) is increasing [3] as can be seen in Figure 1.2. The average daily energy consumption of households in the Netherlands is 8 kWh [4]. The energy capacity of an EV is between 15 and 100 kWh, depending on the model. When the amount of EV keeps increasing, this can have a serious impact on the average energy consumption per household and the capacity limit of the electricity grid can be violated. Already in 1993 has been concluded that charging of EVs would require a change of the (Electric) Utility [5].

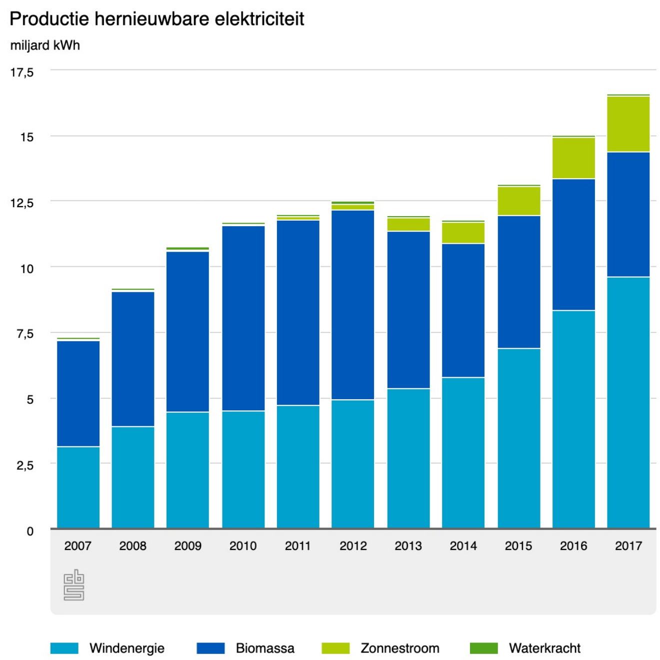

Figure 1.1: Renewable Energy Generation in the Netherlands [billion kWh] [6]. Light blue represents wind energy, blue represents biomass energy, light green is solar energy and green hydro energy production.

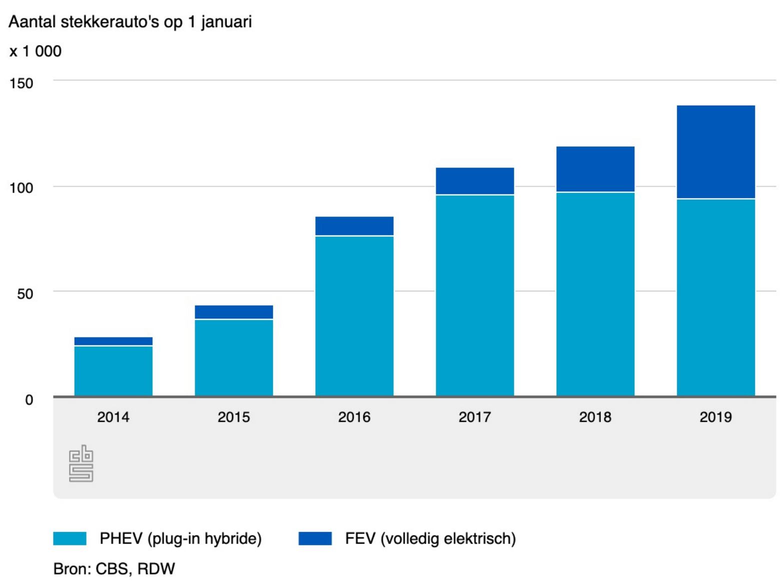

Figure 1.2: Amount of EVs in the Netherlands [3].

The government wants to make sure the supply of energy is sufficient at all times, which means enough capacity on the cables to transport electricity. The government is aware that changing the infrastructure, for example by replacing or adding cables, takes time to prepare. In 2020 the government wants to present an approach for the replacement. Also possibilities like storage and in- and export of energy are mentioned to make sure supply meets demand.

The problems surrounding het Klimaatakkoord do not only involve energy production and consumption, but distribution of energy as well. The responsible stakeholders for the distribution of energy are called the Distribution System Operators (DSOs). Each individual DSO has its own region in which it operates. They are obligated to make sure the capacity of the lines fits production and consumption as stated in article 23 of the Electricity law of 1998. The combination of increasing amount of RES, changing energy consumption and each region creating their own strategy, makes it difficult for the DSO to create a one size fits all solution. This problem is summarised in Figure 1.3.

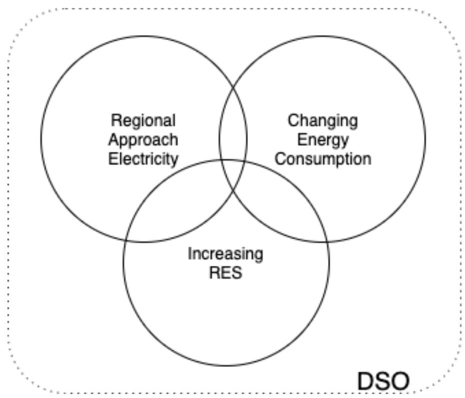

Figure 1.3: The interaction of increasing RES, changing consumption and regional approach for het Klimaatakkoord. The DSO is represented as a support for this change.

A dutch DSO, Alliander, published an overview of physical locations in the grid where new initiatives, regarding production and consumption of electricity, could cause a problem [7], [8]. They state the amount of energy-intensive sectors are increasing, for example solar parks and data centres. The increasing demand for these sectors cause capacity problems in the electricity grid. They already investigated the possibility of congestion management based on market mechanisms influencing demand and supply of electricity. It is concluded that for almost all regions, this method will not suffice. The consequence is companies need to wait up till four years if they want to consume more electricity or deliver electricity to the grid. Alliander needs time to expand the grid capacity. It takes time as they have deficiency of technical personnel and long lasting procedures before they can start replacing cables. They are alarmed as the initiatives to combat climate change just started, but congestion problems already occur currently.

In conclusion the government wants to rapidly increase the renewable energy production while also making sure a suitable infrastructure is provided. However, one of the Dutch DSO's has already alarmed there is not enough capacity in the electricity grid and it takes time to increase the capacity [8]. A suitable solution is desired for this problem. Therefore this thesis will focus on a suitable infrastructure, preventing congestion. Congestion means the capacity limit of the distribution cable is exceeded.

The possible solution focused on in this thesis is the implementation of relocatable Energy Storage System (ESS) in the grid. ESSs can rapidly be deployed as the technology already exists and are possibly a cheaper solution compared to replacing lines. The mobility of the ESS could reduce the total amount of ESS needed as compared to placing them statically. For example: when congestion occurs at 4 different physical places, but each at a different time during the day, it might be more beneficial to move one ESS around in stead of placing an ESS at each location. Examples of ESSs are ion lithium batteries (Tesla Powerwall or Vehicle) or hydrogen tanks. The goal of ESS is to discharge when demand is too high (causing congestion) or charge when production is too high (causing congestion). They can be relocated and this is different from already existing solutions, as being described in Section 1.2.

For more background on the topic, literature in this field is discussed in Section 1.2. It provides background about applications of EVs and ESSs. In Section 1.3, the research question is defined. The possible solution focused on in this thesis is still broad, therefore in Section 1.4 the scope is defined.

1.2 Literature

The goal of this section is to give an overview of research done on congestion management and ESSs. As EVs have a large impact on the grid, they will be discussed separately as well. The topics discussed in this section are congestion management, ancillary services by ESSs and EVs and congestion prevention by EVs.

A method to prevent congestion is the use of ESSs. For example battery energy systems are applied to reduce operational costs for the charging stations of EVs [9], [10]. Also, it helps in preventing congestion, when the power demand is high.

ESSs are used for various reasons besides congestion management. For example, residents could install an ESS in their home for saving their own generated electricity. Also, a method has been studied for storing wind energy that would otherwise have been spilled [11]. It concludes that for a case study, using an ESS for curtailed wind energy, has benefits in terms of cost. Also [12] proposes a method to size and control ESS and a wind farm. The aim is to compensate for the variability in wind power production.

EVs contain ESSs, meaning EVs could be used as an ancillary service to the grid as well. For example in [13] and [14] an optimisation is done a day ahead for an EV fleet, to balance power (regulate frequency) and minimise the cost for charging the fleet.

EVs have an impact on the amount of power flowing through the cables. Too much power flowing through a cable causes congestion. Therefore it is of interest to describe charging methods of EVs for congestion prevention. For example, a method has been developed to charge each individual EV to the wish of the owner, but also without violating grid constraints [15]. Also, methods have been proposed with a similar purpose: focusing on the price of electricity to influence charging behaviour [16], [17]. A centralised organisation, like the Charging Service Provider (CSP) or fleet operator, determines the charging planning for each EV.

1.3 Research question

The role of ESS in the power grid has been researched extensively. Analysing where to place them optimally and when to charge or discharge them, also for EVs. However, research only shows either fixed ESSs in the grid, or EVs used for transport with as secondary use an ancillary service to the grid.

The possibility of a fleet with as only purpose congestion management in the grid needs to be explored: a Relocatable Energy Storage System (RESS) fleet. The added value, as compared to fixed ESS in the grid, is the possibility of being useful at different locations over time. The RESS have the possibility to move to other locations when congestion occurs at a different time. The added value, as compared to EVs, is that they can solely be used for congestion management. The unpredictable behaviour of EV-owners does not have to be taken into account.

The goal of this thesis is to develop a method for the planning of each RESS in order to prevent congestion. We want to minimise the travel distance for this fleet, in order to minimise the operational costs. To prevent the trivial solution, a RESS or multiple RESSs on each bus, we also need to minimise the amount of RESS used. Therefore the research question is:

How can a fleet of Relocatable Energy Storage Systems (RESSs) optimally position and re-position themselves over time through the grid for congestion prevention, while minimising the amount of RESS used and travel distance?

The development of the method can be impacted by the stakeholder operating the RESS fleet. When the fleet is operated by the DSO, they are not allowed to be part of the electricity market [18]. When the fleet is operated by an external party, they could also use the fleet for other purposes than congestion prevention only. Therefore it is of interest to develop a methodology, such that the fleet could be operated externally. So how can the research question be answered, such that the fleet can be operated by an external party?

In order to test the quality of the model, it is of importance to have a performance measure. As cost are an important element to both the fleet operator and DSO, we would like to measure the amount of RESS needed. This amount needs to be compared to the amount of ESS when placing them statically in the grid.

In the electricity grid uncertainties occur. For instance the power consumption might deviate from the predicted values. Also the generation of solar and wind energy could deviate. When the location of the RESS has been determined and it is known with what power they are charging or discharging, the sudden power deviations of consumption or production could still cause congestion. The RESS are not able to change their position instantly. We want to know whether the RESS could adjust their power consumption or production to prevent congestion caused by the uncertainties.

In conclusion, the sub-questions are:

1. How can the research question be answered, such that the fleet can be operated by an external party?
2. Will the model be an improvement in terms of the number of RESS needed, compared to placing ESS statically in the grid?

3. Will uncertainties in the power consumption and renewable energy production cause congestion when the decision for the location of the RESS has been made, but the RESS are allowed to change their level of (dis)charging levels?

In the remainder of this thesis references will be made to ESSs, EVs and RESSs. ESS are energy storage systems placed at a fixed location in the grid. EVs are Electric Vehicles with as main purpose transportation of people and goods. The name RESS is introduced for the solution of congestion as described in this thesis. The names used throughout this thesis are summarised in Table 1.1.

Name	**Definition**
ESS:	energy storage systems placed statically in the grid.
EV:	electric vehicles with as main purpose transportation of people and goods.
RESS:	relocatable energy storage system for the purpose of congestion prevention.

Table 1.1: Terminology used in this thesis for storage systems and EVs.

1.4 Scope

The research question raises multiple questions. What is a RESS? What exactly is the electricity grid and what size does it have? Does optimality mean the least costs? Over what time frame will be optimised? How will there be optimised? Therefore the scope of this thesis has to be defined and narrowed down even further. Decisions are based on available information. The topics of interest are the type of RESS, the grid and optimality.

The RESS units are considered to be lithium ion type EVs. Because of the many applications of EV technology already described in Section 1.2, it is a realistic scenario they could also be used as movable entities to prevent congestion. Furthermore EVs already exist in real life and therefore they could be used to test the model in real life scenario's. Depending on the situation, the type of RESS can be adjusted, for example hydrogen tanks on trucks.

The decision for the grid is a residential low voltage distribution grid. This choice for a residential grid was made because of the availability of data. The UK Power Networks offers smart meter data of around 1100 households [19] and Elia group provide solar generation profiles [20]. The size of the residential grid must be no more than 1100 households. The choice for a low voltage distribution grid was made because of its size. This research is the first step in discovering the potential to relocatable ESS for congestion prevention. Choosing a small size of the grid makes the problem less complex and thus easier to understand how the model behaves. It is a good first step to test the problem on a small scale and if it has potential see how it scales.

The grid will need to be designed accordingly to test the performance of the model for solving congestion at different locations at different times during the day. We want to find out a method to prevent congestion when it occurs at different times at different locations, it is therefore of importance to have a grid with these specifications. One day is chosen to test for the model. We limit ourselves to household consumption and solar generation. From the available data, it is clear the power consumption and production peaks occur during the day. This means congestion will be more probable during day time.

When doing a minimisation, costs is often the main driver. So we want to minimise the amount of RESS used (investment cost) and travel distance (operational costs, when using power for travelling this can be translated to fuel costs). These are needed for comparison reasons, for example: will a fleet of RESS be less costly than replacing a cable. However, there are two things to consider. First, it's difficult and it takes time to make a good estimation of the costs. Second, it depends on the fleet owner what is most important. On the one hand, the benefit of a fleet could be in preventing a cable to be replace. Another benefit could be that a flexible solution is provided for congestion, which makes it easier to rapidly increase the amount of distributed RES as a goal to combat climate change. However, expressing climate change in financial terms is a complex challenge. The result is that costs will be considered, but will not be based on realistic values.

In power grid applications often Optimal Power Flow (OPF) is used to do an optimisation. Various applications of OPF have been proposed including the presence of RES in the grid and/or ESS [21]–[26]. In this thesis OPF will be used as well for the development of the method.

1.5 Outline thesis

In Chapter 2 the methods used in the thesis are discussed. The two main methods the model is built upon are OPF and graph theory. Also the terminology will be explained.

In Chapter 3, the main approach for solving the problem is discussed as well as how the test grid is built. For creating a test grid, many decisions have been made. This chapter will be concluded with a list of assumptions.

In Chapter 4 an optimisation strategy will be discussed to determine the location for the RESS at each time step, while minimising the amount of RESS used and penalising movement of the RESS. This chapter explains the basic optimisation problem and sets a basis for further improvements. The optimisation developed in this chapter will be referred to as Case Basic. Also the results of this chapter are essential to make a planning for each individual RESS.

In Chapter 5 the individual planning for each RESS is described. It gives a planning for an individual RESS based on its location in the grid and the locations where the RESS is needed in the next time step.

Chapter 4 and Chapter 5 are the main method in this thesis. As the Case Basic of Chapter 4 contains assumptions, in Chapter 6 relaxations of assumptions are proposed. Using these relaxations new models are constructed. The relaxations of the model will be referred to as Case Grid and Case P_{RESS}. For these cases the complexity of the model increases to, hopefully, obtain better results. In this section the approach to a sensitivity analysis will be presented as well.

In Chapter 7 the results of Case Basic are discussed. The optimal battery location is presented, as well as the planning for each individual RESS and its State of Charge (SOC). Chapter 8 shows the same results as Chapter 7, only for the cases developed in Chapter 6: Case Grid and Case P_{RESS}. This section also shows the results for the sensitivity analysis. Finally conclusions from the results will be drawn in Chapter 9. An overview of the content of each chapter is presented in Figure 1.4.

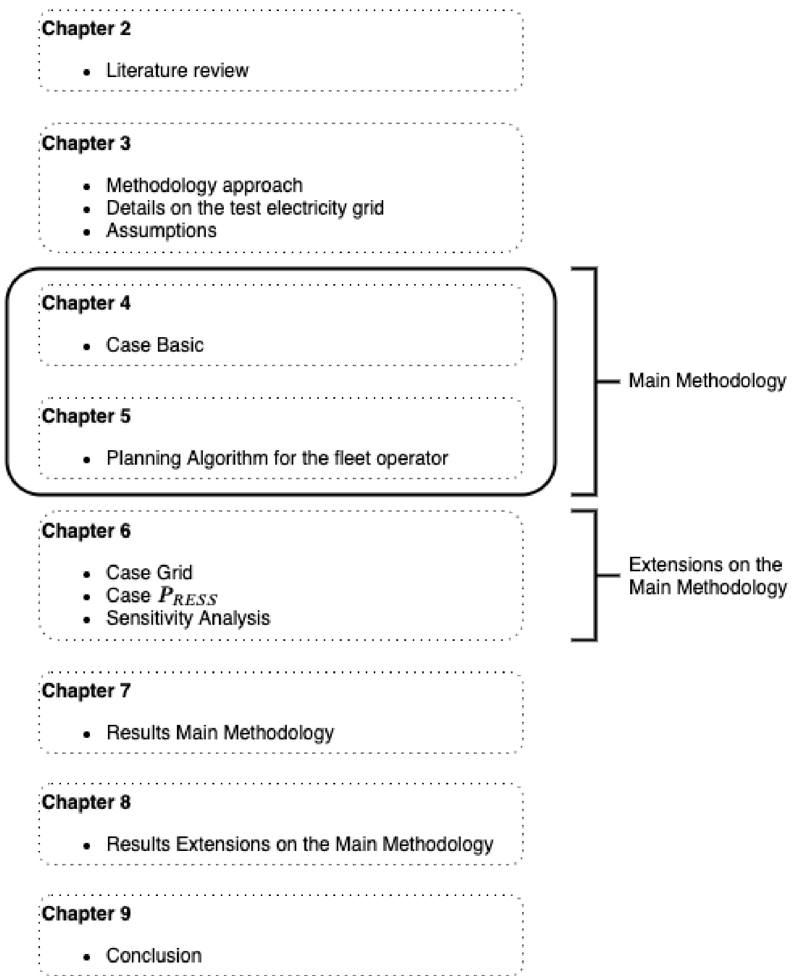

Figure 1.4: Overview of the Chapters in this thesis.

Chapter 2

Related work

In this chapter, the topics used in this research are discussed. In Section 2.1 it is explained what an OPF is. Graph theory is explained in Section 2.2. The terminology used in this thesis is explained in Section 2.3.

2.1 Optimal Power Flow

A standard optimisation problem minimises a function, while taking into account equality and inequality constraints. It is formulated [27] as follows:

$$\begin{aligned} min \quad & f_0(x) \\ s.t. \quad f_i(x) \leq 0, \quad & i = 1, ..., m \\ h_i(x) = 0, \quad & i = 1, ..., p \end{aligned} \tag{2.1}$$

where:

$f_0(x)$	: the objective function to be minimised.
x	: the optimisation variable.
$f_i(x)$	: inequality constraint functions.
$h_i(x)$	: equality constraint functions.
m	: amount of inequality constraints.
p	: amount of equality constraints.

The optimal value is denoted as $f_0^*(x)$. The optimal value gives the minimum value of $f_0(x)$ while also satisfying the constraints. x^* is the optimal point, i.e. $f_0(x^*) = f_0^*(x)$.

The type of optimisation varies. When the objective function and constraints are linear, it is called a linear optimisation problem. When the objective function is quadratic, it is called a quadratic optimisation problem. When the optimisation variable is integer, it is an integer optimisation problem. A mixed integer linear program contains optimisation variables that are integer, but also optimisation variables that are not integer. For each variation it is of importance to make the problem convex. Convexity will enable the solver to find a global minimum.

The OPF is a constrained optimisation problem like in Equation 2.1. The OPF is used to optimise for one snapshot in time [24]. As in general optimisation problems like Equation 2.1, it minimises or maximises a function (often power generation costs) while taking into account equality and inequality constraints representing physical grid constraints.

To optimise for an actual power grid is very complex. There will be thousands of variables and the problems will be non-linear and non-convex. Therefore equations are simplified or left out of the program. Alternating Current (AC) OPF contains more realistic equations to model the grid as it, for example, takes reactive power into account. However it is computationally expensive to run the program and can be non-convex.

As the main goal of this thesis is to prevent congestion, Direct Current (DC) optimal power flow will be used in which only active power flows are considered. DC OPF is a simplified (to reduce the number of equations) linear and convex formulation as it considers only active power flows, with as consequence fast convergence. For these reasons DC OPF is used, which hereafter will be called OPF.

In Equation 2.2 the optimal power flow, in its standard form, is formulated for N buses and L power lines. It minimises the cost of power generation, while making sure the generators produce power within their limits, supply meets demand and the flow limits are not violated.

$$
\begin{aligned}
min \quad \sum_i c_i P_{Gi} \\
P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max} \\
\sum_i P_{Gi} = \sum_i P_{Di} \\
\begin{bmatrix} 0 & H \end{bmatrix} P_{total} \leq F_{ij,max} \quad \forall i,j \in N
\end{aligned}
\tag{2.2}
$$

where:

c_i	: the cost of generator i: G_i.
G_i	: generator i.
P_{Gi}	: the power generated by generator i.
P_D	: the vector of power demand in the grid.
L	: the amount of cables in the grid.
N	: the set of buses in the grid.
H	: the $L \times (N-1)$ distribution factor matrix.
P_{total}	: the power vector of the grid, equal to $P_G + P_D$.
$F_{ij,max}$	: the maximum flow through the cable between bus i and j in [W].

The flow is calculated by multiplying the reduced $L \times (N-1)$ distribution factor matrix H with the power vector of the grid $P_{total} = P_G + P_D$. The first element in the power vector P_{total} is removed (hence it is multiplied by $\begin{bmatrix} 0 & H \end{bmatrix}$ in stead of H), otherwise it would be an overdetermined system. The distribution factor matrix is constructed by the grid topology and the reactance x_{ij} of the cable between bus i and j.

Next to minimising the cost of generation, other objective functions can be used. Other objective functions can be to minimise generation costs or minimise ESS utilisation. The objective functions could also consist of multiple objectives [28]. In this case, there will not be one optimal solution, but a set of optimal solutions known as the Pareto-optimal solution. Constraints are restrictions at which the grid must operate. For example: line limits must not get violated and there should be a power balance.

OPF is used to control variables that are needed for the operation of the power system at a specific time [29]. It makes sure the objective function is minimised or maximised and the outcome satisfies the constraints. The objective function can differ per problem and depends on the variable you want to optimise. For example you can choose to minimise carbon emission or to maximise social welfare.

Various solvers exists for finding an optimal solution [28].

2.2 Graph theory

In this thesis graphs are mentioned. Definitions from a book on Combinatorial Optimisation are used [30]. As graph theory is a subject of study in discrete optimisation, definitions from this book are used to explain graph theory in this section. A graph G is defined as containing finite sets of nodes $N(G)$ and edges $E(G)$, where the ends of each edge contains a pair of nodes. A graph is simple when it does not contain loops (the ends of an edge are the same node) and parallel edges (two edges with the same ends). A subset of graphs are trees. Trees do not contain circuits. Another subset of graphs are bipartite graphs. Bipartite graphs contain two unique sets of nodes, $\{P, Q\}$, for which no two nodes in one set are connected by an edge. The graphs described can be found in Figure 2.1.

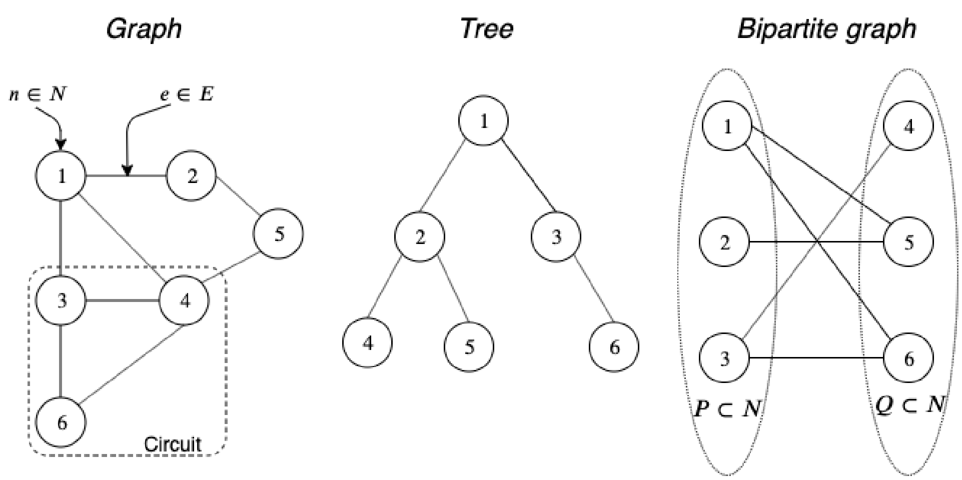

Figure 2.1: A simple graph, tree and bipartite graph.

From electricity grids, a mathematical graph model can be computed. In this model the nodes denote the buses and the edges the cables. Properties of the electricity grid, power input of the buses and line characteristics, can be translated to node and edge characteristics. We consider the electricity grid to be a simple graph, as loops are of no use and for parallel cables the line capacities are added to obtain a single line. If the electricity grid is tree structured, the graph equivalent will be as well. The electricity grid can also be meshed, in which the graph equivalent will contain circuits.

A matching M is a subset of the edges such that none of the edges in the subset have the same node as an ending. For bipartite graphs, the two ends of each edge contains a node in P and a node in Q. In this way, a matching will result in unique node pairs being matched, from which each node of the pair is from a different set P or Q. A maximum matching is a matching for which the edges in M are maximised. A maximum matching can be found in Figure 2.2. When the edges contain weights and the sum of the weights in the maximum matching must be minimised, it is called a minimum weight maximum matching.

NetworkX [31] is a tool for python to work with graph structures (they refer to graphs as networks). NetworkX also contains a tool for bipartite graphs containing a minimum weight maximum matching. This tool is based on an algorithm for solving a minimum weight maximum matching problem in $\mathcal{O}(|P|\,|Q|\log|Q|)$ time [32]. $|P|$ and $|Q|$ are the size of the set P and Q.

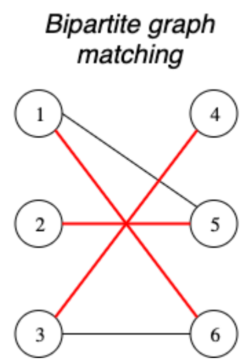

Figure 2.2: Maximum matching in red of a bipartite graph.

2.3 Terminology

To understand the methodology and prevent confusion, this section is written to explain expressions used and agreements made. For example there are certain expressions that are used interchangeably. Also agreements need to be made on the mathematical formulation of power vectors and flows.

As explained before, the electricity networks' mathematical description is a graph. In an electricity network buses are connected with electricity cables or lines (or in short: cables or line). The graph equivalent are nodes being connected by edges. When taking an electricity grid, always one node will be connected to the transmission grid. In a graph, the connection to the transmission grid is always at node 0. Throughout this thesis these expressions may be used interchangeably as they are the equivalence of one another. This terminology is described in Table 2.1.

Electricity network terminology	**Graph equivalent terminology**
Electricity grid	Graph
Bus	Node
Cable/line	Edge
Transmission grid	Node 0

Table 2.1: Electricity network terminology and its graph equivalent.

For the mathematical formulations agreements are made as well. Power production in the grid is positive and power consumption in the grid is negative.

Chapter 3

Design Choices

This section will explain the design choices made for this project. The research question and scope of this thesis have already been discussed in Chapter 1. The research question consists of multiple aspects. These aspects will be decomposed in Section 3.1 from which an approach for the methodology follows. Based on the scope, specific decisions about the grid and the RESS will be made in Section 3.2 and Section 3.3 respectively. Throughout this chapter assumptions will be made and they are summarised in Section 3.4.

3.1 Approach for answering the research question

The question to be answered in this thesis is: How to optimally redistribute the RESSs in the grid for congestion prevention, while minimising the cost of movement and the amount of RESS used. This research question can be split up in three elements:

- Congestion prevention.
- Minimising the amount of RESS used.
- Minimising the cost of travelling.

As already discussed in Chapter 1, the DSO is responsible for the transport of electricity and therefore preventing congestion. They are familiar with the topology of the grid and have insight in the production and demand in the grid. This means they have information to determine at what location a RESS should be placed, to prevent congestion. Also it is in their benefit to minimise the amount of RESS used as it minimises the cost.

After knowing where to place the RESSs (minimising the amount used) it is of interest to minimise the travel distance and therefore the cost of travelling (for example fuel costs). The DSO could choose to own the fleet itself, however with as consequence they are only allowed to use them for the transport of electricity (as is defined by law). This means the net power output of the RESS fleet should always be equal to zero, at each time. This limits the possibilities of the fleet and therefore the outcome. When the fleet is outsourced to another company, this company is allowed to have a net power output of the fleet not equal to zero. Next to that, they also have the possibility to use the RESSs for other purposes, when not used for congestion prevention.

The question of who the fleet owner should be will not be answered in this thesis. To keep the option of an independent fleet owner, the problem will be solved in two steps:

1. Congestion prevention while minimising the amount of RESS used (Chapter 4).
2. Minimising the cost of travelling of the fleet (Chapter 5).

3.2 Grid

In this thesis, the scale tested on will be the size of the Conseil International des Grands Réseaux Électriques (The International Council on Large Electric Systems) (CIGRE) [33] low voltage distribution network (the residential branch). The CIGRE grid model provides power consumption for each bus for one snapshot, to which we can easily scale our input data. In Figure 3.1 the grid used is displayed. The Residential sub-network is focused on and DC load flow is used for simplification.

To apply a methodology, a realistic grid is desirable. Pandapower offers a wide range of test grids, and the decision was made to use the CIGRE low voltage distribution test grid. This grid can be used to extract grid-parameters from (and also for validation). The parameters from the CIGRE grid are used to built up a mathematical model for the methodology in NetworkX. The transformation from a CIGRE grid to NetworkX graph is visualised in Figure 3.2. The CIGRE grid is an AC grid, however in this thesis DC load flow calculations will be used as it is less complex and suffices for flow calculations.

The input and output power in the grid in real life is stochastic. This means the predictions we make about them, could deviate. The more detailed you look, the uncertain the predictions get. For this thesis the input and output power in the grid is deterministic. This means a day ahead, the power consumption of residents and the power production of solar panels is known. Time steps of 30 minutes are assumed, because of the available data.

The grid tested on is the CIGRE low voltage distribution test grid (the residential branch) provided by Pandapower. Each bus contains 5 up to 200 households. In the Pandapower environment, characteristics of the grid can be found that are used for the model. The following information is extracted from the CIGRE grid:

- i^{max} [kA]: the maximum current allowed flow for each cable in [kA].
- x [Ω/km]: the reactance in [ohm/km] for each cable.
- geographical bus data: the geographical position for each bus.
- load power P_{load}: the load power for each bus in [kW].

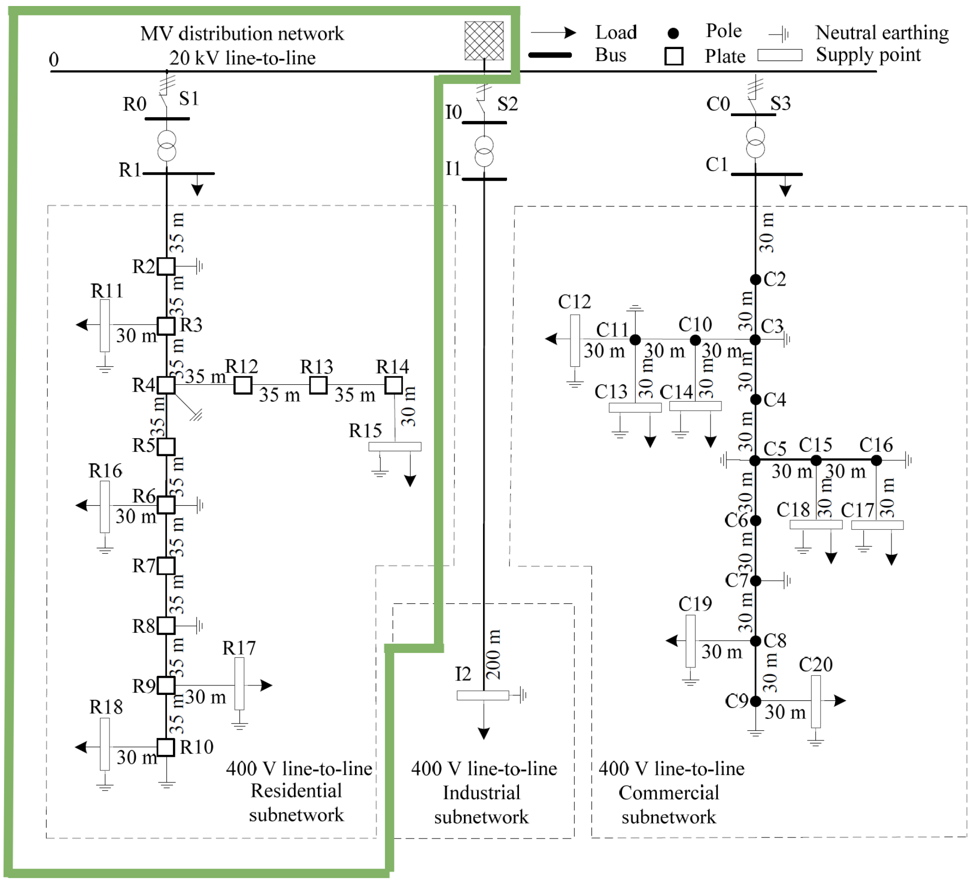

Figure 3.1: Low voltage distribution network from CIGRE used [34], within green is the branch used.

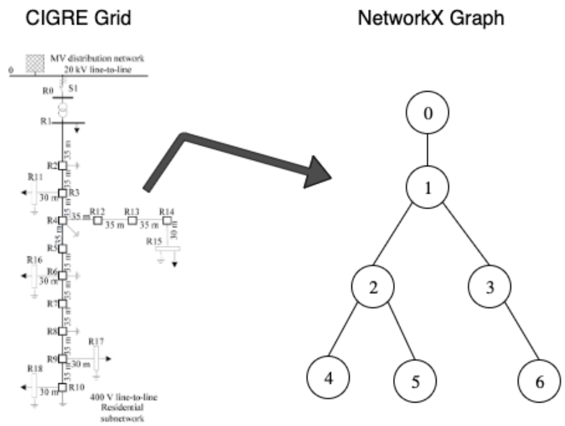

Figure 3.2: The CIGRE grid gets converted to a NetworkX graph.

The information to be added in this model is:

- F^{max} [kW]: maximum power flow in the cables.
- x [pu]: the reactance in pu for each cable.
- $P_{load}(t)$ [kW]: power consumption profiles for each bus for one day for all t.
- $P_{solar}(t)$ [kW]: solar energy production profiles for one day for all t.

F^{max} is calculated by multiplying i^{max} with the voltage level of the grid. x in [pu] is constructed by multiplying x in [Ω/km] with the length of the cable and dividing it with the largest value reactance of all cables. From the geographical data a distance matrix is constructed to present the distance between each bus pair. The distance matrix for this grid can be found in Appendix A.

Research has been performed on load forecasting [35]–[38]. It shows the forecasting percent error can be minimised to 1%-3% for short term forecasting (i.e. one day ahead). The forecasting error for solar generators depends on the type of weather (sunny, cloudy, rainy) [39] and the Mean Absolute Percent Error (MAPE) can vary between 6.36% and 54.44% [40]. In this thesis power consumption and production are assumed to be deterministic and realistic. Therefore, data sets of realistic power consumption and production profiles are used. The CIGRE grid standard load values are used to upscale the data.

The power consumption profile is obtained from [19]. This database consists of the power profiles for 1100 households in London. It contains the power consumption for multiple houses on multiple days. The date used is the 13th of October in 2012. The energy in [kWh] is given for each half an hour. The average power consumption can be obtained by multiplication of 2. The power profiles are scaled such that the peak power, $\hat{P}_i$ in the profile matches the snapshot load power in the CIGRE grid, $P_{cigre,i}$. For each bus, the scaling factor is equal to $P_{cigre,i}/\hat{P}_i$. All values in the load profile will be multiplied with the scaling factor.

The power production profiles by solar energy are obtained from [20]. This is solar generation data from Antwerp, because information from London was not available. Only data was available from recent years, but the date chosen was similar from the consumption data: the 13th of October. However, in this case the year was 2018. The data set contains the forecasts but also the corrected scaled up measurement in [kW]. This column was used for the data. However, this data set contains the power production for each 15 minutes. Therefore the data of only each other 15 minutes was selected. The data was scaled in proportion to the estimated amount of houses for each bus, equal to the scaling factor. RES have an intermittent power output, Photo Voltaic (PV) output can even change suddenly [23]. However it is still assumed to be deterministic in this case.

We assume there will not be optimised for the grid, to keep the model simple. The power input from the transmission grid is known beforehand. For each time step is calculated what the power from the transmission grid is, in order for supply to meet demand. This implies the net power output of the RESSs should be zero as there is a power balance in the grid.

To test the method, the grid must have congested lines at different locations for different time steps. In this way can be tested how it will cope with minimising the amount of RESS while preventing congestion and minimising travel distance. Even by scaling the consumption profiles with a factor of 2, still no congestion is detected. In stead of adjusting (rather complicated) power consumption profiles, there is chosen to reduce the standard maximum flow F^{max} of 400 kW in some of the cables, such that congestion occurs at different locations over time. However, the congestion in the grid is assumed to be such that the congestion in the grid can be prevented placing a maximum of one RESS at each node.

Furthermore it is assumed there is a connection for a RESS at each bus, however only one RESS per bus is allowed.

How the data is transformed from a CIGRE grid to a NetworkX structure, is visualised in Figure 3.3. When the graph has been constructed, we are able to calculate the flow in the lines and see if congestion occurs. In Appendix B the complete NetworkX graph can be found. The red edges represent the cables in which congestion occurs at least once during the day. Also the adjusted cable line limits are presented.

3.3 Energy Storage Systems

It is assumed a RESS is able to travel within 30 minutes to a new location.

As the amount of EVs is increasing, it is of relevance to inspire the characteristics of the relocatable RESS by the EV. It will be an interesting result under what circumstances the EVs can prevent congestion in the grid. Also they are able to disconnect themselves from to the grid, travel autonomously to a next location and connect themselves to the grid again. The power used when travelling will be the same as for EVs. Also the power in- and output is the same. This results in the following characteristics:

- Power consumption in travelling mode: 0.1 kWh/5km of travelling.
- Maximum power output: 120 kW (fast charging).

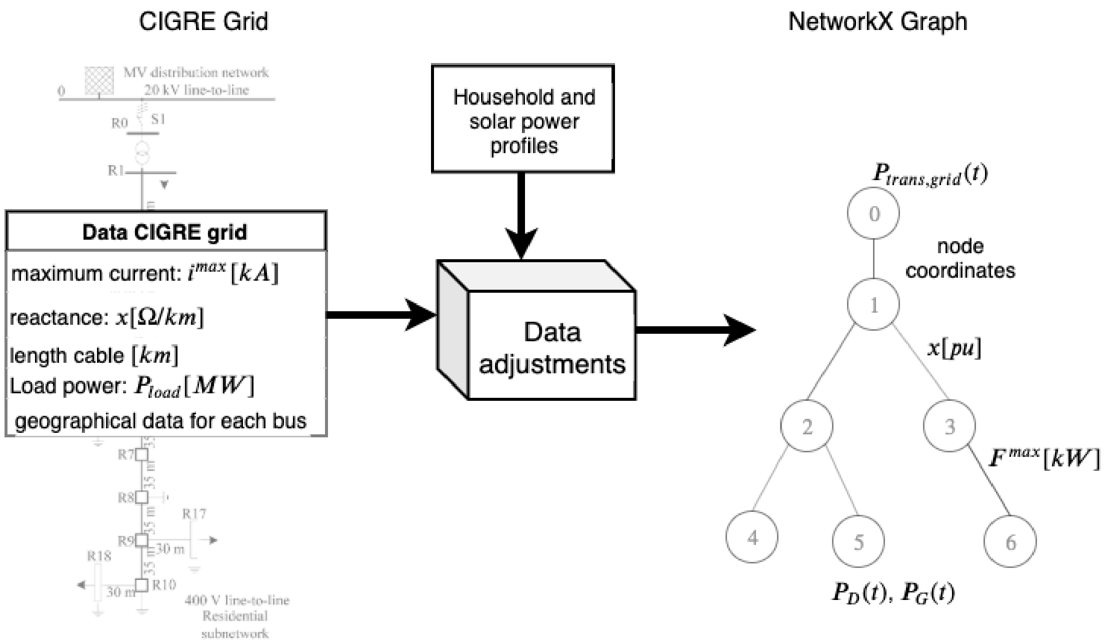

Figure 3.3: How data is transformed.

- Minimum power output: 120 kW.
- Energy capacity: 85 kWh (Tesla model S), though the SOC will not be optimised for.

Though it will be better for the RESS its lifespan, we will not try to minimise the charging and discharging of the RESS. Also we assume a RESS can be (dis)charged unlimited, meaning we do not take into account the SOC of the RESS. The SOC of the RESS will be tracked to analyse its behaviour.

3.4 Summary of assumptions

In Section 3.2 and Section 3.3 design choices have been made. It was necessary to make assumptions to simplify the problem. Making assumptions has the advantage making it easier to make a model and it is clearer what the effect is of different parameters on the solution. The disadvantage is the solution might not be based on a realistic case, however it is always possible to extend the model to a more realistic case. Therefore the assumptions will be repeated in this section and the disadvantages will be stated. Finally they will be summarised in a table.

The first assumption made was the consumption and production of the power in the grid to be of a deterministic nature. This is done for simplification. It is assumed they are known one day ahead. The disadvantage is that when they deviate, the solution found could not be the optimal one or even not solve the problem.

The second assumption made was that the exchange of energy with the grid is not be optimised for. This simplifies the problem as we do not have to optimise the exchange of energy with the grid, but also limits the solution as the net power output of all the RESS should be equal to zero.

The third assumption is that there are connection points at each bus for a RESS. This is done for simplification reasons, but also has the advantage that a pattern could be recognised at what buses the RESS are needed the most.

The fourth assumption is that there is only one RESS allowed per bus. This is to simplify the problem. It has a negative impact on the problem space, because it increases the total (dis)charging quantity for each bus as more RESS are allowed to connect.

The fifth assumption made was that RESS are able to travel to a new location within 30 minutes. This travel time depends on the size of the grid. When a larger grid is optimised for, it will take a RESS a longer time to travel to a next location. It simplifies the model for that we can assume a RESS can drive to a new location in one step.

The seventh assumption made is there will not be minimised for the input and output power of the RESS. We want to start with a simple model and therefore the RESS can (dis)charge within its limits but is not minimised for. The disadvantage is that there might be a solution with smaller charging and discharging values for the RESSs and thus maximising the lifespan.

Finally the assumption has been made that the SOC of the RESS is not taken into account. This simplifies the problem, however situations could occur in which the SOC limits will be exceeded.

The assumptions are summarised in Table 3.1. They are in order of priority. When the assumption is of high priority, it means it has a large impact in real life and therefore is very important to take into account for the results.

Assumption	**Disadvantage**
Deterministic model	The real time power of consumption and production could deviate from what was predicted. As a result the outcome of the model could not be suitable for the real time situation.
Power balance	There could exist a more optimal solution, when also optimising for the grid input.
Power RESS	Not minimising the power causes a smaller life time for the RESS.
1 RESS per bus	Especially for tree structures, the problem space reduces when only one RESS per bus is allowed.
Connection points	Reduces the problem space when a feasible outcome is wanted.
Travel time	When the grid increases in physical size, a RESS might not be able to reach the other bus in time.
SOC	The SOC might exceed its limits.

Table 3.1: List of the assumptions and their disadvantages.

Chapter 4

Optimal node location for RESS over time

As was discussed in chapter Section 3.1, the method is split up into two parts: finding the optimal location for the RESSs while minimising the amount of RESS used and finding the route each individual RESS has to follow over time. The goal of this division is twofold. One reason is to give insight in how the RESS are distributed over time, given the topology of the electric grid and the behaviour of energy consumption and production in the grid. The other reason is for the DSO to be able to outsource the RESSs.

This chapter is about the first part: finding the optimal location for the RESSs while minimising the amount of RESS used. In Section 4.1 the OPF discussed in Chapter 2 is repeated from which the basic elements of the optimisation are developed. In Section 4.2 is discussed how to minimise the amount of RESS used. Finally in Section 4.3 a method will be described for minimising the amount of RESS over time.

4.1 Optimisation Basis

From Chapter 2 we learned the OPF constraints contain the power balance, limitations of the flow on each line and limitation on the maximum generation. The objective function depends on what you want to optimise for. The vector of total grid power is defined as the sum of the vectors of production and consumption: $P_{grid} = P_G + P_D$.

Because we want to minimise for the amount of RESS used, it is of importance have a separate vector of RESS power: P. Together with the grid power, it forms the total power in the grid: $P_{tot} = P_{grid} + P$.

When adding P to the OPF constraints, we obtain:

$$\sum_{i=1}^{N} P_{i,tot} = 0 \tag{4.1}$$

$$-F^{max} \leq \begin{bmatrix} 0 & H \end{bmatrix} P_{tot} \leq F^{max} \tag{4.2}$$

$$P^{min} \leq P \leq P^{max} \tag{4.3}$$

where:

P	: the vector of RESS in/output at each node.
N	: total amount of nodes in the grid.
P_{grid}	: vector of power output and input other than from batteries (RES and load).
F^{max}	: maximum flow at each line.
H	: the distribution factor matrix.
P_{tot}	: The total in- and output power of the grid. Equal to $P_{grid} + P$.
P^{min}, P^{max}	: the minimum and maximum power input of the batteries respectively.

Equation 4.3 is the only power constraint we use, as we assume the big grid input is fixed.

Writing P_{tot} as $P + P_{grid}$ in Equation 4.1 and Equation 4.2 and rewriting Equation 4.2 gives us the following set of equations:

$$\sum_{i=1}^{N} P_{i,grid} = -\sum_{i=1}^{N} P_i \tag{4.4}$$

$$\begin{bmatrix} 0 & H \\ 0 & -H \end{bmatrix} P \leq \begin{bmatrix} F^{max} - \begin{bmatrix} 0 & H \end{bmatrix} P_{grid} \\ F^{max} + \begin{bmatrix} 0 & H \end{bmatrix} P_{grid} \end{bmatrix} \tag{4.5}$$

$$P^{min} \leq P \leq P^{max} \tag{4.6}$$

4.2 Minimising number of ESS

In Section 4.1 the main constraints of the optimisation were stated. As we want to minimise the amount of RESS used, we will explain a method to achieve this.

A way of minimising the amount of RESS used is by introducing a new vector x. This is a binary vector in which an entry i is equal to one, when a RESS is present at node i. What the resulting x vector represents is explained in Figure 4.1. This means that when x_i equals one, P_i should contain

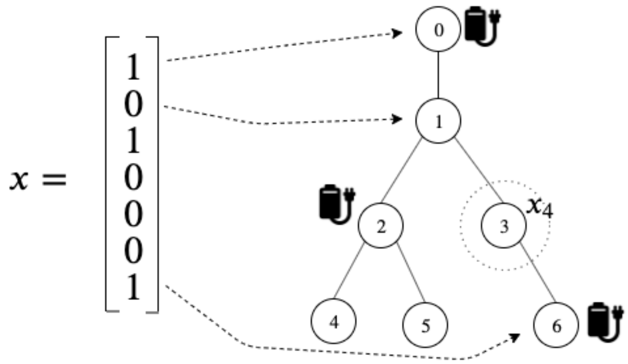

Figure 4.1: Representation of vector x. x_4 is the fourth entry in vector x.

a nonzero value. Vector P is the same size as vector x and their entries coincide. To obtain this method of mapping x to P, the Big M method is used.

In the big M method, a Boolean vector x is mapped to a vector P containing values. Meaning, when an entry of x is one, the corresponding entry in P is allowed to have a value other than zero. When an entry of x is zero, the corresponding entry in P must be zero:

$$\begin{aligned} x_i = 0 \rightarrow P_i = 0 \\ P_i \neq 0 \rightarrow x_i = 1 \end{aligned} \tag{4.7}$$

To obtain this result, the following equations needs to be used in the optimisation:

$$\begin{aligned} P \leq Mx \\ -P \leq Mx \end{aligned} \tag{4.8}$$

This is an important feature, as we rather want to minimise the amount of RESS used than the amount of power used from the RESS. We add the big M constraints to the OPF constraints and the objective functions becomes the minimisation of the amount of RESS used. The result is a mixed integer linear program and results in the following optimisation problem:

$$\begin{aligned} min \quad & \sum_{i=1}^{N} x_i \\ s.t. \quad \sum_{i=1}^{N} P_{i,grid} &= -\sum_{i=1}^{N} P_i \\ \begin{bmatrix} 0 & H \\ 0 & -H \end{bmatrix} P \leq & \begin{bmatrix} F^{max} - \begin{bmatrix} 0 & H \end{bmatrix} P_{grid} \\ F^{max} + \begin{bmatrix} 0 & H \end{bmatrix} P_{grid} \end{bmatrix} \\ P^{min} \leq P &\leq P^{max} \\ P &\leq Mx \\ -P &\leq Mx \end{aligned} \tag{4.9}$$

where:

x : binary vector. $x_i = 1$ when a battery is connected to node i. x_i 0 otherwise.
M : big M, a very large number

It is important to make a careful decision for M. On the one hand we want M to be large enough in order for the entries in P not to be unnecessarily limited. However, even though the variable x is defined as a Boolean variable, values equal to zero are not exactly equal to zero, but a very small value instead. This means when M is too large, $M * x_i$ is actually not close to zero and the corresponding value of P_i will have a value unequal to zero.

4.3 Multiple time steps (Case Basic)

In Section 4.2 was discussed how the amount of RESS used could be minimised. It will be used for optimising over time. As the cost of travelling needs to be minimised, we must not only penalise the amount of RESS used, but also the displacement of RESS, i.e. the difference of the location between time step t and $t+1$. We are able, with the big M method, to split the vector to be optimised in two vectors: one which gives the power out- and input of the battery and the other which simply states if the RESS is present at a node, it makes it possible to optimise the location over time.

At each time step, the power vector of the grid P_{grid} changes and is therefore dependent on time: $P_{grid}(t)$. This also changes the optimisation variables for each time step. Resulting in variables depending on time: $x(t), P(t)$. When including the time dependency in the optimisation, it results in the main optimisation: the amount of RESS is being minimised for and displacement penalised. This optimisation is referred to as Case Basic and results in the following optimisation:

$$
\begin{aligned}
min \quad \alpha \sum_{t=1}^{T} |x(t) - x(t+1)|_1 + \beta \sum_{t=1}^{T} \sum_{i=1}^{N} x_i(t) & \\
s.t. \quad \sum_{i=1}^{N} P_i(t) = - \sum_{i=1}^{N} P_{i,grid}(t) & \quad \forall t \\
\begin{bmatrix} 0 & H \\ 0 & -H \end{bmatrix} P(t) \leq \begin{bmatrix} F^{max} - \begin{bmatrix} 0 & H \end{bmatrix} P_{grid}(t) \\ F^{max} + \begin{bmatrix} 0 & H \end{bmatrix} P_{grid}(t) \end{bmatrix} & \quad \forall t \\
P^{min} \leq P(t) \leq P^{max} & \quad \forall t \\
P(t) \leq M x(t) & \quad \forall t \\
-P(t) \leq M x(t) & \quad \forall t
\end{aligned}
\tag{4.10}
$$

where:

$x(t)$	: binary vector of RESS locations at time t. $x_i = 1$ when a battery is connected to node i. x_i 0 otherwise.
α, β	: constants to be determined.
$P(t)$	: vector of power output/input of the batteries at time t. p_i is the power input/output of node i.
$P_{grid}(t)$	: vector of power output+input other than from batteries (RES and load) at time t. $p_{total,i}$ is the power output+input at node i.
F^{max}	: maximum flow at each line.
H	: the distribution factor matrix.
P^{min}, P^{max}	: the minimum and maximum power input of the batteries respectively.
M	: big M, a very large number.

To make x sparse: $\alpha \leq \beta$. This means the usage of each RESS is penalised more than the displacement, making sure the solution for x is not the same at each time step.

The output of this method describes the positioning (vector $x(t)$) and power (vector $P(t)$) of the RESS in order to prevent congestion for each time step t.

4.4 Statically placed ESS (Case Static)

To compare the method with statically placed ESS a similar optimisation is presented. The objective function changes as there is no displacement of the ESS. In the objective function, only the amount of ESS will be minimised, in other words the sum of all the entries in x. Also, the vector does not depend on t as it is the same in each time step. This results in the following optimisation, referred to as Case Static:

$$\begin{aligned} min \quad & \sum_{i=1}^{N} x_i \\ s.t. \quad \sum_{i=1}^{N} P_i(t) &= -\sum_{i=1}^{N} P_{i,grid}(t) \quad \forall t \\ \begin{bmatrix} 0 & H \\ 0 & -H \end{bmatrix} P(t) &\leq \begin{bmatrix} F^{max} - \begin{bmatrix} 0 & H \end{bmatrix} P_{grid}(t) \\ F^{max} + \begin{bmatrix} 0 & H \end{bmatrix} P_{grid}(t) \end{bmatrix} \quad \forall t \\ P^{min} \leq P(t) &\leq P^{max} \quad \forall t \\ P(t) &\leq Mx \quad \forall t \\ -P(t) &\leq Mx \quad \forall t \end{aligned} \tag{4.11}$$

where:

x	: binary vector of ESS location. $x_i = 1$ when a battery is connected to node i. $x_i = 0$ otherwise.
$P(t)$	: vector of power output/input of the batteries at time t. $P_i(t)$ is the power input/output of node i at time t.
$P_{grid}(t)$	: vector of power output+input other than from batteries (RES and load) at time t.

The amount of ESS is minimised but they are not allowed to move, i.e. the vector x is the same for each time step.

Chapter 5

Planning for each individual RESS

From Chapter 4 it was determined at what nodes a RESS must be placed for each time step. It was represented as the vector $x(t)$. In this chapter will be discussed how to make a planning for each individual RESS to decide what it should do at each time step. This is the second part of the research question. The question to be answered is: what route should an individual RESS follow to minimise travel cost? For each time step a RESS is allowed to travel, be connected to the grid or be in a free state. When travelling, the RESS is of course consuming energy. When it is connected to the grid, it is either consuming or producing energy. In the free state, it is neither travelling or connected to the grid.

In this section first will be explained how to determine the amount of RESS needed over the optimisation time span. Then the planning algorithm for each individual RESS will be explained.

5.1 Number of RESS needed

It is important to calculate the amount of RESS needed, such that at each time step a RESS can be located at a bus where it's needed. We need to keep in mind that a RESS needs one time step to travel to a new location. This means when at time step 1, RESSs are needed at node 1 and 2, and at time step 2 at node 2 and 3, it means 3 RESS are needed to make sure the RESS for node 3 is at the correct position in time. This can be solved by knowing the union of the nonzero entries of vectors $x(t)$ and $x(t+1)$, for each time step t.

The largest of all unions will be the amount of RESS needed and can be expresses as the maximum over t for $card(x(t) + x(t+1))$. Cardinality is defined as the amount of elements in a set.

$$v = \underset{t}{max}\ \text{card}(x(t) + x(t+1)) \tag{5.1}$$

5.2 Planning algorithm

When making a planning for each individual RESS, we define in what state they can be. A RESS is either travelling, doing nothing or connected to the grid. When it is connected to the grid in one time step, it is not possible to be connected to another bus in the next time step. It always needs one time step to move to a new location.

For the design of the implementation, we assume we know the current location (at time t) of the RESS. From there we decide what the location at time $t+1$ will be. This means we do not take into account the location at a time larger than $t+1$.

The algorithm is designed with the following rules:

1. If $RESS_i$ is connected to bus n and at the next time step a RESS is needed at bus n, $RESS_i$ will stay at its position. In time step $t+1$, bus n will be occupied.

2. If $RESS_i$ is connected to bus n and at the next time step **no** RESS is needed at bus n, $RESS_i$ will go into a Free state.

3. If $RESS_i$ is in state F, it's previous location will be checked: n. If there is a node where n needs to go to, it will stay at this node.

4. If in the next time step nodes in N^*_{t+1} are not occupied, an optimal decision will be made on which RESS in state F will go to which bus in the **Matching Algorithm**.

where:

N	: set of nodes with $n \in N$ as variable.
N^*_t	: set of nodes in the solution at time step t. $N^*_t \subseteq N$.
F	: The free state, so the RESS is not connected to a node n.
$RESS_i$	: Element of the set $[ESS_1, ..., ESS_v]$.

For a single RESS, this will lead to the decision tree as in Figure 5.1.

The Decision Algorithm of Figure 5.1 collects all RESSs in the free state and the nodes not occupied yet. It will create a full bipartite graph with in the first set of nodes the RESS and their node position. The second set of nodes will be the unoccupied nodes. The weight of the edge between the nodes in the two sets is equal to their physical distance.

For example in Figure 5.2 a situation is depicted. At nodes 3, 5 and 6 a RESS is needed. The green RESS is already in the correct position and therefore stays at its location. In this situation the blue RESSs were in the Free state and able to travel to nodes 5 and 3. A bipartite graph is constructed with as bipartition the sets $Y = \{0, 2\}$ (where the RESSs are) and $Z = \{3, 5\}$ where a RESS is needed. The weight on the edges is the physical distance between the nodepair connected to the edge.

A matching is a set of edges, such that none of the edges in the set have the same node as an ending. When doing a maximum matching, the amount of edges in the set are maximised. Doing a maximum matching on our bipartite graph will have as consequence all nodes from set Z are matched to a node from set Y, because we know there are always enough RESSs available (Section 5.1), i.e. set Y.

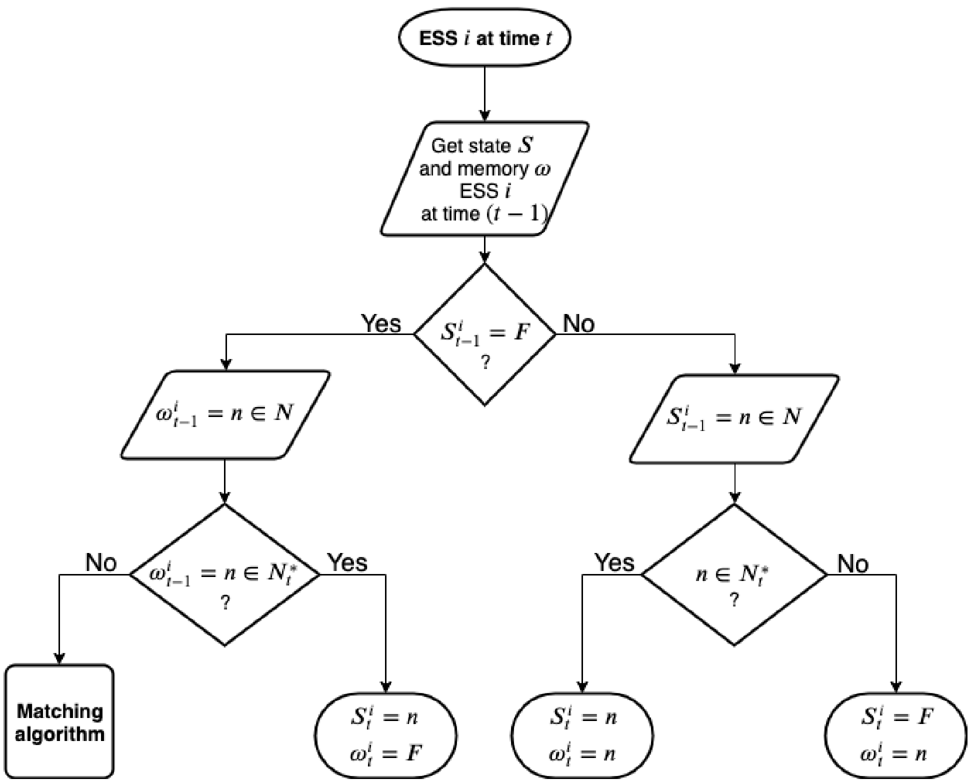

Figure 5.1: Decision tree for one RESS. When all the RESS have been through the decision tree, the matching algorithm starts. S_t^i is the state and ω_t^i a previous node location.

The next step is to minimise for the costs of the maximum matching. In this situation the cost of an edge is similar to the distance between the two nodes the edge is connected to. Minimising the cost of the maximum matching means the total travel distance for the RESS is minimised. NetworkX [31] contains a package to work with bipartite graphs. It contains an algorithm to compute a minimum cost maximum matching algorithm. Applying this algorithm will solve the problem.

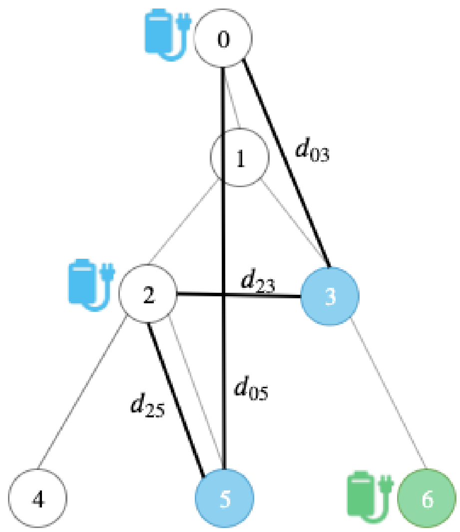

Figure 5.2: This figure shows how the matching algorithm is applied in this thesis. In grey the electricity grid is represented. The blue nodes are connected with a black edge to both RESSs. The weight on each edge, d_{ij}, is equal to the distance between node i and j.

Chapter 6

Extensions to Case Basic

As discussed in Chapter 3, assumptions have been made. Assumptions limit the model. The first three assumptions are chosen to extend the model. These three assumptions are summarised again in Table 6.1. Also the disadvantage can be found and a suggested solution. In this chapter will be described how to change the model in order to take other assumptions into account.

Assumption	**Disadvantage**	**Suggested action/solution**
Deterministic model	The real time power of consumption and production could deviate from what was predicted. As a result the outcome of the model could not be suitable for the real time situation.	Estimate if the outcome of the model is still suitable for an uncertainty with a maximum of 5%.
Power balance	There could exist a more optimal solution, when also optimising for the grid input.	Optimise for the grid as well.
Power RESS	Not minimising the power causes a smaller life time for the RESS.	Minimise power consumption/ production of the RESS.

Table 6.1: Overview of the assumptions improved in this chapter, its disadvantage and suggested solution.

6.1 Optimising for the grid (Case Grid)

In Equation 4.10 the grid input was assumed to be fixed. When we want to take the input from the grid into account in the optimisation (node 0 is connected to the grid), we slightly have to adjust the optimisation. In the model, node 0 is the node connected to the grid. In stead of being able to place a RESS at node 0, the transmission grid is able to supply power with much larger quantities than a RESS is allowed.

First the upper and lower bounds for vector P were 120 and -120 kW respectively. Now we change the upper and lower limit of the first entry in vector P (corresponding to node 0) to be equal to 10e6 and -10e6 kW. The new limits of vector P will be called $P^{max,0}$ and $P^{min,0}$ as can be found in Equation 6.1.

$$\begin{aligned} min \quad \alpha \sum_t |x(t) - x(t+1)|_1 + \beta \sum_t \sum_{i=1}^{N} |x_i(t)| \\ s.t. \quad \sum_i P_i(t) = - \sum_i P_{i,grid}(t) \\ \begin{bmatrix} 0 & H \\ 0 & -H \end{bmatrix} P(t) \leq \begin{bmatrix} F^{max} - \begin{bmatrix} 0 & H \end{bmatrix} P_{grid}(t) \\ F^{max} + \begin{bmatrix} 0 & H \end{bmatrix} P_{grid}(t) \end{bmatrix} \\ P^{min,0} \leq P(t) \leq P^{max,0} \\ P(t) \leq Mx(t) \\ -P(t) \leq Mx(t) \end{aligned} \tag{6.1}$$

where:

$x(t)$	: binary vector of RESS locations at time t. $x_i = 1$ when a battery is connected to node i. x_i 0 otherwise.
α, β	: constants to be determined.
$P(t)$	: vector of power output/input of the batteries at time t. p_i is the power input/output of node i.
$P_{grid}(t)$	: vector of power output+input other than from batteries (RES and load) at time t. $p_{total,i}$ is the power output+input at node i.
F^{max}	: maximum flow at each line.
H	: the distribution factor matrix.
$P^{min,0}, P^{max,0}$	: the minimum and maximum power input of the batteries respectively in which the first entry is relaxed to represent the input from the grid.
M	: big M, a very large number.

6.2 Minimising Power RESS (Case PRESS)

If we want to minimise the absolute value of the power used, it should be included in the objective function. A cost equal to γ is used and could cause an increase in the amount of RESSs needed.

The resulting optimisation is presented in Equation 6.2.

$$
\begin{aligned}
min \quad \alpha \sum_{t=1}^{T} |x(t) - x(t+1)|_1 + \beta \sum_{t=1}^{T}\sum_{i=1}^{N} x_i(t) + \sum_{t} |\gamma P(t)|_1 \\
s.t. \quad \sum_{i=1}^{N} P_i(t) = -\sum_{i=1}^{N} P_{i,grid}(t) \quad \forall t \\
\begin{bmatrix} 0 & H \\ 0 & -H \end{bmatrix} P(t) \leq \begin{bmatrix} F^{max} - \begin{bmatrix} 0 & H \end{bmatrix} P_{grid}(t) \\ F^{max} + \begin{bmatrix} 0 & H \end{bmatrix} P_{grid}(t) \end{bmatrix} \quad \forall t \\
P^{min} \leq P(t) \leq P^{max} \quad \forall t \\
P(t) \leq Mx(t) \quad \forall t \\
-P(t) \leq Mx(t) \quad \forall t
\end{aligned}
\tag{6.2}
$$

6.3 Deterministic model

Currently the model is based on deterministic data. The power consumption and production is known a day ahead. In a realistic case, these values might deviate. When there is a deviation in the grid data, the resulting x and P vectors obtained from the optimisation might not suffice. In real life it is impossible to relocate a RESS in one snapshot. However it is possible to adjust the input power of the RESS within a time step.

Therefore, first the optimisation with deterministic (predicted) data will be run. The resulting optimal $x^*(t)$ vector for all time steps will be remembered. Then the optimisation will be run again, however the vector x is no variable anymore, but an input vector. This means in the basic optimisation (Equation 4.10) and when there is a connection to the grid (Equation 6.1), the objective function becomes zero. It will find a vector P satisfying the constraints.

Second, new load data of the grid, $P_{i,grid}(t)$, will be constructed. $P_{i,grid}(t)$ consists of $P_{i,load}(t) + P_{i,solar}(t)$. $P_{i,load}(t)$ and $P_{i,solar}(t)$ will be adjusted as follows. A value from a normal distribution will be drawn. The normal distribution will be computed with a mean of $P_{i,load}(t)$ or $P_{i,solar}(t)$ and σ equal to a percentage of $P_{i,load}(t)$ and $P_{i,solar}(t)$. In Chapter 3 the prediction accuracy of load and solar power was discussed. For load power a common percentage error for the prediction is 1%-3%. For solar power, often a Mean Absolute Percentage Error (MAPE) is used and can vary a lot. The percentage tested for load power is set to be 0.1%, 1%, 3%, 5%, 10% or 25%. For solar power it is more complicated as the error is averaged over time. Depending on the weather type, the error varies. For simplification the accuracy error for solar power is the same as for load power.

So for example, the new value, $P_{i,load,new}(t)$, will be computed with the following two steps:

1. $\sigma = 1\% * P_{i,load}(t)$ (of course the percentage can change).
2. $P_{i,load,new}(t) = p_{i,load}(t) \in \mathcal{N}(P_{i,load}(t), \sigma)$.

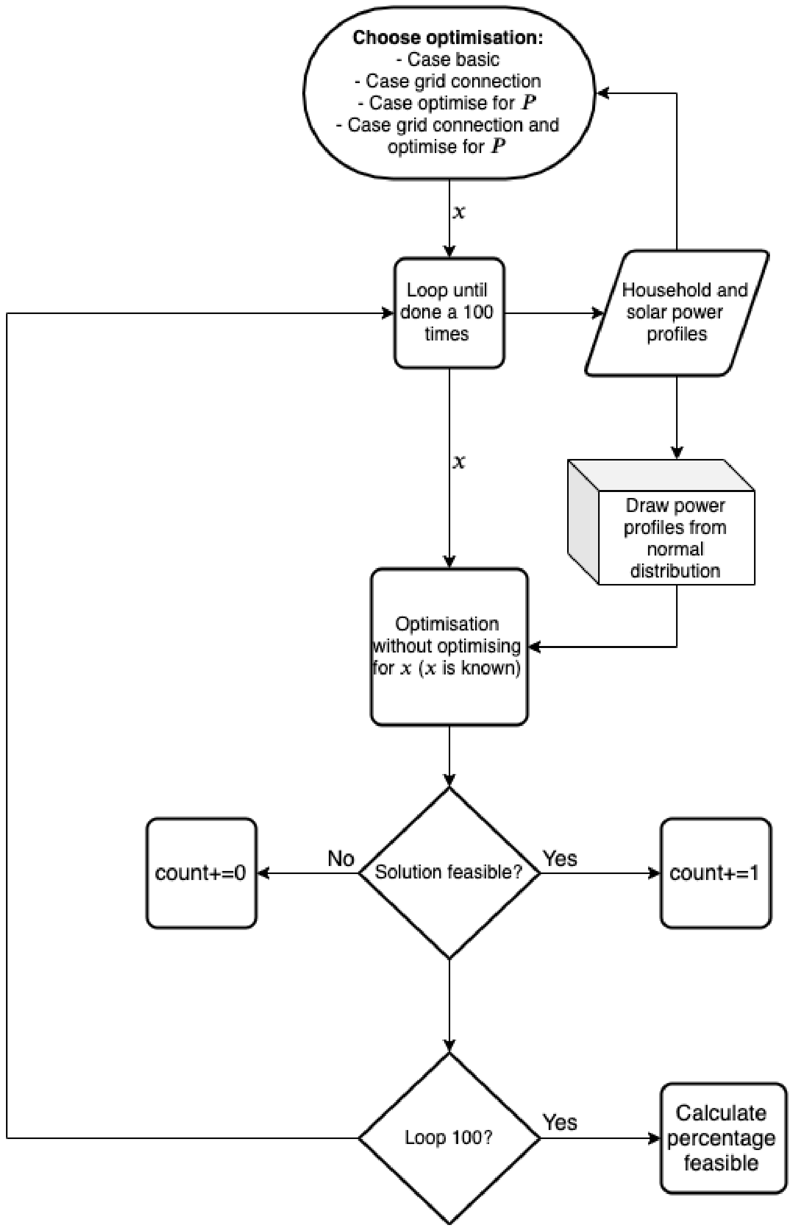

Figure 6.1: Sensitivity test. A case is chosen to test the sensitivity. First the optimisation will be run to determine x, where after will be tested whether there exists a feasible solution for P when load and solar power change.

6.4 Summary Cases

To minimise the amount of RESS used and penalise displacement of the RESSs, a method has been proposed in Chapter 4 (Case Basic). This method forms the basis for the extended methods as described in this chapter (Case Grid and Case P_{RESS}. In Chapter 4, also a method was described to position ESS statically in the grid (Case Static). A summary of these methods is presented in table Table 6.2.

Case	**Description**	**Methodology**
Case Basic	Minimising the amount of RESS used and penalising displacement of the RESSs. This optimisation is used as basis for Case Grid and Case P_{RESS} over time.	Mixed integer linear program. The Big M method is used make the entries of location vector $x(t)$ coincide with the entries in the RESS power vector $P(t)$.
Case Static	The same optimisation as Case Basic is used, only there is no displacement involved. It only minimises the amount of statically placed ESS used over time.	Similar to Case Basic, only displacement of the RESSs is not penalised for.
Case Grid	The input from the grid, at node 0, is optimised for.	The method for Case Basic is used with as addition the power limit constraints at node 0 are relaxed. The effect is the RESS net power output is not forced to be equal to zero.
Case P_{RESS}	The (dis)charging levels of the RESS are minimised for. The goal to increase the RESS lifespan.	The method for Case Basic is used with addition the RESS power vector $P(t)$ is minimised for and therefore added to the objective function.

Table 6.2: Overview of the cases, their description and how it is applied in the methodology.

Chapter 7

Results of Case Basic

This chapter presents the results of Case Basic as described in Chapter 4 and its corresponding planning as decribed in Chapter 5. We also present the results for Case Static, where the RESSs are not allowed to move and, consequently, do not need a planning.

In this chapter, the nodes that do not require a RESS during the optimisation window (24 hours) are excluded from the illustrations. To present the results for the (dis)charging levels of the RESSs, we aggregate the power flow of every RESS over the optimisation window to obtain its SOC over time, providing us insight in charging levels of the RESSs over time.

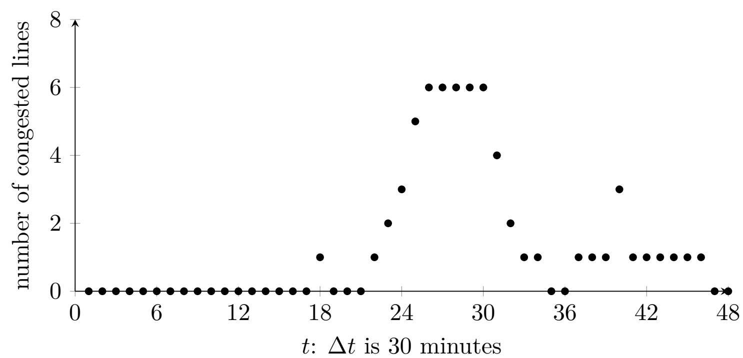

Figure 7.1: Amount of congested links per time step.

In Chapter 3 the design choices for a test grid were presented. The argumentation for using relocatable RESS is that they can travel to a new location when congestion occurs at a different time and a different location. For this reason, a test grid was designed in which congestion occurs at different locations throughout one day. Figure 7.1 illustrates the total amount of congested lines per time step. A congestion peak occurs during the day between 11am and 5pm.

In Figure 7.2 the results for the location of the ESSs for Case Static are presented. The grey lines represent the ESS staying at the same location for the time optimised for. The black dots represent the ESS being in use. Six ESSs are needed. Also from time step 18 on (6pm), at least two ESSs are in use at each time step. As presented at Figure 7.1, there are no lines congested at time step 35 and 36. The ESS in Case Static are not optimised for their (dis)charging power. This explains the ESS being in use when there is no congestion in the grid.

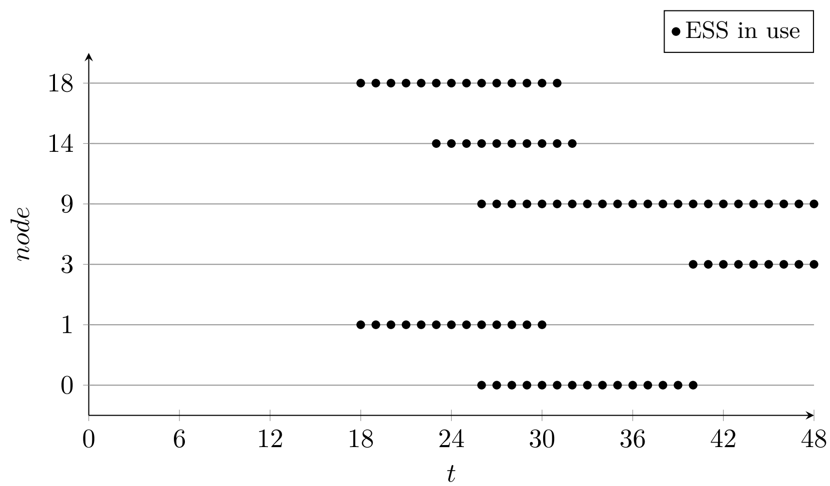

Figure 7.2: Case Static node location ESS and ESS in use.

There is no planning required for the location of the ESS for Case Static. They stay at their position the entire day. To illustrate at what node each ESS is positioned, Figure 7.3 is presented.

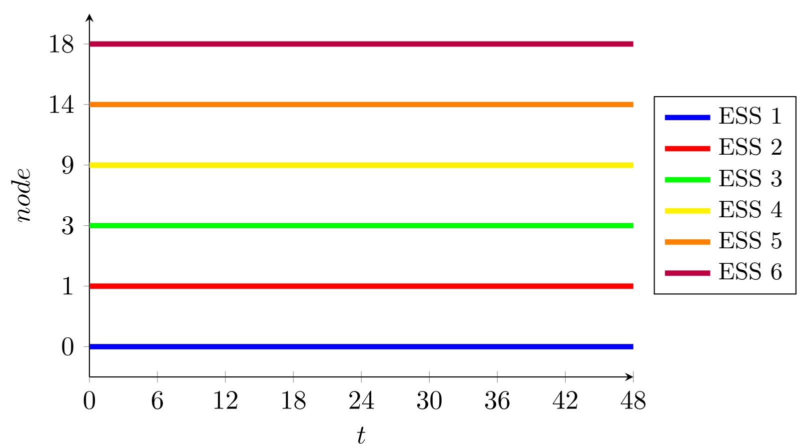

Figure 7.3: Case Static node positions ESS.

In Figure 7.4 the results for the location for Case Basic are presented. The results are presented from time step 18 on, as before this time no RESS are needed. As opposed to Case Static, there are time instances in which no RESS is in use from time step 18 on.

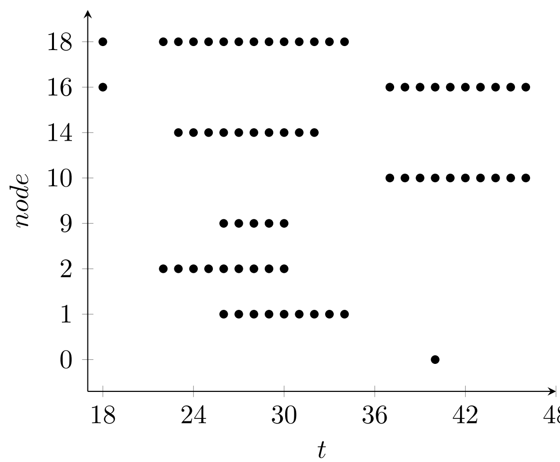

Figure 7.4: RESS location Case Basic.

The planning for each individual RESS in Case Basic is presented in Figure 7.5. Five RESSs are required in total. The distances between each node can be found in the distance matrix in Appendix A. The starting positions for RESS 1 to RESS 5 are chosen, arbitrarily, as node 0, 2, 4, 6 and 8 respectively. To keep the graph of the planning small, the starting positions are not represented in Figure 7.5. The travel distances, including starting positions, are summarised in Table 7.1. From Appendix A can be seen that RESS 1 travels from node 0 to node 1. This distance is shorter than node 0 to node 10 or node 16. It also holds for RESS 3 travelling from node 9 to node 10 and for RESS 4 travelling from node 16 to node 14 and back. For this grid setup, the travel distance is minimised. The total travel distance for all RESSs together is 17.09 km.

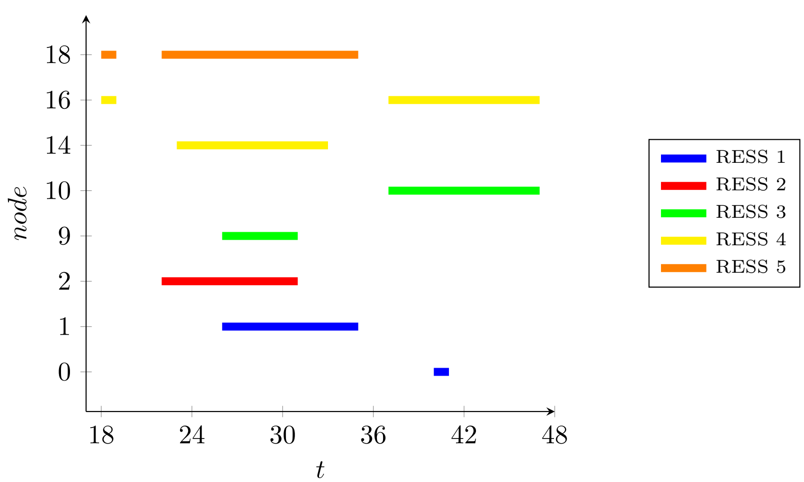

Figure 7.5: Planning RESS for Case Basic.

	Nodepair	Distance [km]	Nodepair	Distance [km]	..	..	Total
ESS 1	(0,1)	0.20	(1,0)	0.20	-	-	0.40
ESS 2	(2,2)	0	-	-	-	-	0
ESS 3	(4,9)	5.30	(9,10)	1.00	-	-	6.30
ESS 4	(6,16)	3.35	(16,14)	2.00	(14,16)	2.00	7.35
ESS 5	(8,18)	3.04	-	-	-	-	3.04

Table 7.1: Distance travelled for each ESS for Case Basic.

The SOC is compared for Case Static and Case Basic. For both cases the maximum SOC is exceeded excessively. The energy capacity of each RESS was set to be 85 kWh. For this grid setup, the energy capacity needs to be around 500 kWh. The SOC for the RESS drifts away more compared to using fixed ESS. This can be explained by the fact that in Case Static more ESS are used.

For both cases, between time step 0 and 17 (night time), no ESSs are needed. This means they can be charged or discharged accordingly to the planning based on the predictions during the day.

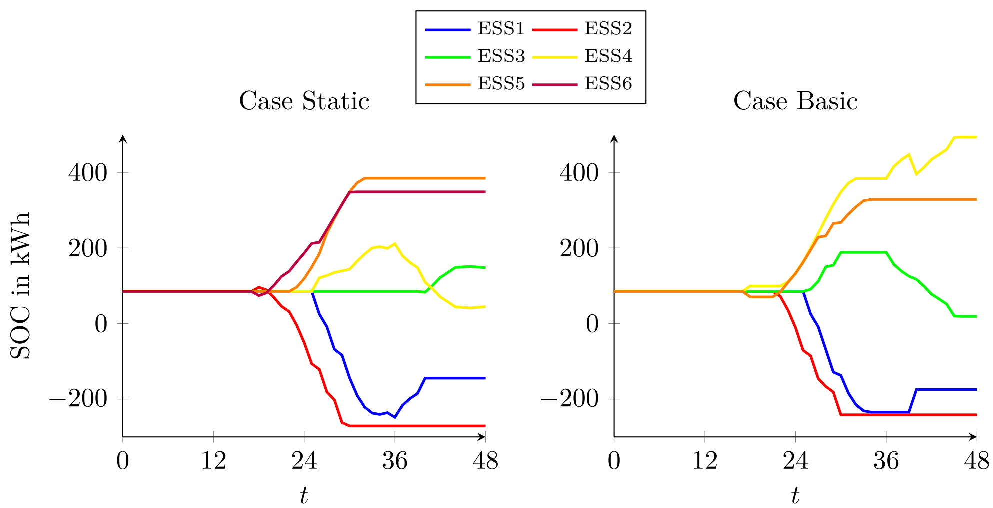

Figure 7.6: SOC for Case Static and Case Basic.

To summarise, the results for Chapter 4 were presented. It shows Case Basic needs less RESS compared to the amount of ESS in Case Static. This means there is an improvement on using relocatable ESS instead of placing them fixed in the grid. Also an effort was made to minimise travel distance. It shows this method is suboptimal as it only minimises distances for one time step. The energy capacity of the RESSs must be higher than the energy capacity of the ESS placed statically. This can be explained as in Case Static more RESSs are used.

Chapter 8

Results of the model extensions

In Chapter 7, the results of Case Basic of Chapter 4 were presented. Also, a comparison was made with the results from Case Static. In this chapter the results for Case Basic and Case P_{RESS} and their planning are presented, as well as the approach for a sensitivity analysis. The extended methods are variations of Case Basic and described in Chapter 6. The approach for a sensitivity analysis is described in Chapter 6 as well.

8.1 Case Grid and Case PRESS

Case Grid

In Figure 8.1 the results for the location of Case Grid are presented. In Figure 8.1, the data points at node 0 represent the extra energy production or consumption from the grid and does not represent a RESS location. Compared to Case Basic less RESS are needed for each time step.

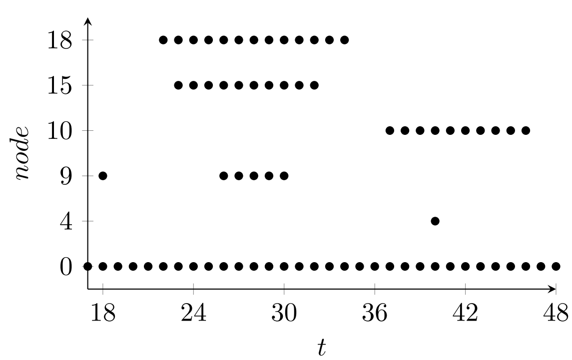

Figure 8.1: Result vector x for Case Grid.

The planning for each individual RESS, for Case Grid, is shown in Figure 8.2. Three RESSs are required in total. Their starting positions are chosen, arbitrarily, to be at node 0, node 2 and node 4 respectively. In Table 8.1 the distances each node has to travel are presented. The starting nodes are not presented in Figure 8.2, but are present in Table 8.1.

When comparing the travel distances to other possibilities in which the RESSs could travel, it is not the optimal solution. For example, the planning for RESS 1 are the nodes 0-9-10 with a total travel distance of 9.70 km. The planning for RESS 3 is 4-9-18 with a total travel distance of 7.36 km. This means for the planning made, RESS 1 and 3 together have a total travel distance of 17.06 km. When the planning is changed, RESS 1 could have the travel route 0-9-9 with a total travel distance of 8.7 km. RESS 3 will in this case have a travel route 4-18-10 with a total travel distance of 8.23 km. Together they have a total travel distance of 16.93 km which is less than the travel distance the original route: 17.06.

The algorithm does not give the optimal solution for the entire day, but only makes a decision based on a snapshot. The algorithm does not take into account future locations. This means at time step 17, it knows a RESS is needed at node 9. The algorithms best option is for RESS 3 to travel to this location with a travel distance of 5.30 km, compared to RESS 1 which would have to travel 8.7 km.

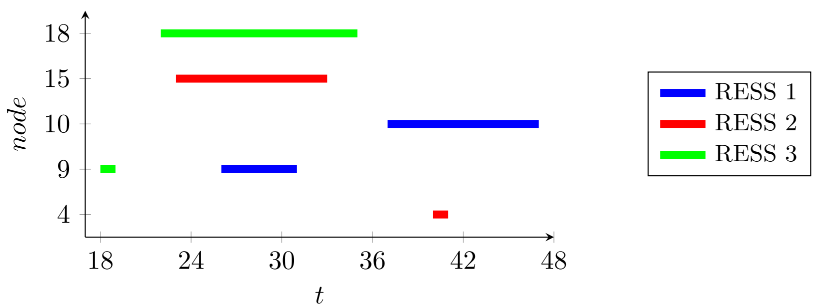

Figure 8.2: Planning for Case Grid.

	Nodepair	Distance [km]	Nodepair	Distance [km]	Total
ESS 1	(0,9)	8.7	(9,10)	1.00	9.70
ESS 2	(2,15)	6.01	(15,4)	4.01	10.02
ESS 3	(4,9)	5.30	(9,18)	2.06	7.36

Table 8.1: Distance travelled for each ESS for Case Grid.

Case P_{RESS}

In Figure 8.3 the results for the location for Case P_{RESS} are presented. One of the differences compared to Case Basic, is node 15 being used as a location in stead of node 10 and 16. Also at $t = 40$, 3 ESSs are placed in the grid in stead of 2 at Case Basic. This can be explained as we are trying to minimise the contribution of each RESS. Using more RESSs, could reduce the (dis)charging levels for an individual RESS.

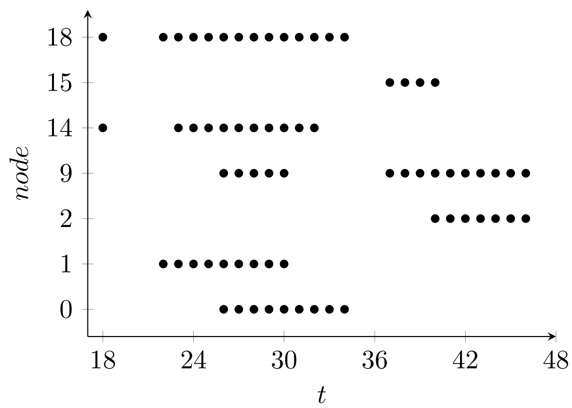

Figure 8.3: Result vector x for Case P_{RESS}.

The planning for each individual RESS are presented in Figure 8.4. The same amount of RESS are needed compared to Case Basic: five RESSs. The starting positions of the RESS are, arbitrarily, chosen to be node 0, 2, 4, 6, and 8 and they are not presented in the figure, but are present in Table 8.2.

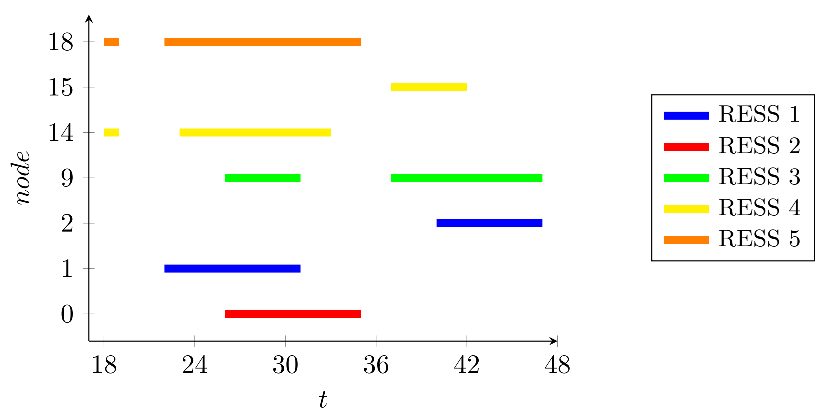

Figure 8.4: Planning for Case P_{RESS}.

Table 8.2 shows the travel distance for each individual RESS. This is not the most optimal solution. For example, the node locations of RESS 1 and 2 should be exchanged. As the starting position of RESS 1 is node 0, staying there would require no travelling. RESS 2 has a starting position at node 2. From node 2, the distance to node 1 is 1.77 km. Again this is explained as the algorithm only takes into account the next time step, not the entire day.

Comparing the SOC for the two cases (Case Grid and Case P_{RESS}) results in the plots of Figure 8.5.

When optimising for the grid, there is no situation in which one RESS is charging and the other is discharging. As explained in Chapter 6, to optimise for the grid the power limits of the power consumption and production of node 0 were relaxed. When node 0 is producing power (it is a

	Nodepair	Distance [km]	Nodepair	Distance [km]	Total
ESS 1	(0,1)	0.20	(1,2)	1.77	1.97
ESS 2	(2,0)	1.94	-	-	1.94
ESS 3	(4,9)	5.30	-	-	5.30
ESS 4	(6,14)	1.80	(14,15)	1.00	2.80
ESS 5	(8,18)	3.04	-	-	3.04

Table 8.2: Distance travelled for each ESS for Case power ESS.

source of power), because of power equality in the grid, the RESSs in the grid need to charge (they are a sink for power).

The SOC, when minimising for the power of the RESS, looks similar to the SOC in Case Basic (Figure 7.6). The differences will be pointed out. For example RESS 4 reaches only 400 kWh while for Case Basic it approaches 500 kWh. Also RESS 2 and 3 show some differences. They reach levels closer to 0 compared to Case Basic. We can conclude minimising the RESS input shows in the resulting SOC of the method.

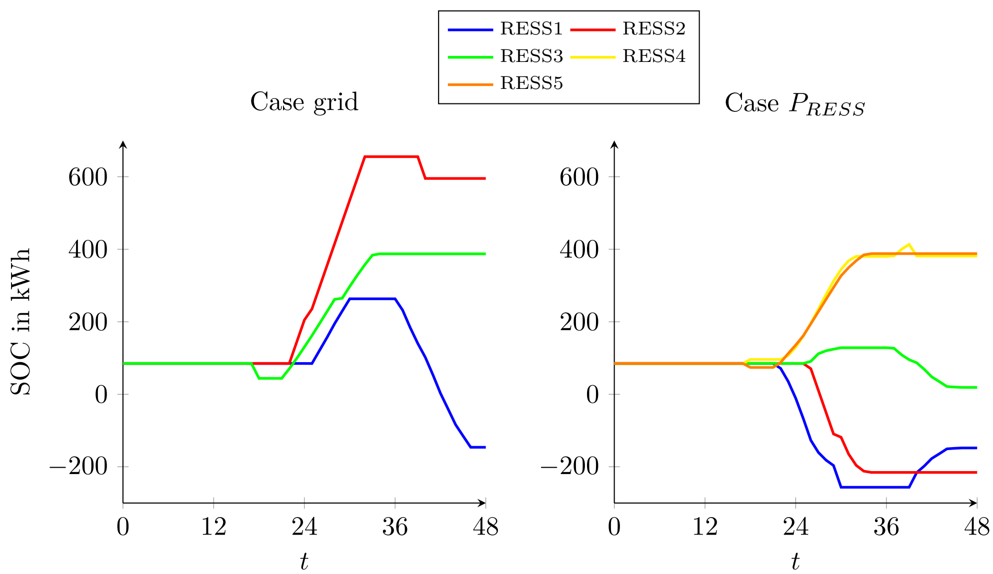

Figure 8.5: State of Charge Case Grid and Case P_{RESS}.

8.2 Sensitivity Analysis

In Table 8.3 the results of probabilistic input power is presented as described in Chapter 6. For each percentage tested for and each case, 100 tests were run. From these test runs was determined what percentage did not cause congestion problems.

	$\sigma/mean * 100\%$					
Case	0.1%	1%	3%	5%	10%	25%
Basic	100	100	100	97	78	23
Grid	100	100	100	100	100	97
P_{RESS}	100	100	100	100	78	23

Table 8.3: Percentage of 100 test runs with no congestion.

It is of interest when in 100% of the test runs congestion can be prevented. For Case Basic, the percentage to determine the standard deviation can be 3%. For Case Grid this percentage is 10% and for Case P_{RESS} 5%. The improvement of Case P_{RESS} could be explained because it limits the power input of the RESS. This leaves more room for adjustments. The RESS could change its (dis)charging levels with a larger amount compared to Case Basic. The improvement to cope with deviations in the consumption and solar profiles for Case Grid is even larger. The optimisation for the grid can be seen as an infinitely large ESS charging and discharging at node 0. The RESS are able to (dis)charge with 120 kW. For each path from node 0 to the node the RESS is positioned, the effect will be minus or plus 120 kW on each line. Because there are 3 ESS and power balance holds, the maximum change of flow on a line is 360 kW. When using solely RESS to prevent congestion, in Case Basic and Case P_{RESS} there are 5 RESS. This means only 2 of them can only charge at maximum power output of 120 kW, for which the other RESS have to compensate. Therefore in one path between two nodes where RESS are positioned, the maximum change in flow is only 240 kW.

Conclusions can be drawn from the results of this chapter. Regarding the amount of RESS needed, Case Grid performs best. This does mean the DSO cannot be the fleet operator as the fleet is involved in the electricity market. The disadvantage of this method is RESS with larger energy capacities are needed. Regarding the energy capacity of the RESS, Case P_{RESS} performs best.

Chapter 9

Conclusion

The Dutch government rapidly wants to increase renewable energy production, while also making sure supply meets demand and a suitable infrastructure is provided. A Dutch DSO already alarmed the grid capacity is not sufficient in many areas where they operate [8]. There were mentioned several methods for congestion prevention, involving ESSs and EVs. These methods were discussed in Section 1.2. However, the size of capacity problems seems to be large [7]. Also the congestion problems could occur only once in a while. So for solving this problem, Relocatable Energy Storage System (RESS) were introduced. The aim of this thesis is to develop a method to prevent congestion by a RESS fleet.

To answer the research question, first a test grid was defined (Chapter 3). Then the methodology was proposed (Chapters 4-6). The methodology was tested on the grid and presented (Chapters 7-8). In this chapter the answers to the research question and subquestions will be discussed. First, the research questions are repeated and answered. A reflection on this thesis is presented as well.

9.1 Research questions and first subquestion

> *How can a fleet of Relocatable Energy Storage System (RESS) optimally position and re-position themselves over time through the grid for congestion prevention, while minimising the amount of RESS used and travel distance?*

Because of the first subquestion,

> How can the research question be answered, such that the fleet can be operated by an external party?

the research question was answered by splitting up the problem in two parts:

1. Preventing congestion while minimising the amount of required RESSs and minimising the amount of changes in RESS locations.
2. Given an overview of nodes that require a RESS over time and a number of available RESS, minimise the travel distances of the RESSs.

The first part is solved mathematically by using the OPF equations. The objective function was chosen to minimise displacement of the RESS and minimising the total amount of RESS used. The charging or discharging power of the RESS were taken into account in the constraints.

Three variations of the method were developed:

- Case Basic: for this method the amount of RESS were minimised and displacement over time penalised.
- Case Grid: this method was similar to the basic case, with addition the grid input could change. In this case, the fleet operator can **not** be an external party.
- Case P_{RESS}: this method was also similar to the basic method, only now the minimisation of (dis)charging power of the RESS was added to the objective function.

The second part is solved by optimising a relocation planning for all the RESSs in a predetermined time window. The following steps are followed to achieve such a planning:

- If at time t a RESS is at node i and at time $t+1$ a RESS is needed at node i, the the RESS stays at its position.
- If at time t a RESS is at node i and at time $t+1$ **no** RESS is needed at node i, then the RESS goes into a Free state where it is able to travel.
- The remaining RESSs are matched to unoccupied nodes with a minimum cost maximum matching algorithm.

From the results was shown the algorithm is not optimal over the entire day, but only shows optimality for one time step.

9.2 Second subquestion

> Will the model be an improvement in terms of the number of RESS needed, compared to placing ESS statically in the grid?

Yes, for each case less RESSs are needed compared to statically placed RESSs. The amount of RESS/ESS needed was:

- Case Static: 6 ESS.

- Case Basic: 5 ESS.
- Case Grid: 3 ESS.
- Case P_{RESS}: 5 ESS.

It can be concluded Case Grid is the most promising regarding the minimisation of the amount of RESS.

9.3 Third subquestion

> Will uncertainties in the power consumption and renewable energy production cause congestion when the decision for the location of the RESS has been made, but the RESS are allowed to change their level of (dis)charging?

To answer this question, new samples were drawn from a random distribution to create the new power consumption and solar generation profiles. The location of the RESS was determined by the deterministic power profiles. It was tested whether the RESS could change their (dis)charging levels, in order to prevent congestion.

The tests were run 100 times for each standard deviation. The results are presented in Table 8.3. It can be concluded that for a standard deviation of up till 3% the method can prevent congestion. When minimising for the (dis)charging power of the RESS or optimising for the grid input, a standard deviation of respectively 5% and 10% still shows the method can prevent congestion.

9.4 Reflection

This thesis proposed a method to optimally relocate RESS in the grid over time for congestion prevention, while minimising the amount of RESS used and their travel distance. A **test grid** was designed to test the methodology. The **methodology** consisted of a part in which the optimal location was determined and a part in which the planning for each individual RESS was made. The **results** concluded optimising for the grid (Case Grid) was the most effective methodology to use regarding robustness to uncertainties and amount of RESSs needed, but the RESS fleet did need larger energy capacities.

Test grid

The test grid developed for this thesis was done by using the parameters of the residential low voltage distribution grid from CIGRE [33]. Input data was taken from household power profiles in London [19] and solar data from a typical generation profile in Antwerp [20]. They were scaled accordingly to the snapshot CIGRE power of each bus. In order to create congestion in the grid some of the maximum flow values in the line were decreased as shown in Appendix B.

It is unrealistic the capacity of some lines in a low voltage distribution grid are more than 10 times smaller than the capacity of the other lines. It was out of the scope of this thesis to create many realistic test grids. The main goal of this test grid was to test the methodology and make a comparison to the case in which only static RESSs are used.

To test the method in real life scenarios, it is advised to work close with the DSO. Alliander, for example, published reports on the expected location of congestion in the grid [7]. Reports were published for regions where problems occur regarding capacity of the grid. These reports contain the (postal codes of the) regions where problems occur, the cause of the problem, the available grid capacity and the capacity to be available according to the contracts made with the users of the grid. If realistic grid models can be provided of these regions, the potential of using RESS in these regions can be tested.

Power consumption of the dataset is given in [kWh/hh], kWh per half an hour. These values are transformed to average power consumption. This means we don't know how the power consumption is distributed within that half an hour. If we want to increase the reliability, we should find a dataset containing a smaller time slot for energy consumption (5 minutes, 1 second etc).

The Methodology

The method was split up in two parts:

1. Preventing congestion while minimising the amount of required RESSs and minimising the amount of changes in RESS locations.
2. Given an overview of nodes that require a RESS over time and a number of available RESS, minimise the travel distances of the RESSs.

The first part was solved by the use of OPF and the Big M method. In an OPF, for simplifications the resistance is assumed to be negligible as compared to the reactance. However in a low voltage distribution grid, this is not the case. In the CIGRE grid, the resistance is even larger than the reactance. Also the Big M method needs extra caution. Big M is multiplied by the location vector x. However, because of computer precision, entries in x might not be exactly zero. This causes an entry of x close to zero being multiplied by a very large number, to become a number unequal to zero.

The flaw of the optimisation as described in Chapter 4 and Chapter 6 is only replacement is penalised. The cost for going to a node further away is not taken into account.

The starting positions of the RESS were not taken into account in the optimisation. Better results could be shown when including their starting positions. As the optimisation starts at $t = 1$, we could add a vector $x(t = 0)$ containing the starting locations of each RESS.

The second part was solved by an algorithm containing minimum cost maximum matching. However this algorithm is only able to optimise for one time step. For this thesis, travelling would only consume 0.1 kWh/5km. Whether travel distance is of great interest to the problem is debatable because of two reasons. The first reason is because the test grid tested for contains small distances between nodes. Compared to the total storage capacity of the RESS and the (dis)charging power of the RESS, the energy needed for travelling can be negligible. However, when we want to scale up our test grid, it gets more beneficial to increase optimality of the planning algorithm. The second reason is because of uncertainties. It is unclear to what extend DSOs are able to predict congestion. If the margins are large, this means adjusting the planning during the optimisation time span could be desired. Therefore it could be beneficial to just minimise the distance for one time step.

The bipartite matching algorithm is redundant for small problems like for the test grid discussed in this thesis. Often only there is only one change in node location for the RESS at a time. This means the solution is trivial: the RESS closest by will travel to the node. However, when the test grid increases, it might happen there are multiple node changes at one time. The planning algorithm has to be extended by taking future locations into account. When future node locations are be taken into account, the amount of nodes where an RESS is needed increases. This complicates the problem and the bipartite matching algorithm will be an efficient method to solve it.

Results

The research question was answered by splitting up the problem in two parts. The motivation for this partition is the DSO will not have to participate in the electricity market. This partition was necessary for the development of Case Grid, for which the grid input was optimised for. It is still debatable whether the partition has been made correctly. The DSO does determine the location of the RESS and the (dis)charging levels. They instruct the fleet operator to position their RESS at the correct location with the proposed (dis)charging levels. This could be a grey area in which the DSO pays the fleet operator to have a net nonzero power input of the fleet. The net nonzero (dis)charging levels could be beneficial in terms of cost. It should be researched whether this is an indirect participation in the electricity market and whether this is legal.

The grid tested for is not realistic. Various line power limits were reduced in order to create congestion. The test results are therefore not representable for real life situations. The next step will be to test on (more) realistic cases and obtain realistic values for the costs. When this is achieved, conclusions can be drawn when comparing RESS with ESS.

A future scenario could be a highly congested grid, where the power flows (due to the predicted power load) and generation profiles are closer to the grid line limits. It is expected small deviations easily result in congestion. The expectation is the RESS will, positioned at a location, more often not be able to prevent the congestion in the entire grid. So the sensitivity analysis will show results which are worse compared to the results in this thesis.

Also the percentage used for the deviation seems arbitrary. It is adviced not to interpret them as performance metric. For example in Case Grid the maximum percentage is allowed to be 10% before congestion starts to occur. This does not mean in Case Grid the load power and solar power are allowed to deviate with 10%. We can use this analysis to compare the different cases. The grid they are tested on is the same and therefore it gives insight in which case performs better.

The methodology was tested on a small grid. To determine the travel route of each RESS a distance matrix was used. In this distance matrix, the distance between each node was defined. This travel distance is not realistic, as the RESS will not travel in a straight line to a new node position (the scope of this project did not discuss RESS with wings). An effort can be made on improving the accuracy of the travel distance, the current travel distance is just an indication.

9.5 Future Work

In Chapter 3, important assumptions made were summarised. The first three assumptions have been relaxed in Chapter 6. The remaining list of assumptions need some attention. These assumptions and their proposed solutions are listed in Table 9.1.

The first assumption listed is the amount of RESS able to connect to each bus and this amount is constricted to a maximum of one RESS for each bus. When the number of allowed connections increases, it means the RESS energy capacity can be lower as the energy is divided over the RESSs.

The second assumption is the amount of connection points in the grid. In this thesis a connection could be made at each bus, in real life this is probably not a realistic scenario. When the connection points are limited, entries in the position vector x can be constrained to be zero. When this constraints causes an infeasible solution, the constraint should be dropped to find the buses where connections should be made in real life.

The third assumption is the RES is able to travel to a new location in 30 minutes. This time might not be sufficient for grids the size of a province. The time step could be increased, but this makes the method less accurate. A better option is to look for a solution in the planning. This could mean the fleet operator needs to use more RESSs and the planning needs to be adjusted accordingly.

The fourth assumptions made is the SOC is not optimised for. The consequence is the SOC might exceed its limits. This could be solved by (dis)charging the RESS when not in use for congestion prevention. Caution must be taken to ensure the regulation of the SOC, by (dis)charing the RESS, does not cause congestion in the grid.

Assumption	**Disadvantage**	**Suggested action/solution**
1 RESS per bus	Especially for tree structures, the problem space reduces when only one RESS per bus is allowed.	Increase the amount of variables in the optimisation.
Connection points	Reduces the problem space when a feasible outcome is wanted.	Predict the critical buses where connection points should be made.
Travel time	When the grid increases in physical size, a RESS might not be able to reach the other bus in time.	The fleet operator uses more RESSs.
SOC	The SOC might exceed its limits.	When a RESS is in travel mode, for multiple time steps, it could (dis)charge.

Table 9.1: Overview of the assumptions, its disadvantage and suggested solution.

In this thesis there are time steps in which in RESS is not used. However there are many other applications for energy storage system in the grid, as described in Section 1.2. This method could be combined with other ancillary services to the grid, when the ESS is not needed for congestion prevention. They could also be part of the electricity market. The RESS can charge when prices are low and discharge when prices are high. The SOC must be taken into account, as it still must be able to execute its primary task: congestion prevention. This means when electricity prices are low, but the RESS is needed somewhere later in time to charge in order to prevent congestion, it is not able to charge fully.

The specifications of the RESS were chosen as to match the specifications of an EV (Chapter 3). Depending on the situation, we might want to choose different specifications. For example, if the flow violation in a cable is very large, a larger energy capacity of the RESS is needed. It depends on the grid what specifications are desired. A case study could be done to test which RESS specifications apply to what type of problems.

When designing test scenarios, there are some things to take into account. Scenarios already exist of congestion problems [7]. The type of grid can vary for each scenario. It could be a solar farm at the end of a long and thin cable or it could be a high density populated city area with many EV owners. Because load profiles are not available for each region, load profiles should be chosen according to demographic areas. In stead of scaling one load profile, multiple load profiles should be added to get the total profile of the correct amount of houses.

To proceed on this topic, before extending and complicating the model, it is recommended to first explore realistic case studies provided by DSOs. This can give insight in design choices to make, for example the energy capacity of the RESSs needed and travel time between buses. It is clear from this chapter the method should be improved and can be improved in many ways. It is of importance to first gain insights from case studies. From these insights, design choices should be adjusted. When the design choices have been incorporated in the method, a choice should be made on the focus for improvement.

Abbreviations

AC Alternating Current. 12, 17

CIGRE Conseil International des Grands Réseaux Électriques (The International Council on Large Electric Systems). 17–20, 51, 52

CSP Charging Service Provider. 6

DC Direct Current. 12, 17

DSO Distribution System Operator. 5, 7, 16, 23, 48, 49, 52, 53, 55

ESS Energy Storage System. 6–9, 13, 27, 28, 38, 40, 41, 43, 45, 48–51, 53, 54

EV Electric Vehicle. 3, 4, 6–8, 20, 49, 55

OPF Optimal Power Flow. 9, 11–13, 23–25, 50, 52

PV Photo Voltaic. 20

RES Renewable Energy Sources. 3, 5, 9, 20, 24, 27, 28, 35, 54

RESS Relocatable Energy Storage System. 7–9, 16, 17, 20–27, 30–36, 38, 40–55

SOC State of Charge. 9, 21, 22, 40, 43, 46, 47, 54

Nomenclature

(Electric) Utility a company in the distribution and/or generation of electricity. To make sure supply meets demand. 3

het Klimaatakkoord a collection of measures and agreements between companies, social organisations and governments to halve the emissions of greenhouse gasses in the Netherlands in 2030 (compared to 1990). [1]. 3

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Appendix A

Distance matrix

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
0	0,00	0,20	1,94	2,60	3,43	4,55	5,78	6,67	7,79	8,70	9,62	10,74	4,16	5,19	6,16	7,14	8,12	7,40	10,41	11,67
1	0,20	0,00	1,77	2,48	3,34	4,45	5,69	6,58	7,70	8,62	9,55	10,67	4,11	5,14	6,12	7,10	8,09	7,34	10,36	11,61
2	1,94	1,77	0,00	1,00	2,00	3,04	4,19	5,15	6,25	7,22	8,19	9,28	3,04	4,01	5,01	6,01	7,00	6,05	9,09	10,25
3	2,60	2,48	1,00	0,00	1,00	2,06	3,25	4,19	5,30	6,25	7,22	8,31	2,06	3,01	4,01	5,01	6,01	5,06	8,10	9,28
4	3,43	3,34	2,00	1,00	0,00	1,12	2,36	3,25	4,37	5,30	6,25	7,35	1,12	2,02	3,01	4,01	5,01	4,07	7,11	8,31
5	4,55	4,45	3,04	2,06	1,12	0,00	1,25	2,14	3,25	4,19	5,15	6,25	1,00	1,25	2,14	3,09	4,07	3,01	6,05	7,22
6	5,78	5,69	4,19	3,25	2,36	1,25	0,00	1,00	2,06	3,04	4,03	5,10	2,02	1,50	1,80	2,50	3,35	2,06	5,00	6,08
7	6,67	6,58	5,15	4,19	3,25	2,14	1,00	0,00	1,12	2,06	3,04	4,12	2,66	1,80	1,50	1,80	2,50	1,12	4,00	5,10
8	7,79	7,70	6,25	5,30	4,37	3,25	2,06	1,12	0,00	1,00	2,00	3,04	3,75	2,83	2,24	2,00	2,24	1,00	3,04	4,03
9	8,70	8,62	7,22	6,25	5,30	4,19	3,04	2,06	1,00	0,00	1,00	2,06	4,59	3,61	2,83	2,24	2,00	1,41	2,06	3,04
10	9,62	9,55	8,19	7,22	6,25	5,15	4,03	3,04	2,00	1,00	0,00	1,12	5,48	4,47	3,61	2,83	2,24	2,24	1,12	2,06
11	10,74	10,67	9,28	8,31	7,35	6,25	5,10	4,12	3,04	2,06	1,12	0,00	6,60	5,59	4,72	3,91	3,20	3,35	1,00	1,00
12	4,16	4,11	3,04	2,06	1,12	1,00	2,02	2,66	3,75	4,59	5,48	6,60	0,00	1,03	2,02	3,01	4,01	3,25	6,25	7,52
13	5,19	5,14	4,01	3,01	2,02	1,25	1,50	1,80	2,83	3,61	4,47	5,59	1,03	0,00	1,00	2,00	3,00	2,24	5,22	6,50
14	6,16	6,12	5,01	4,01	3,01	2,14	1,80	1,50	2,24	2,83	3,61	4,72	2,02	1,00	0,00	1,00	2,00	1,41	4,27	5,59
15	7,14	7,10	6,01	5,01	4,01	3,09	2,50	1,80	2,00	2,24	2,83	3,91	3,01	2,00	1,00	0,00	1,00	1,00	3,35	4,72
16	8,12	8,09	7,00	6,01	5,01	4,07	3,35	2,50	2,24	2,00	2,24	3,20	4,01	3,00	2,00	1,00	0,00	1,41	2,50	3,91
17	7,40	7,34	6,05	5,06	4,07	3,01	2,06	1,12	1,00	1,41	2,24	3,35	3,25	2,24	1,41	1,00	1,41	0,00	3,04	4,27
18	10,41	10,36	9,09	8,10	7,11	6,05	5,00	4,00	3,04	2,06	1,12	1,00	6,25	5,22	4,27	3,35	2,50	3,04	0,00	1,41
19	11,67	11,61	10,25	9,28	8,31	7,22	6,08	5,10	4,03	3,04	2,06	1,00	7,52	6,50	5,59	4,72	3,91	4,27	1,41	0,00

Table A.1: Distance matrix of the nodes in the grid.

Appendix B

NetworkX model of the electricity grid

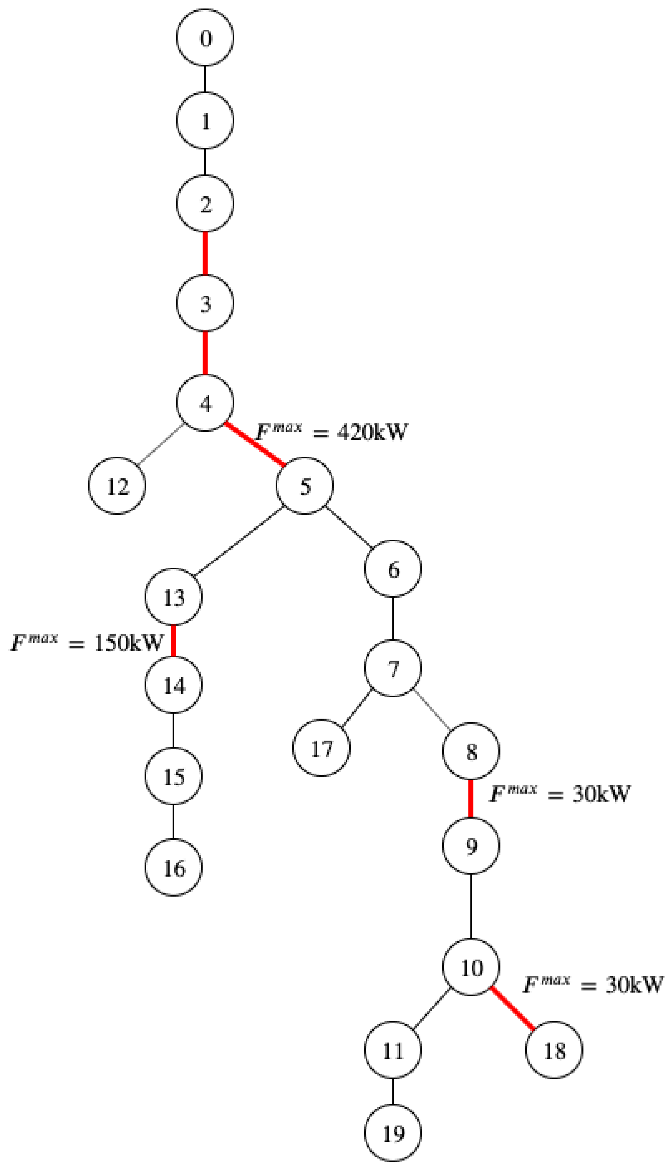

Figure B.1: The total NetworkX graph computed from the CIGRE grid. In red are lines that are at least congested once during the day. $F^{max} = 400$kW unless stated differently.