Graduation thesis for Construction Management & Engineering MSc @ TU/e

Smart grids with Electrical Energy Storage for a sustainable energy supply system

A business case on the role of electrical energy storage to achieve reliable energy supply systems that feature decentralized variable renewable energy systems for a sustainable future, case studied on the neighbourhood of Hoog Dalem.

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Rosmalen, 11-04-2016

"All people everywhere should have free energy sources. [..] Electric power is everywhere present in unlimited quantities and can drive the world's machinery without the need for coal, oil or gas."

- Nikola Tesla (1856 – 1943)

I. Colophon

Title:	Electrical Energy Storage and smart grids to enable the next energy revolution
Subtitle:	A business case for the role of electrical energy storage to achieve reliable energy supply systems that feature decentralized renewable energy generation systems for a sustainable future case studied on the neighbourhood of Hoog Dalem.
Front page artwork:	http://blog.aquionenergy.com/blog/bid/169441/Making-the-Grid-Smarter-with-Smart-Energy-Storage-Part-2
Date:	11-04-2016
Thesis defence date:	7 April 2016
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Please note that the report, final presentation, model, videos and most data can be downloaded from a public Dropbox folder. Due to confidentiality of the data-sets used they are not included, datasets are required to perform simulations and should be provided yourself. If there are any questions stemming from my thesis or model don't hesitate to contact me on melvinvanmelzen@gmail.com or Linked-in. Please let me know when continuing work on my topic or extending the model.

https://www.dropbox.com/sh/9hvcldkay1j4ll5/AADBOMa8eNT-2ldEXdafylJba?dl=0

II. Preface

In my studies I became fascinated with the concept of energy storage and recognized the potential to enable the energy transition. Heijmans technologies shared my interest and this research on energy storage in the project of Hoog Dalem was the result. The thesis is the last piece of my master and hopefully a steppingstone to a sustainable energy supply system.

A project this large and complex is exactly the kind I like the most but of course I could not have done it without the help of others. I found great help in my tutors Bauke de Vries, Dick Timmermans and Saleh Mohammedia. Milo Broekmans from Stedin was of great help and provided me with a great insight into the operations of the low voltage power grid and technical support for implementation in the model. As a result of this project I got inspired by the people I met; Guido Dalessi and Emil Goosen which passionately told about their innovative energy storage products, as did many other people in Heijmans partner meetings and at the *vakbeurs energie*.

Working at Heijmans was a very pleasant experience and whenever I asked someone for help they were willing to do so. I would like to thank Gerard de Leede, Michiel van Ierssel, Joris Hooijberg, Patrick Koch, Jan-Willem Schmid and Avindre Ramnath for providing expertise in the their respective fields of energy, dwellings and innovations. Ralph, Christiaan and Agririos were always in for some brainstorming or to provide some inspiration, thanks guys for a great time.

Most of all would I like to thank my parents for financing and support. The infinite support from my girlfriend was the best and without it entropy would have taken over our apartment. My friends remained interested during the many endless energy and storage monologues, thanks!

Now I am on to the next adventure. Energy and energy storage in particular will always continue to be on the top of my interest list. Everything we do requires energy and the economy needs a cheap sustainable energy supply system so developments can result in amazing things. I hope this thesis inspires others to study energy supply systems and help realize the next energy revolution.

III. Contents

IV. Summary

Our energy supply system generation capacity relies mostly on fossil fuels as an energy source. The ongoing energy transition results in less fossil fuel consumption and accompanying smaller carbon emissions. New energy sources are renewable and relatively inexhaustible but are accompanied by variability in generation which is dependent on external conditions like weather, time of the day, season and geographical location and orientation. This results in a more comprehensive description of such energy sources: Variable Renewable Energy Sources (VRES). Fossil fuels can conveniently be deployed to fulfil demand while VRES can only be deployed when external conditions are met which typically do not coincide with demand. The variability causes imbalance in supply and demand which needs to be compensated by traditional generators at the costs of reduced efficiency and increased emissions and generation costs.

On a more local scale of a neighbourhood different issues are causing problems; power quality is at risk of deteriorating due to overvoltage or overloading. Excessive VRES generation can cause overvoltage when generation is high and demand is low which occurs in summer. Demand in winter is higher and peak demand keeps on increasing due to electrification of appliances of which the foremost troubling is that of the Electrical Vehicle (EV). A too high demand can cause overloading of the infrastructure leading to power quality issues. Either of these power quality issues need to be addressed by the grid operator and caution is taken to prevent such situations by over dimensioning grids for realistic worst-case scenarios that may realistically be expected to take place during the lifetime of the infrastructure. As a result most of the time the infrastructure is stressed nowhere near the limits. Upgrading the capacity of infrastructure while in operation is very costly.

Electrical Energy Storage (EES) can be regarded as a hybrid of a generator and consumer, it can charge or discharge to fulfil most power supply system related functions. Peak-shaving is the concept on which most grid supportive functions work, removing extremes in supply or demand to prevent problems. Overloading of the grid when peak demand exceeds restrictions can be resolved by discharging EES to relieve the energy supply system locally, of course EES needs to be charged in order to do this which the system can do when demand is low. Similarly when over-voltage is present in the grid this can be resolved by absorbing the generated power in the event of peak generation during minimum demand in EES. Then when demand exceeds generation EES can be discharged. Smart grids that feature EES can be used to control energy flows and maintain power quality while reducing operating and generation costs. Small areas can be islanded into a subsection of the grid. These Sustainable Energy Microsystems (SEM) are capable of functions semi-independent from the main grid.

Trends in residential energy consumption related to power quality are electrification of appliances and increased VRES generation. Traditionally most Dutch dwellings are heated by gas powered furnaces but electrically operated heat-pumps are becoming more common due to increased energy efficiency, this results in fully electric neighbourhoods and a large electrical energy demand during heating season. Electric bikes and EV’s are bringing transportation energy demand into the neighbourhood. By 2025 there are one million EV's expected on the Dutch roads. VRES generation capacity in the Netherlands is far behind on neighbouring countries, only 1GW of installed PV capacity is installed. By 2025 an installed capacity of 9 to 10GW is expected. A model is created to simulate the operations of the power supply grid when the trends for 2025 are realized. The model calculates energy flows from demands and can add generation capacity or EV demands to simulate the 2025 scenarios. The model is made in NetLogo on a quarter hourly time scale, GIS is used to visualize the building outlines and to render the power supply grid. CSV files are used to import demand patterns into the model. Voltages resulting from the demand and generation patterns are also monitored on a per dwellings scale. Violations of the voltage and loading limitations are used to determine a objective performance figure, this performance is used to assess the severity of power quality issues in the grid. A lithium battery, and a small and large flow battery are considered.

Simulations were used to show that the spatial component of PV system placement greatly influences the performance of the grid, placement in the extremities and in high concentrations resulted in the poorest performance. Peak demand caused by overloading of the infrastructure did not have a spatial dependence on performance degradation. EES was then deployed to resolve the issues and it was found that it was able to improve performance of the grid. As batteries are added performance will improve but to what extend greatly depends on the combination of battery-type, battery logic and relative placement of the storage compared to the most dense location of generation. Restoring performance with a high number of VRES was most effective by placing batteries in the same extremities as the issues were occurring. Restoring performance with peak demand was possible but placement of batteries was not related to the effectiveness of the performance gains. Most importantly it was found that the battery logic greatly influenced the performance gains from EES, three different battery logics were tested and found effective in different scenarios of which the voltage-controlled logic proved best in most situations. Battery logics were designed to give the best overall performance in most combinations of batteries and scenarios and therefore need to be optimized for each specific configuration.

EES was found to be able to perform grid support for both voltage-quality control and peak-shaving function and as a result make more efficient use of energy supply infrastructure. Applying storage for these functions is most interesting since it is able to maintain power quality while it doesn't require energy consumers to modify their behaviour. Flexibility is what EES offers to the grid to better work with a variable generation pattern. Alternatively demand can be altered through application of smart appliances with smart start or smart charging of EV's to prevent overloading of the infrastructure. A smart grid should therefore feature flexibility through both storage and demand management. Traditional grid infrastructure would cost around € 60.000 while the EES solution would cost more than this amount additionally making it a costly solution, with declining prices storage will make economic sense hopefully before trouble arises since it offers many societal benefits over traditional solutions like allowing more PV generation without increased carbon emissions.

V. Samenvatting

Onze energieproductie is voornamelijk afhankelijk van fossiele brandstoffen als energiebron. De energietransitie die gaande is zal zorgen voor een lager gebruik van fossiele brandstoffen en resulteren in een lagere emissie van koolstof. Nieuwe energiebronnen zijn duurzaam en vrijwel onuitputbaar maar hebben een zekere variabiliteit in de generatie welke afhankelijk is van externe factoren zoals weer, tijdstip, seizoen en geografische locatie en oriëntatie. Dit resulteert in een meer accurate beschrijving van deze energie bronnen, namelijk: Variërende Duurzame Energie Bronnen (VRES). Fossiele brandstoffen kunnen gemakkelijk ingezet worden om aan de energievraag te voldoen terwijl VRES alleen kan worden ingezet wanneer de externe condities dit toestaan wat doorgaans niet samenvalt met de energievraag. De variabiliteit zorgt voor een onbalans tussen vraag en aanbod welke door middel van traditionele energiegeneratoren moet worden gecompenseerd ten koste van een verlaagde efficiëntie en toenemende generatiekosten.

Op een lokale schaal zoals een woonwijk zijn er andere problemen: stroomkwaliteit kan verslechteren door over-voltage of overbelasting. Te hoge VRES generatie kan leiden tot over-voltage als er veel generatie is maar weinig vraag zoals in de zomer gebeurt. In de winter is de vraag hoog, de piekvraag wordt steeds hoger door elektrificatie van toepassingen waarvan de meest zorgwekkende het laden van elektrische auto's (EV) is. Een te hoge energievraag kan resulteren in overbelasting van de infrastructuur wat de stroomkwaliteit doet verslechteren. Beide oorzaken van lage stroomkwaliteit zijn de verantwoordelijkheid van de netbeheerder, deze voorkomt problemen door het net te over dimensioneren voor een realistisch haalbaar slechtste geval dat kan voorkomen gedurende de levensduur van het net. Als resultaat werkt het net vrijwel continue verre van de limieten. Het achteraf verzwaren van de infrastructuur is zeer kostbaar.

Elektrische Energie Opslag (EES) kan worden gezien als een hybride vorm van energiegeneratie en consumptie. Het kan worden ge-/ontladen om de meeste energie netwerk functies uit te kunnen voeren. Peak-shaving is het concept dat gebruikt wordt om het net te ondersteunen, extremen gevallen van productie of consumptie worden afgevlakt om problemen te voorkomen. Overbelasting van het net bij piekvraag kan worden opgelost door EES te ontladen en zo lokaal het net te ontlasten. Uiteraard dient EES geladen te zijn om deze functie uit te oefenen wat gedaan kan worden ten tijde van lage vraag. Omgekeerd als over-voltage plaatsvindt kan dit worden verholpen door gegenereerde energie op te slaan terwijl de energievraag minimaal is. Zodra dan de vraag groter is dan productie kan de opgeslagen energie terug geleverd worden. Slimme netten met EES kunnen energie stromen beheren en de stroomkwaliteit bewaken terwijl operationele en generatiekosten lager worden. Kleine onderdelen van het net kunnen als los eiland opereren, deze Duurzame Energie Micronetten (SEM) kunnen gedeeltelijk zelfstandig opereren van het hoofdnet.

Energiegebruik in woningen verandert door meer VRES en elektrificatie van toepassingen. Traditionele Nederlandse woningen worden verwarmd door middel van gas. Elektrische warmtepompen worden echter steeds gebruikelijker en zijn efficiënter. Dit resulteert in volledige elektrische wijken en toenemende elektrische energievraag. Elektrische fietsen en EV's zorgen voor een toename in de elektrische energievraag voor transport welke in de wijk moet worden voorzien. In 2025 worden één miljoen EV's verwacht op de Nederlandse wegen. De VRES generatie capaciteit in Nederland is erg laag, er is slechts 1GW geïnstalleerd. In 2025 wordt tussen de 9 en 10GW geïnstalleerde capaciteit verwacht.

Een model is gemaakt om het opereren van het net te simuleren, trends uit 2025 kunnen getoetst worden. Het model berekent energiestromen aan de hand van energievragen, kan extra energieproductie toevoegen of EV vraag toevoegen. Het model is in NetLogo gemaakt op de tijdsschaal van een kwartier, GIS wordt gebruikt om de gebouwomtrek te tekenen en om het net te genereren. CSV bestanden worden gebruikt om de energievragen te importeren. Voltages resulterend uit de energievraag en generatiepatronen worden gemonitord per woning. Overschrijdingen van de limieten worden gebruikt om een objectieve prestatie van het net te bepalen. De prestatie functie wordt gebruikt om de ernst van slechte stroomkwaliteit te bepalen. Een lithiumbatterij en een kleine en grote flow batterij zijn toegepast.

Simulaties laten zien dat er een ruimtelijke relatie is tussen de plaatsing van PV systemen en de prestaties van het net. Een hoge dichtheid van PV systemen in een uiteinde van een net zorgt voor de minst goede prestaties. Piekvraag zorgt voor het overbelasten van het net en hierbij is er geen relatie gevonden tussen plaatsing van de extra vraag en afname in prestaties. EES is succesvol gebruikt om de prestaties te herstellen. Terwijl meer batterijen geplaatst worden in alle gevallen de prestaties verbeterd maar in hoeverre is sterk afhankelijk van de combinatie van batterijtype, batterijlogica en plaatsing relatief aan de generatie systemen. De prestaties herstellen in een geval met hoge PV generatie werkt het best als EES geplaatst wordt in dezelfde uiteindes van het net waarin de problemen optreden. Het herstellen van de prestaties in geval van overbelasting is ook mogelijk met EES maar de plaatsing heeft geen invloed op de prestatieverbetering. Bovenal is gevonden dat de batterijlogica de grootste invloed heeft op de prestatieverbetering met EES. Er zijn drie logica getest en alle hebben een voordeel in bepaalde combinaties van batterijtype en scenario en dus moet per situatie de logica worden gekalibreerd.

Er is gebleken dat EES de prestaties kan verbeteren in het geval van slechte voltagekwaliteit en overbelasting. Door toepassing van EES wordt het net efficiënter gebruikt. Het toepassen van energie opslag voor stroomkwaliteit bewaking is zeer interessant en experimenteel bewezen. Er zijn van de consumenten geen veranderingen in gedrag nodig. EES biedt flexibiliteit aan het net die gebruikt kan worden om de variabele beschikbaarheid van stroom toe te staan. Een alternatief voor EES is vraagmanagement door middel van slimme apparaten met slimme start of slim laden van EV's dat voorkomt dat het net overbelast wordt. Een slim net heeft dan ook zowel opslag als vraagmanagement om maximale flexibiliteit te kunnen bieden. Traditionele infrastructuur zoals in deze case onderzocht kost rond de € 60.000 terwijl de EES configuratie nog meer kost dan dat en dus een dure toevoeging is. Dalende prijzen moeten zorgen voor een meer economische zinvollere investering, hopelijk voor de noodzaak hiertoe aanleiding vormt want het toepassen van EES biedt vele maatschappelijke voordelen zoals het toestaan van meer PV generatie zonder toenemende koolstofemissie.

VI. Abstract

Electrification of appliances and increased decentralized Variable Renewable Energy Systems (VRES) generation strain power supply grids and can result in power quality issues. Excessive photovoltaics (PV) generation capacity can cause overvoltage in summer when demand is low. In winter when peak demand is high due to electrification and in particular due to electric vehicle charging the infrastructure is overloaded. A model was made to assess the severity of these performance issues using simulations which were then resolved by the means of electrical energy storage (EES). It was found that the overvoltage related power quality decline was related to placement of PV systems within extremities in the neighbourhood' grid, restoring power quality was best done by placement of EES in the same extremities of the grid in which the problems occur. No spatial component was found in the winter overloading situation and here placement of EES was not critical to restoring power quality.

Keywords: *Energy storage, Smart grid, Power quality, PV, Neighbourhood, NetLogo, GIS*

1

Heading for an energy revolution

This chapter provides a contextual approach to the relevance of the problem. There is an energy transition ongoing and we need to be technologically prepared for the challenges that might result from it. Besides technological challenges there are societal benefits to the energy transition, namely reducing our dependence on the limited resources of fossil fuels while decreasing emissions. A sustainable energy supply system would be ideal to achieve but there are problems in transitioning and there are investment risks. The complications are discussed to motivate the topic of this research. Research questions are proposed and consecutively methodology is given to answer these questions.

1.1 Introduction

Urbanization is ever increasing and it is estimated that by 2050 around 85% of the world's population will live in cities which are larger owing to technological advancements (Caragliu, Del Bo, & Nijkamp, 2011). Cities need to become smart to be able to efficiently handle its inhabitants, their activities and most importantly the energy flows required to sustain those people and activities. Currently our society greatly depends on non-renewable fossil fuels for our energy supplies (Foidart, Oliver-Solá, Gasol, Gabarrell, & Rieradevall, 2010) and the finite limits of their production capacity may pose a severe risk to the high quality life style we are used to. Access to affordable energy is what thrives our civilisation, thanks to energy availability the world is smaller than ever. Cars and trucks are part of the landscape and thanks to many transportation methods goods and people can travel the whole world within a day.

Every revolution in terms of development can be attributed to the ability to harness a new energy source which allows rapid growth in energy demand which in turn enables an increase in productivity. The industrial revolution in which the steam engine allowed factories to be more productive was not just a mechanical innovation, the machine allowed harnessing the abundantly available energy source of coal resulting in an economic growth spurt. All energy sources can be considered renewable. Coal is naturally occurring due to geological events in which biomass is converted - albeit at a very slow rate. Using an energy source past its natural production rate effectively turns the energy source into a finite source which can be depleted. Resulting energy shortage may result in increased prices or limit availability of energy, both hampering economic growth.

Our latest economic growth spurt was thanks to fossil fuels. Oil is a very compact and potent energy source attributed to high energy density and low specific mass. Having access to plenty of energy at low prices enables economic growth. Increasing energy prices will in turn result in reduced economic growth. Behind the scenes of the companies responsible for the world's largest energy supplies, namely the oil and natural gas producing companies, there may be trouble maintaining ample energy supply. The concept of Peak Oil may seem to be upon us, the depletion of our reliable and affordable energy source oil is probable and with it a reduced availability and increase in prices (Okullo, Reynès, & Hofkes, 2015).

As a result of energy price volatility and ever increasing energy performance requirements there is a lot of interest in decentralized energy production. This results in a strain on grids due to the variability of production which leads to the necessity of smart infrastructure which can handle such ongoing developments. *"Today, the smart city is a red-hot topic on the urban strategy agendas of governments worldwide. This is especially so in the advanced countries, where fast-paced urban growth has thrown open the door to a mounting number of complex infrastructural and social issues."* (NEC Corporation, 2014)

Our modern way of life depends on the availability of plentiful energy and now would be the time to start a new energy revolution before energy supplies could cause economic standstill and potential welfare deterioration. Besides energy dependence there is an increasing awareness on the topic of global warming. To stop global warming and indirectly conserve oil there are

CO_2 or carbon emission reduction targets which governments are finding hard to conform to. Renewable energy generation is required to achieve these targets and there are many other innovations ongoing in the EU to reduce carbon emissions. Achieving carbon emission reduction targets requires many innovations, especially in the Netherlands where the share of renewable energy generation is very small there is room for improvement. Only 1GW of Photo Voltaic (PV) generation capacity is installed out of the total generation capacity of 30 GW (Centraal Bureau voor de Statistiek, 2014). Fortunately the Dutch electricity supply grid is one of the most reliable and robust in the world and it is able to handle the introduction of new systems like PV very well until now and in the direct future (ECN, Energie-Nederland, & Netbeheer, 2014).

As a society we should move away from energy sources that are unreliable and feature volatile prices. Moving to renewable energy generation removes dependence on geopolitics and lowers energy prices and would most probably result in accelerated economic growth (Carley, Lawrence, Brown, Nourafshan, & Benami, 2011). Lower energy prices open the door to the next industrial revolution and a sustainable living climate without pollution and slow down global warming. To get to a sustainable future there are many hurdles to be overcome, renewable generation is variable by nature and our current power supply system is not able to handle such fluctuations which brings forth the problem definition.

The role of smart grids with EES and decentralized energy generation needs to be further investigated to advise project developers, contractors, network operators and governments how to design the smart cities of the future. Advise on EES for smart grids needs to consider quantitative factors like investment and operational costs besides qualitative factors and societal benefits like increased number of potential VRES systems and decrease in fossil fuelled energy generation dependence.

"We think storage will be absolutely necessary to enable the deployment of solar across the grid at extremely high penetrations." said Eric Carlson, lead architect of energy systems at SolarCity, speaking about the company's experience with its first 100 installations of residential energy storage systems. Ibrahim et al. (2008): *"There is obviously a cost associated to storing energy, but we have seen that, in many cases, storage is already cost effective."* Given that this conclusion was drawn eight years ago and the rate at which storage is decreasing in price this statement should become more true as time passes. This research is therefore conducted to determine the profitability of EES in a neighbourhood while allowing increased renewable generation.

1.2 Problem definition

Introducing decentralized Variable Renewable Energy Systems (VRES) into the grid can cause difficulties which need to be carefully managed to maintain a high quality power supply system and ensure a reliable power system. Besides high VRES integration the electrification of appliances is causing new loads and peak loads may exceed infrastructural limitations. Two mayor issues arise in urban environments with high PV penetration (Barton & Infield, 2004;

Beaudin, Zareipour, Schellenberg, & Rosehart, 2015; Marra & Yang, 2015; Pahwa, Hodges, Scoglio, & Wood, 2010; Wade, Taylor, Lang, & Jones, 2010);

1. *Voltage quality deterioration (overvoltage)*
2. *Overloading of transmission infrastructure*

Research by Marra & Yang (2015) already showed the benefits of Electrical Energy Storage (EES) for voltage control in neighbourhoods that were not designed with PV integration in mind. While it may be obvious to use EES as a means to reduce peak loads via peak-shaving the most benefit will be made from the combination of multiple functions into one EES system which has not been investigated on a neighbourhood scale yet. Keeping in mind that reinforcing underground infrastructure like the grid is very costly, there is a large overcapacity present of which a realistic worst-case scenario dictates the dimensions.

1.3 Research questions

The research objective is to develop a model to simulate electrical energy supply systems and to develop a method to find the optimal configuration of storage devices to maintain power quality. This leads to the main research question:

" Which Electric Energy Storage method is most suitable for application within the scale of a neighbourhood for voltage control and peak shaving? "

The following questions are used as intermediate steps to answering the main research question:

1. What is the relation between Smart Cities, Smart Grids and EES?
2. How do power supply systems operate?
    a. What is the relation between decentralized variable renewable energy generation and power quality?
    b. What is the relation between decentralized variable renewable energy generation and network operation costs?
3. What are the possible electric energy storage methods within the urban environment of a neighbourhood or dwelling?
    a. What are the strengths and weaknesses of these storage methods?
    b. What boundary conditions do these storage methods impose?
4. Which financial-economic and social-demographic trends can be identified?
    a. What future scenarios can be expected based on these trends?
5. Can EES be applied for the functions of voltage control and peak-shaving?
6. What configuration of EES systems is optimal for the functions of voltage control and peak shaving in the case of Hoog Dalem?

1.4 Research design

A combination of literature review and model simulations will be used to develop answers to the research questions as visualized in Figure 1. Literature reviews are done on research questions 1 through 5 and on the basis of the results from these reviews a model will be constructed to simulate the operations of a low voltage grid as found in a neighbourhood. The model is designed so it can contain any type of project by the use of GIS and through it a visual representation can be made. NetLogo is chosen to use as a basis for multiple reasons:

- It allows spatial data in- and output for accurate case studying through GIS data
- It has the ability to import lists of data through CSV files
- It allows addition of behavioural models (for future purposes)

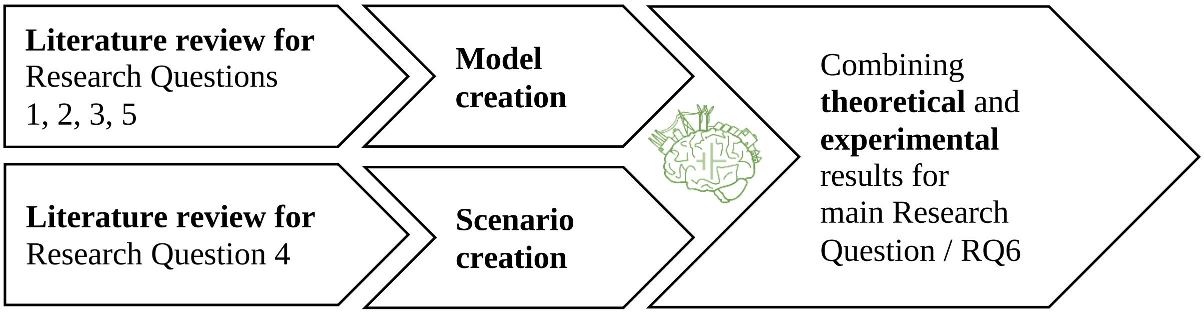

FIGURE 1: RESEARCH DESIGN

As seen in Figure 2 the NetLogo model will have GIS and CSV data as inputs, there is also an input consisting of a variable number of PV systems or EV's. As output there are performance variables to quantify overvoltage and overloading severity. Besides performance variables there will be demand monitors to assess holistic cause and effect relations. Multiple energy storage systems will be available to add to the simulation to assess their performance improving capabilities. Similarly additional generation capacity and loads can be added to the simulation to assess their power quality affecting effects.

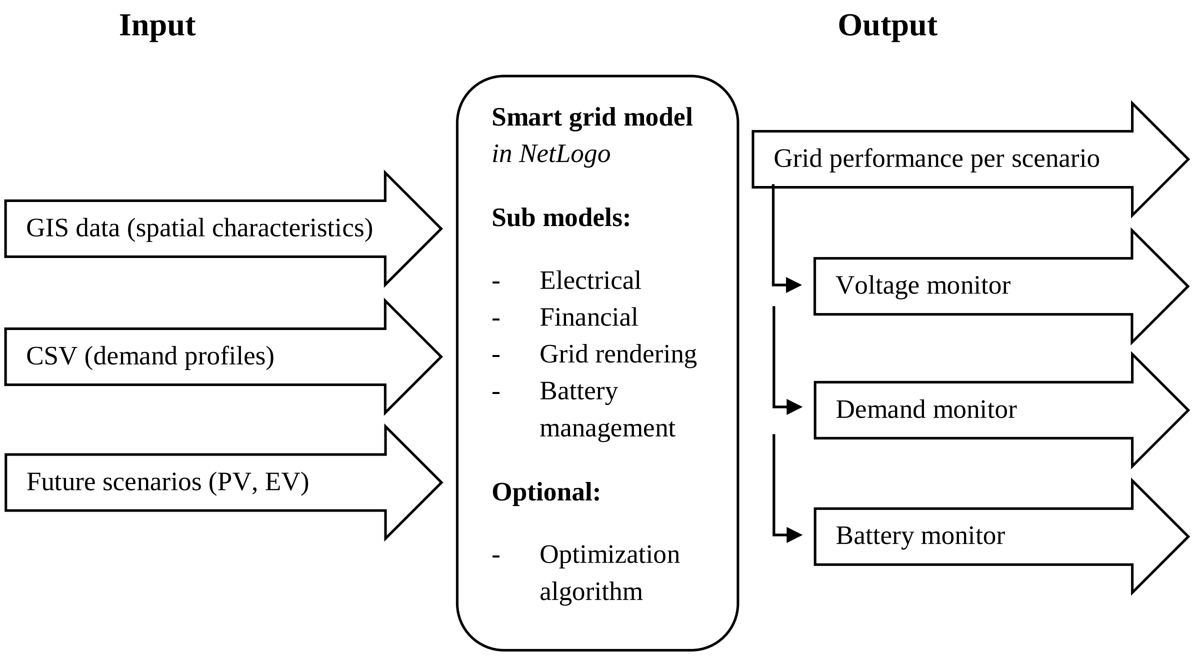

FIGURE 2: MODEL DESIGN

Since the problem is complex and involves many possible storage configurations there may be a necessity for an automated optimization algorithm. For this kind of configurational optimization the Simulated Annealing process is chosen since it allows small optimizations to find local optima while also allowing adverse changes to escape local optima. The optimization algorithm should only be used when researchers are unable to find the optimal storage configuration manually since automated optimizations require much computational power and extended computation time.

1.5 Expected results

The model will provide insight into the location and causes of power quality issues in the low voltage grid caused by the addition of excess generation capacity or increased peak demand. Then by experimentally applying EES the effects on restoring performance can be observed which should lead to insights in how to best configure storage devices in a smart grid. Costs of each solution should offer additional benefits, they could help to forecast operational costs of the grid and can give an indication of the investment costs.

2

Glossary

This chapter provides an overview of terms and abbreviations among with a description.

Miscellaneous terms	
Term	**Description**
CSV (Comma Separated Values)	A file type that holds values separated by comma's which can be used to store plain text tables
GIS (Geographical Information System)	A term to describe software aided geographical information systems and files
NetLogo	A software tool that uses agents and a 2d world consisting of patches to run complex simulations
Ʈ	Translated to English from original language

Model and results related	
Term	**Description**
Baseline scenario	As a benchmark the current operations of the case are used, these scenarios are called the base-line scenario. On top of this scenario additional loads or generators are added to create new scenarios.
Performance	This term is used in the model and results often. Performance is used to assess the severity of power quality issues and a perfect performance is 0, good performance will be represented by a low number and the worse the performance is the higher the number will be.
Power quality	The grid needs to comply to certain technical restrictions of which voltage is one. If the technical restrictions are met there is a good power quality and the performance of the grid is good. As technical restrictions are violated the power quality will deteriorate and the grid's performance will become poor.

Energy trends related terms	
Term	**Description**
Autarkic	Self-sufficient. A dwelling can be energetically autarkic needing no external power supply
Electrification	A trend in (residential) energy consumption is that appliances are becoming more electrically powered
EV (Electric Vehicle)	A vehicle (car) that uses an electric engine for its propulsion, typically it will get its energy from a battery
Grid	A power supply system, it consists of cables, transformers, generation and consumers
PV (Photo Voltaic)	A device that generates electrical energy from solar radiation

SEM (Sustainable Energy Microsystem)	Part of the electrical supply system which is able to function (semi) independently from the rest of the supply system. Does so using smart grids with energy storage.
Smart grid	The grid supplies electrical energy to consumers. Using ICT this system is made smarter as to function more efficient and reliable
Standing reserves	Generators that operate below their optimum so they can respond to fluctuations in energy production at the cost of lowered efficiency
VRES (Variable Renewable Energy System)	A system that generates energy from a renewable source and can only be deployed when conditions allow it resulting in a varying generation capacity

Energy storage related terms	
Term	**Description**
BESS (secondary Battery Energy Storage Systems)	A type of energy storage that uses electro-chemical processes
CAES (Compressed Air Energy storage)	A type of energy storage that stores energy by compressing air
DLC (Double Layer Capacitor)	A type of energy storage that stores energy by creating an electric field in a dielectric
EES (Electrical Energy Storage)	An appliance to store electrical energy with, mostly revered to as a battery
FBES (Flow Battery Energy Storage)	A type of energy storage that uses electro-chemical processes and a flowing storage medium
FC-HES (Fuel Cell Hydrogen Energy Storage)	A type of energy storage that chemically stores energy in the form of hydrogen and uses a fuel cell to recover electric energy
FES (Flywheel Energy Storage)	A type of energy storage that stores energy by creating rotational inertia in a mass
NGS (Natural Gas Storage)	A type of energy storage that chemically stores energy in the form of natural gas which can be used to recover thermal energy
PHS (Pumped Hydro Storage)	An electro-mechanical type of energy storage device which uses water at an elevation to store energy in the form of potential gravitational force
SMES (Superconducting Magnetic Energy Storage)	An type of energy storage that stores energy in a magnetic field in a superconductor
TES (Thermal Energy Storage)	A type of energy storage that stores latent heat

Electrical engineering related terms	
Term	**Description**
A (Ampere)	A measure of electric flow
AC (Alternating Current)	Alternating current occurs when charge carriers in a conductor periodically reverse their direction of movement

DC (Direct Current)	Direct current is the unidirectional flow of electric charge carriers in a conductor
GW (Giga Watt)	1E9 Watt
kW (Kilo Watt)	1E3 Watt
kWh (Kilo Watt hour)	Amount of energy; 1 kWh for an appliance of 1000 W ran for one hour or a 50 W appliance for 20 hours.
kWp (Kilo Watt peak)	A measure of peak generation capacity of a PV panel in kW
MW (Mega Watt)	1E6 Watt
TW (Terra Watt)	1E12 Watt
V (Voltage)	A measure of electric potential
W (Watt)	Measure of electric power

Financial related terms	
Term	**Description**
CAPEX (Capital Expenses)	Expenses related to acquiring a system
Economic viability	The financial performance quality describing the ability of a business case to result in a profit
LCOS (Levelized Costs Of Storage)	A financial performance figure to reflect the total costs of ownership per kWh of storage
OPEX (Operational Expenses)	Expenses related to operating a system
Profitability	A financial performance quality to describe how economical viable a business case is
TCO (Total Costs of Ownership)	Total costs of a system during the lifetime of the system, it is the sum of CAPEX and OPEX

3

Energy supply systems

In this chapter energy supply systems, also known as power supply grids or in short grids are studied in literature. Dutch grids are very reliable, robust and stable but there are many trends that may disturb the power quality: electrification of appliances like heating and transportation results in increased peak-demands and PV panels are added to dwellings to generate electricity which can turn neighbourhoods from consuming into energy producing. The architecture of traditional grids are discussed which consist of energy production, transportation and consumption agents. There is an energy transition ongoing which strains the traditional grids calling for smart grids and as a result electrical energy storage comes into the picture as a means to reduce generation costs, reduce network operation costs and to allow a larger amount of decentralized variable renewable energy generation systems.

3.1 Smart grids and energy

Smart cities are an appealing concept but energy is undeniably a more urgent topic to consider since 75% of the world's energy production is consumed in cities (Lazaroiu & Roscia, 2012). There is however a way to utilize smart cities to improve the efficiency in which energy is used and with that reduce energy demand, costs and dependence on fossil fuels. Many smart city concepts exists in literature, a short literature study on these is available in Appendix 8.1. Contained within smart cities are in any case smart grids which offer opportunities for optimizing energy supply systems.

Brenna et al. (2012) considers the energy systems in a smart city separately from the overall infrastructure. It is recognized that decentralized energy production is gaining popularity and with it the network stability is at stake due to fluctuating power generation of renewables. Then the design of a Sustainable Energy Microsystem (SEM) which integrates currently independent energy subsystems into one and allows them to work together in a smart way can yield a more stable and efficient energy system. The design of these SEM's yields energy islands or micro-grids which can operate mostly independent from the grid. These islands tethered together constitute the future smart grids and are essential to integrate intermittent renewable energy production. Islanding of the grid can be used to mitigate cascading failures (Pahwa et al., 2010).

The UK Smart grid Forum (Ofgem, Department of Energy and Climate Change, & Smart Grid Forum, 2014) combines these statements in a smart grid vision that embodies a sustainable power supply system: *A smart electricity grid that develops to support an efficient, timely transition to a low carbon economy to help the UK meet its carbon reduction targets, ensure energy security and wider energy goals while minimising costs to consumers. In modernising our energy system, the smart grid will underpin flexible, efficient networks and create jobs, innovation and growth to 2020 and beyond. It will empower and incentivise consumers to manage their demand, adopt new technologies and minimise costs to their benefit and that of the electricity system as a whole.*

EES systems are both generators and consumers if you will, when either charging or discharging stored energy to or from the grid. To further comprehend smart grids a review of the current power grid is done and with that knowledge in section 3.4 the role of energy storage will be discussed as a part of smart grids.

3.2 Operation of the power supply grid

Power quality is a very important aspect of the power grid and a pinnacle of the Dutch and other first world countries' grids. Power quality is determined by the compliance of frequency and voltage to specifications. Mismatch between supply and demand results in over or under frequency while decentralized power generation in lower voltage grids will locally increases voltage and can cause power quality issues (Marra & Yang, 2015). Power generation is traditionally done centralized and far from where it is consumed (Ibrahim et al., 2008; IEC, 2009), grids are laid out to best support this top down power delivery concept.

This brings a first topological issue, a part of the grid may develop itself to operate close to its designed limits; for instance when a region's power consumption develops beyond a certain threshold. In the event of grid congestion, power is routed through secondary transmission lines at the cost of increased transmission losses or in a more extreme situation a black out will occur when power supplies are halted to prevent propagation of the problem trough the network, known as the cascading effect (Pahwa et al., 2010). Research by Kakigano (2008) found that a DC grid, instead of AC, would be more reliable and less prone to cascading failures, also the integration of DC generation and storage would be more easily done and require fewer conversion between AC and DC benefiting from lower conversion losses.

Congestion in power supplies occurs only at peak demand times or when faults are present, preventing congestion is necessary to maintain a reliable and stable power supply (IEC, 2009). Over-dimensioning of transmission lines is therefore necessary to maintain a stable network, however a larger capacity brings forth larger investment and maintenance costs let alone the unexpected cost of upgrading sections of the grid afterwards. At off-peak hours there is an even larger over-dimensioning situation present which means the costs of the grid infrastructure are determined by a realistic worst case scenario peak demand which is amplified by the annually increasing peak demand (IEC, 2009). Increasing transmission capacity is very costly and a lot of care is taken to make sure transmission lines are able to sustain the growth in power demands for the foreseeable future. If however the grid needs reinforcement there are alternatives like investing in EES (see section 3.5.2) or smartening the grid in other ways like for instance can be done through demand management.

The second concern in the current grid is demand matching. Given there is ample grid capacity there still is a need for a close match in demand and supply in order to maintain stability (IEC, 2009). Any imbalance between supply and demand will cause quality deterioration (overvoltage (Marra & Yang, 2015)) and instability of the grid. Both supply and demand can equally influence the grid stability. Demand forecasting is quite predictable thanks to statistical data from which load profiles are determined. Typical power generation is done by either a thermal plants using fossil fuels or additionally with Pumped Hydro Storage (PHS). Their reservoirs can both be considered energy storage devices which hold fossil fuels or water. Globally there is a total of 90GW of PHS capacity which only accounts for 2.6% of the global energy production capacity of 3400GW (Ibrahim et al., 2008). Dispatching of energy generators is done on a marginal costs basis or Merit Order Dispatch logic (Enzyklopädie, 2015) and is scheduled to follow demand profiles and during times of peak demand the more costly generators are required to maintain ample power supply. Out of the yearly domestic energy production 80% is generated from fossil fuels, coal and natural gas are the most important sources. This resulted in a yearly natural gas demand for electricity production of 107,5 billion m^3 and 51.2 billion kg of coal in 2013. (ECN et al., 2014)

Renewable energy generation is typically intermittent by nature and does not generate energy demand driven (Marra & Yang, 2015). Introduction of VRES to the grid means energy generation now contains an uncertainty which can also be considered as an offset to the demand.

Fluctuations are compensated by standing reserves; generators that operate below their optimum so they can respond to fluctuations in energy produciton at the cost of lowered efficiency (IEC, 2009) and with that the adverse effect of CO_2 emissions and fossil fuel consumption in order to maintain power quality. There is however a limit to how quickly these standing reserves can ramp or respond to follow fluctuations. Forecasting the nominal power generated in the grid by VRES is complex and depends on weather conditions like solar irradiation, cloud coverage, wind speed and obstacles, let alone the unpredictability of variations in all these factors. Employing a larger area for VRES generation decreases the uncertainty which results in only 3% variation on a 2400MW wind farm while a 5MW wind farm varies as much as 12% (Beaudin et al., 2015). This means the standing reserves are relatively small when incorporating a larger portfolio of VRES generation and reduces fossil fuel consumption and greenhouse gas emissions. Alternatively to standing reserves in the form of thermal plants EES can be applied to mitigate short term fluctuations as discussed further in section 3.5.1.

PV is highly suited for urban applications because of its silent operation and moderately low profile visual appearance, the generation pattern matches the domestic energy demand quite well. Both domestic demand and PV production are highest during the day and lowest during the night, relieving the higher voltage grids and reducing transmissions losses. However power quality is adversely affected by decentralized VRES in low voltage grids, especially between 12 and 2 when there is peak production of PV. Marra (2015): *"All domestic appliances are designed to operate according to the power-quality standard EN 50160. This standard states that 95% of the 10-minute average values of the supply voltage should be within the rand +-10% of the nominal mean value of the supply voltage, which for a European network is 400V AC or 230V considering only a phase-to-ground voltage."* To ensure compliance in voltage levels there is an Automatic Voltage Control (AVC) system in the grid which malfunctions slightly in the case of distributed (decentralized) generation of energy, the voltage of the feeder output will increase which means the AVC thinks there is less power consumption, this was not taken into account in AVC systems. Feeder power from other feeders are to be used to dictate the AVC voltage more accurately (Wade et al., 2010).

Putting together all factors that constitute the energy grid and its future fate is done beautifully by Wade et al. (2010): *"Electricity distribution networks have entered a period of considerable change, driven by several interconnected factors; aging network assets, installation of distributed generators, carbon reduction targets, regulatory incentives, and the availability of new technologies. In this climate, the use of distributed storage has re-emerged as an area of considerable interest. The end of this period of transition will be signalled by the successful establishment of the technology and practices that must go together to create what is termed the smart grid."* Adding to this statement there are large investments that need to be made to solve the problems that are foretold, these large investments are made for 30 to 50 years and because of the current uncertainty in legislation changes the investments are put off or put in safe investments like grid reinforcements or cheap solutions like coal fired thermal generation plants at the costs of increased emissions. It may be known how the smart grids of the future are laid out but the implementation roadmap of the required innovations is unknown, complex and for now governed by uncertainty. Innovation of grids are required since renewable energy generation integration is growing, especially PV is expected to develop rather quickly (Marra & Yang, 2015), this fuels the necessity of smart grids and energy storage. The current capacity of PV in Germany is 35 GW (of which 13 GW is in low voltage grids), 18 GW in Italy, while the Netherlands are far behind at 1 GW (van Sark & de Rijk, 2014). Only 0.14% of the Dutch energy demand is produced from PV (Centraal Bureau voor de Statistiek, 2014) by non-utilities like owners of dwellings and offices, in other words decentralized.

Demand responses and smart appliances are also part of the solution of supply and demand matching. There is an inherent flexibility in the energy demand of many functions, like dishwashers are most of the time turned on between 7 and 10 in the evening while they could work somewhere during the night when there is a surplus of energy available. Smart grids offer these smart response systems to reduce generation costs and lower network costs due to peak shaving. (Ofgem et al., 2014)

3.3 Trends in residential energy consumption

There used to be an upward trend in energy demand per dwelling. Lately this growth is stagnant or even a small decline can be observed. The average family size is decreasing and the amount of living space per person is increasing. Residential energy demand is composed of appliances and building related energy usage. Electrification of these both aspects results in a shift from gas energy to electrical energy resulting in an increased electrical demand, at the same time appliances and buildings thermal shells are becoming more energy efficient leading to a decrease in energy demand. The combination of these effects results in a decreased gas demand and a stable electricity demand. Energy costs in the Netherlands are also in motion, due to changes in taxes and transportation fees gas prices are going up while electricity prices are going down resulting in a higher energy bill for most consumers. (ECN et al., 2014)

Electrification of appliances is happing in many places and is driven by convenience and an energy savings mentality. People are becoming more energy conscious and smartening of appliances and meters (smart meters) result in insights into the consumption patterns. Heating demand of dwellings is getting fulfilled by electrically operated heat pumps which are much more efficient than their gas powered counterparts but add to the electricity demand. Cooking appliances like stoves and ovens are electrified. Bikes which used to be man powered are now electrically assisted, these so called E-bikes are gaining a lot of popularity and result in a new energy demanding appliance. The foremost appliance that is getting electrified is the personal transportation. Besides the E-bikes, cars are now electrified and fully electric vehicles come with a huge electrical demand which used to be collected from an exterior fuelling station resulting in new and huge energy flows into neighbourhoods. By the year 2025 there are one million EV's expected to be driving on the Dutch roads (RVO, 2015). These new energy demands may coincide and are expected to most likely overload the infrastructure which is why network operators are working on smart charging protocols.

Dwellings used to be exclusively energy consuming but lately dwellings are becoming equipped with their own generation systems. Decentralized Variable Renewable Energy Systems (VRES) offer energy generation to dwellings, a logical step to reduce energy bills. Photo Voltaic (PV) generation is the most common application of VRES on the neighbourhood scale and are retrofitted to some houses or even part of the energy demand reducing features of a newly built dwelling. PV generation in the Netherlands is far behind on the developments in the neighbouring countries, only 1 GW of PV capacity is installed but 9 or 10 GW are expected by the year 2025 (van der Lee, 2015). PV systems are popular (Centraal Bureau voor de Statistiek, 2014) since they are economically viable business cases which reduce energy bills thanks to the investment in the generation system. Legislation allows PV owners to supply sur plus generation to the grid and later subtract this generation from the dwellings consumption, effectively using the grid as a perfect battery system for free. This so called net metering law (salderingswet) dictates energy suppliers to maintain equal prices for buying and selling of energy. Net metering law is announced to be adversely changed in 2020 at which time all of the sudden investments in PV may not be so viable anymore. Uncertainty caused by the announcement combined with the financial risk and size of the investment cause reluctance in people to invest in PV today. There are already exceptions made to the announced deterioration of the net metering law, tenants of rental dwellings are allowed net metering. Even though there is this large uncertainty in the legislation from 2020 and on there is still a huge growth in PV generation capacity expected which could stress the grid, network operators are tasked to prevent problems to occur.

3.4 EES: Electrical Energy Storage

Electrical energy storage has been used since at least 1870 in the form of hydroelectric power stations (Bowers, 1982 as quoted in Wade, 2010). Electricity is to be used instantaneous or if energy storage is required over a reasonably long time frame it needs to be converted into a different form of energy (Ibrahim et al., 2008). In Table 1 a concise overview of energy storage forms and the most important applications which employ them is shown (Ibrahim et al., 2008; IEC, 2009; Nair & Garimella, 2010; Stedin, 2014). Liquid and solid energy sources like petrol and coal can conveniently be stored in containers without discernible losses, however generated electrical energy can’t just be “poured” into a container for storage purposes. The closest analogy to an electricity container are a (super) capacitor and super conductive magnetic energy storage (SMES) device but these storage types requires large volumes (low volumetric energy density) and self-discharges rather quickly while also requiring substantial investments.

When there is then a demand for stored energy it is to be converted to electric energy, depending on the storage method this is either readily done or requires a complex conversion process. Electrical storage doesn’t require any conversion and uses electrical or magnetic fields to store energy, this storage type typically has an extremely short response time. Mechanical storage uses potential energy from kinetic or gravitational sources stored in a mass, here the conversion in both ways is rather straightforward using pumps or motors. Electrochemical storage or battery storage is also straightforward, and works by inducing a reversible chemical reaction triggered by charging or discharging the battery by adding a load or a power source. Chemical and thermal energy are very complicated in their conversion to electricity; hydrogen or biogas can be produced using electrical processes but harvesting them back to acquire electricity requires a wholly different procedure either through combustion in a thermal plant or conversion in a fuel cell. Thermal storage can easily be done using small/medium scale resistive heating but low grade heat that is produced can't efficiently be transformed to electricity on a non-industrial scale, only heat pumps can be efficiently used for energy recovery but do so in the form of heat. Taking into account the conversion complexity that thermal and chemical storage methods comprise they are disregarded for small-medium scale electricity storage.

TABLE 1: ENERGY STORAGE FORMS AND APPLICATIONS

Form of energy storage	**Energy storage applications**
Electrical storage	Double layer capacitors (DLC) or supercapacitors
	Super conducting magnetic energy storage (SMES)
Mechanical storage	Pumped hydro storage (PHS)
	Compressed air energy storage (CAES)
	Flywheel energy storage (FES)
Electrochemical storage	Secondary batteries (BESS)
	Flow batteries (FBES)
Chemical energy storage	Hydrogen fuel cell storage (FC-HES)
	Natural gas storage (NGS)
	Synthetic natural gas (power to gas)
Thermal energy storage (TES)	Latent heat storage using molten salts
	Sensible heat storage

3.5 EES applications

EES can be the key to reducing fossil fuel consumption by enabling the ability to use renewable energy production more efficiently and when needed instead of only when generated. There are three main economic advantages for integrating electrical energy storage into the infrastructure (Ibrahim et al., 2008): Allowing more accurate load profiling by employing energy transfer between peak loads or temporary production losses, network savings can be substantial by using EES to reduce the current over-dimensioning due to fluctuations and huge differences between peak and off-peak demand, the kinetic advantage will make energy delivery response times much faster and therefor result in a more stable and flexible energy network.

EES can then be used to replace existing systems, for example in the following application areas (Wade et al., 2010):

- Voltage control (power quality control)
- Power flow management (congestion prevention)

these are the most important functions for smart LV grids

- Restoration
- Energy market
- Commercial/regulatory (quality control)
- Network management

The latter four functions are not found very often in low voltage grid but can certainly be executed by means of EES systems. Therefore having an EES configuration in place for the first two functions means that it can be used to enable the other less common functions in times where storage is not needed to maintain power quality in the low voltage grid. Combining multiple functions into one EES system can make it more competitive compared to traditional solutions (Wade et al., 2010). Due to declining capital costs, within 5 years storage is already expected to be competitive for the function of peak-demand generation compared to a gas peaker (Lazard, 2015). As one storage device can create value in a number of ways the combined value of the stacked benefits (as seen in Figure 3) could prove to be more than the levelized costs of storage and a provide a compelling business case. Adding of functions can result in economic gains of a grid connected EES system, for example through participation in the energy market which is known to regularly have extremely low or even negative prices for buying electricity in order to maintain a proper demand and supply match.

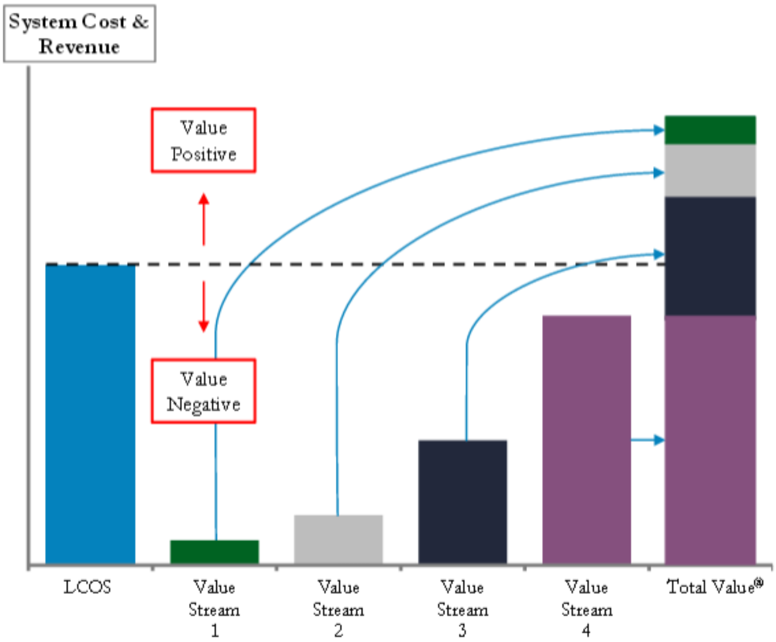

FIGURE 3: STACKED VALUE CONCEPT TO RESULT IN POTENTIALLY PROFITABLE EES SOLUTION TO OVERCOMES LEVELIZED COSTS OF STORAGE (Lazard, 2015)

3.5.1 EES for reducing generation costs

The costs for generating electricity can be greatly reduced, on peak hours the more costly generators are operating. EES can prevent these generators from operating by storing off peak energy for peak demand supply at much lower prices. When intermittent energy is produced (Wind or PV) there are times of cost-free or negatively priced surplus energy, this can be used to charge EES and used to reduce generation costs later. Also, EES can be used to better make use of resources and prevent load shedding (Ibrahim et al., 2008). Instead of fossil fuelled generators which maintain power quality trough flexibility in production and frequency control, an energy storage system can replace both these functions with the potential of less fossil fuel consumption, PHS and batteries are already used for such functions (IEC, 2009). Finally the ability to store off-peak energy for peak demand unloading can reduce energy prices since peak demand energy generation is the most expensive. Generation becomes less intermittent and operating efficiency will increase (IEC, 2009). When EES is used to optimize generation response by smart charging and discharging a higher quality network and more balanced supply can be obtained, however this operation method is limited by storage and power capacity and should be used in conjunction with other power management systems (Wade et al., 2010).

3.5.2 EES for network savings

EES can be used to propagate congestion situations by storing energy in off-peak hours to relieve congestion during peak demand (Wade et al., 2010), IEC (2009): *"EES established at appropriate sites such as substations at the ends of heavily-loaded lines can mitigate congestion, by storing electricity while transmission lines maintain enough capacity and by using it when lines are not available due to congestion. This approach also helps utilities to postpone or suspend the reinforcement of power networks."* This method to postpone network reinforcement is now proposed in Italy due to a lack of financial resources, proving its value in real life (as heard on the Energy Storage Day on the Vakbeurs Energie, October 7th 2015). Unloading of peaks to relieve the infrastructure in case of residential applications coincides with peak demand and therefore employing EES for this function results in the possibility to combine the function of lowering generation costs as discussed in 3.5.2.

Power quality can be controlled by employing EES to maintain proper voltage and frequency more efficiently than do conventional methods. It was found that in small parts of the grid you can solve voltage problems by adding loads because of the resistance ratio to the power in the wires (Wade et al., 2010). Quote by Wade: *"Operating an ESS embedded in the distribution network has a positive impact on the tasks of voltage control and power flow management."* And benefits from being in between two networks were gained, greater than the sum of benefits of the two separate applications. Vehicle to grid and smart charging can be used for smart use of the network in conjuncture with or alternative to storage. ESS is best if combined with a broader smartening of the network with instrumentation and control equipment and is set to be an integral part of smart grids (Wade et al., 2010).

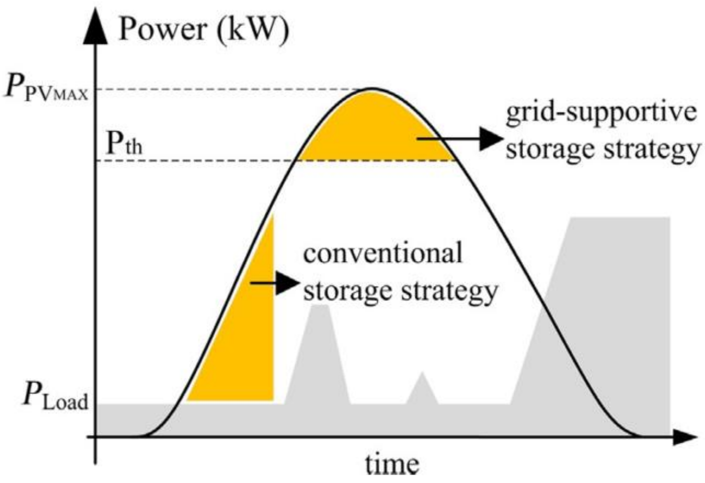

FIGURE 4: GRID SUPPORTIVE BATTERY STORAGE
(MARRA & YANG, 2015)

When decentralized energy generation exceeds the demand in a piece of the grid fed by a certain substation, reverse flow is observed. This is technically not always possible or limited. If reverse flow is possible there is a high change of overloading the higher voltage network. At a later time there is a deficit in energy production in the same grid area and power is drawn from the substation again, EES can then prevent the reverse flow and prevent congestion/overload on the grid connected to the substation while reducing energy losses. Power curtailment, grid reinforcement and reactive power-based options like demand side management are alternatives to the EES solution. (Marra & Yang, 2015; Wade et al., 2010)

PV induced overvoltage in low voltage grids occurs when generation exceeds demand. As PV is further located from the feeder the overvoltage will become larger than a PV system located near to the feeder. Charging of EES on peak production times will function as grid support, charging is triggered when the PV installation exceeds a certain threshold, for instance 70% of peak capacity, and depends on the grid and other PV installations. This concept of charging on peak production to support the grid is shown in Figure 4, as well is the regular storage strategy in which charging starts at the first instance production exceeds demand. Transmission losses can be reduced by as much as 6.6 or 7.3% upon introduction of EES in order to maintain power quality (Marra & Yang, 2015). PV penetration, a fraction of installed PV capacity and feeder capacity is the variable that indicates power quality issues in the grid (Marra & Yang, 2015):

$$PV_{penetration} = \frac{PV_{installed\ capacity}}{feeder\ capacity}$$

3.5.3 EES to allow increased VRES integration

Ibrahim et al. (2008): *"Renewable resources have a major inconvenient: they fluctuate independently from demand."* Renewable energy production is dependent on the weather conditions and therefor Variable Renewable Energy Systems (VRES) introduce fluctuations (Beaudin et al., 2015) in the generation capacity of the network which can result in power quality deterioration or even power outages. To prevent this fossil fuelled generators are operated outside their optimum range to be able to respond to these fluctuations at the cost of lowered efficiency and accompanying increased CO_2 emissions (Beaudin et al., 2015; Black & Strbac, 2007; IEC, 2009). Margins on which fossil fuelled generators operate are increasing to accommodate the increasing variability of the also increasing number of VRES, as a result the efficiency of these thermal generators will decline. The concept known as the kinetic advantage applies EES to mitigate fluctuations so fossil fuelled standing reserves can operate with smaller margins and closer to or at their optimum generating range at higher efficiencies. Especially when distributed VRES operate in the extremities of the grid (the low voltage grid) there may be adverse effects. A close match between supply and demand prevents voltage issues in the extremities of the grid. (Barton & Infield, 2004; Wade et al., 2010).

Short term fluctuations in large wind park production can be managed cost efficiently through EES with batteries (Wade et al., 2010), redox flow cells or fly-wheels (Barton & Infield, 2004). Longer variations are more economically managed through standing reserves or even more so in combination with EES (Black & Strbac, 2007). 24 hour energy storage with energy curtailment can improve wind energy integration into weak grids by a factor of 3 (Barton & Infield, 2004). Concluding remarks on storage to improve VRES integration in the generation mix are in a quote by Ibrahim et al. (2008): *"Storage is the weakest link of the energy domain, but is a key element for the growth of renewable energies. When the energy source is intermittent and located in an isolated area which cannot be connected to the distribution network, storage becomes crucial. This need is not as obvious when the source of energy is connected to the network but storage could become unavoidable in the future."*

3.5.4 EES for dwelling-owners

In the case of a dwelling-owner there are also some benefits. An EES equipped dwelling can be considered semi-autarkic, is less dependent on grid stability and makes the users of the system more aware of their energy consumption patterns and habits. The increased electrification of the energy consumption can be supported by the integration of EES. Integration of EES into the grid can result in lower costs through network savings but additionally integration of EES into a dwelling allows the owner to time-shift energy between high and low prices and doubles as an emergency power supply. Investment costs of EES can be recuperated by incentivizing their owners to support the grid. (IEC, 2009; Wade et al., 2010)

In this day and age dwellings are also becoming energy generators by the aid of PV or small wind turbines, surplus energy can be stored within the confines of the dwelling instead of being sold to the network or withheld until the energy prices are more viable. Storing surplus energy is assessed for profitability in Table 2. When there is no price differential, as there is until 2020 with the net metering legislation, there cannot be made any profit from storing energy. As the price differential increases the net profit per MWh cycled also increases. On the other hand the efficiency of EES reduces the net profit. Taking a 94% roundtrip efficiency which is typical for lithium batteries as an example there is a potential profit of 36 €/MWh. Or if taking the German scenario found in the last column as an example, the net profit will be 128 €/MWh. Taking the 2.4 kWh lithium battery used in the model as an example for the German case requires 417 cycles per MWh and more than 20% of the batteries lifespan. At an investment of € 2500 this results in a € 500 loss of lifetime which is four times more than the net profit of € 128 from storage cycling making lithium batteries too expensive for this purpose. A Blue or HBr battery has a roundtrip efficiency of about 85% so costing more to operate, their more modular design however may very well result in much lower depreciation costs and therefore could in practice prove to be profitable. The same principle of profitability applies to price arbitration, the price differential needs to be large enough to overcome the investment costs or depreciation.

TABLE 2: ASSESSMENT OF PROFITABILITY OF EES FOR IMPROVING PV FINANCIAL PERFORMANCE UNDER VARIOUS ENERGY RATES AND NET METERING SCENARIOS. SHOWN ARE; 5 PERFORMANCES OF STORAGE DEVICES AND 5 ENERGY PRICING SCENARIOS. THE RESULTING NET PROFIT INCLUDES ENERGY LOSSES AND PROFITS FROM AVOIDED LOSSES AND EXCLUDES BATTERY WEAR.

Energy rate (€/kWh)	0,23				0,28
Price differential (€/kWh)	0	0,05	0,12	0,23	0,145
Full cycle efficiency of EES (%)	Net profit per MWh cycled				
100	€ -	€ 50,00	€ 120,00	€ 230,00	€ 145,00
97	€ -6,90	€ 43,10	€ 113,10	€ 223,10	€ 136,60
94	€ -13,80	€ 36,20	€ 106,20	€ 216,20	€ 128,20
90	€ -23,00	€ 27,00	€ 97,00	€ 207,00	€ 117,00
85	€ -34,50	€ 15,50	€ 85,50	€ 195,50	€ 103,00

3.6 Concluding the theoretical research

There is an energy transition ongoing and we need to be technologically prepared for the challenges that result from it. Besides technological challenges there are societal benefits to the energy transition, namely reducing our dependence on the limited resources of fossil fuels while decreasing emissions and reducing energy generation costs. A sustainable energy supply system would be ideal to achieve but the problems of transitioning and the investment risks are too complex to solve theoretically. In the next chapter the model will be constructed and the knowledge gained on the topics of overvoltage and overloading of low voltage grids will be used to design the model.

4

Modelling the smart grid

There may be consensus regarding the design of smart cities but these cities are not built from scratch and develop themselves continuously out of the currently “unsmart” cities. Transitioning to a fully renewable energy supplied city requires extensive changes to the power supply grid leading to the emergence of smart grids. Decentralized renewable energy generation will eventually require substantial voltage quality function deployment and the electrification of appliances causes large peaks in demand that do not coincide with generation patterns of renewables resulting in a demand and supply mismatch. Electrical energy storage is hereby researched as one of the means to balance supply, preventing peaks in demand and safeguard the voltage quality in an urban environment. Only when the power supply grid is able to cope with high levels of renewable energy generation integration there will be a possibility to reduce our dependence on fossil fuels and move to the projected smart cities of the future. In this chapter literature is used as a basis to construct a model to aid the development of future smart grids.

4.1 Introduction

Since the research is carried out in collaboration with a contractor the project scale is regarded since this is the size at which a contractor operates. A recent project will be examined and the potential to transform the neighbourhood to a smart micro-grid will be examined. Storage will be employed to support the grid in safeguarding voltage quality and optimizing the use of the installed infrastructure. As more renewables are integrated into the grid problems arise leading to curtailment and costly investments in traditional grid reinforcements, EES can provide a more efficient and versatile solution but choosing the most economically viable method may be precarious.

This leads to the main issue, innovations may seem technologically interesting but lack economic feasibility. Innovative energy supply systems operations are unknown still and relying on them may prove to require very costly upgrading of the grid if done poorly. Technical benefits are known on an abstract level but monetizing innovations requires investment and introduces additional risk into a project. Contractors can be considered conservative and risk-adverse and innovating require a generous financial performance before allowing risks to be undertaken. Contractors in the Netherlands are struggling in their operations because of marginal returns on projects as a result of the economic crisis in 2008. Heijmans' risk aversion is therefore fully justified but corporations may never stop innovating otherwise risking losing competitive advantages in the future. Betting on an innovation is then a huge risk and without financial means to take multiple bets it is necessary to bet only on safe innovations.

As told by Guido Dalessi from Elestor: *"If it is not profitable, it is not sustainable".* So the question for energy storage is not if it is sustainable but how can it be made into an economically feasible business opportunity? From Wade (2010) and Lazard (2015) it is known that a viable business case is only gained by application of multiple functions of EES in one system, these are at least peak-shaving and voltage quality control in case of this research. Profitability uncertainty is what dissuades stakeholders in energy supply systems to innovate. In the next chapters a model will be constructed to determine the business case conditions on basis of different forecasted scenarios that could prove to occur within 10 years. Additional benefits may be found in time-shifting demands via storage and indirectly by decreasing peak loads the generation costs should decrease. Technical benefits need to be known to all stakeholders that benefit and in this case smartening the grid will decrease generation and grid operation costs while reducing fossil fuel dependence. From these qualitative benefits additional economic value can be obtained, to make a valid proposition comparison these benefits need to be expressed in terms of economic benefits.

In the Heijmans Technology network are some companies that offer interesting EES devices. A lot of support was available during the implementation of these products and their specifications are rather different which should provide some interesting insights. The products from Heijmans' partners are shown in Table 3. Interesting to note is that all three have very different power to storage capacity ratios. While lithium batteries offer a fixed ratio there is the possibility for flow batteries to adjust the ratio at low costs so performance of these devices can be optimized by adjusting the device specifications. Checking possibilities beyond lithium batteries is highly recommended since the availability of raw lithium in the earth's crust is rather limited and not even sufficient to power future lithium demand for EV's (Vikström, Davidsson, & Höök, 2013) while the elements that store energy in the other devices are (far) more abundant.

Battery-type	Storage capacity (kWh)	Power capacity (kW)	Efficiency	Power to storage ratio
Lithium battery by Victron	2.4	0.6 *	0.97	0.25
Salt water flow battery by Blue energy	10	3	0.9	0.3 **
HBr flow battery by Elestor	250	50	0.9	0.2 **

TABLE 3: OVERVIEW OF SPECIFICATIONS OF EES SYSTEMS USED IN MODEL
* LIMITED BY BATTERY MANAGEMENT SOFTWARE ** RATIO CAN INHERENTLY BE ADJUSTED

4.2 Methodology

There are two functions that need to be implemented on a neighbourhood scale. The first one is voltage control, this requires a model on a per dwelling resolution. As described in section 4.3.1 the voltage in the grid will differentiate in each section of the grid caused by electrical resistance in the infrastructure. Resistance in the infrastructure depends on conductor used, dimensions of the material and the length of the connections. Loads then cause voltage differences which are load dependent and vary with demand. Peak shaving can be modelled as an integral model, namely the dwellings or loads per feeder in the infrastructure, the feeder is where if the peaks cause trouble investments in equipment need to be made. If peaks occur and the cables in the infrastructure are insufficient this will lead to overvoltage, the capacity of the cables determines the bandwidth of the infrastructure. Huge costs are related to upgrading the underground infrastructure, this could be necessary when voltage bandwidth proofs to be insufficient.

Dwellings and batteries are operated independently from each other. The demand patterns the dwellings exhibit are a rather complex combination of factors of which the most important are listed here:

- Social factors
  - Working hours of inhabitants
  - Demographic properties of inhabitants (amount, age, sex)
  - Standard of living
- Technical factors
  - Efficiency of appliances
  - Performance of thermal fabric
- External factors
  - Temperature, heating demand

- Irradiance from sun, heating, PV generation

A short understanding of these factors is interesting to discuss. Factors are of influence on the demand of all dwellings. External factors are similar to all dwellings since the neighbourhood is rather small, only the orientation of dwellings differentiates the influence by external factors. Social factors are the largest and least predictable of the factors. In it the behaviour of inhabitants is reflected which when analysed on a per dwelling scale can be considered erratic and unpredictable as can be seen from the consumption patterns of a single dwelling. An aggregation of demand patterns in the neighbourhood improves the predictability by averaging out extremes similar to a portfolio of stocks on the stock market.

Behaviour of each dwelling is independent from the others and mostly depends on social factors. From a technical viewpoint the individual dwelling level is also the most appropriate level. The infrastructure model requires real dimensions and a topological relation to the dwellings. A model is therefore constructed on the basis of NetLogo and its GIS-plugin. This combination allows the incorporation of independent behaviour to be modelled and influenced with the added benefit of real spatial orientation and dimensions of grid and dwellings. It is also great to allow future additions to the model to dynamically determine VRES generation on the basis of a weather model which would make the scenarios more elaborate. User behaviour for dynamic demand patterns could also be conceived. Finally to allow importing demand patterns as lists from external files the CSV-plugin is used.

Battery management in the real project is very straightforward and batteries are either charging, discharging until full/empty/stopped or waiting to do one of the former. Batteries are programmed for the functions of peak shaving and price arbitration or can be externally requested to support the grid. Only the latter function of grid support is interesting for this research but combined with the per dwelling peak shaving it should relieve the grid. External control mechanisms are not known so a solution is devised to allow the batteries to function optimally in most situations. Dwellings feature an efficient small lithium battery pack which is not yet present in the baseline scenarios.

The goal of this research is to determine the optimal configuration of EES. Of course the grid has to conform to some restrictions related to power quality. For this the performance variable Smart Grid Performance will be implemented in the model. For the function of peak shaving the amount of batteries will be most interesting and for voltage control the spatial distribution is also of influence on the performance of the grid.

An optimal configuration of the grid will combine a minimal Total Costs of Ownership (TCO) of the storage devices while ensuring a compliant performance. First the problem areas in the grid are located. Then the performance improvements upon adding batteries will be analysed to understand the potential of the storage devices. The complexity of the model could result in having a very complex solution space, if based on gathered insights no storage configuration can be determined then an automated optimization algorithm will be applied. Automated optimization is done on the basis of the Simulated Annealing algorithm. It allows small optimizations for each of the many variables until a local optimum is found.

4.3 Model design

The model which is constructed will feature various aspects and is constructed in the software package NetLogo. By the aid of GIS the world will be constructed and basically shows a map of the neighbourhood that is being researched. This section will cover a background from literature to support the design decisions made in the model. Implementation in NetLogo are found in addenda 8.3 through 8.10.

4.3.1 Electrical model

From section 3.2 we know the grid consists of generators, transmissions lines and consumers. Grids can then be interpreted as a network of nodes (junctures of transmission lines) connected via links (transmission lines) and connected to the ends of the links are generators and consumers or hybrids of both functions. The electro-dynamical characteristics can be attributed to each link of which the foremost important attribute is reactance of the transmissions lines which can be addressed as weights. (Pahwa et al., 2010)

From Ginnakidis (2013) we confirm that the power each node i has to process is equal to the sum of the power of all outgoing links going to nodes j as seen in the following equation. This statement follows from the conservation of charge or Kirchhoff's Current Law which states that any charge going into a node must be equal to the outgoing currents or must be conserved in this location, this results in the following continuity function:

$$Q(t1) = Q(t2) + Q_{in} - Q_{out}$$

When there is no charge conservation capability in a location then Q will remain constant and the equation can be restated:

$$Q_{in} - Q_{out} = 0$$

Charge entering or leaving a volume or node in the case of a grid is equivalent to the flow in Amperes (I) and there may be multiple in and outgoing flows which leads to final restatement of the equation:

$$\sum I_{in} - \sum I_{out} = 0$$

$$\sum I_{in} = \sum I_{out}$$

Voltage differentials in grids are related to the transported power in a line proportional to the reactance. Each links voltage drop can be calculated from the transported power and reactance. Knowing the voltage at a part of the low voltage grid can be done using an equation found in Marra (2015). It is based on Ohms Law ($U = I \cdot R$) but uses the complex form for AC grids while Ohms Law is stated for DC currents. Kirchhoff's Voltage Law states that the sum of all voltages in a loop must be 0, then to determine the voltage you can start at a known voltage and add the (summed) voltage differential to obtain the local voltage. In an AC network the voltage drop (ΔU) is a combination of real and imaginary impedances which both attribute to the voltage differential and resultant power consumption in a cable. The imaginary components of an AC grid result in reactive power (Q_L) that contribute a load to transmissions lines and reduce the effective capacity of the connection while not adding to the real power transmitted (P_L) to the end-user. However for simplification was chosen to implement only the real component of AC currents. In Figure 5 is shown how the voltage differential can be visualized. Loads Q_L and P_L both contribute to a voltage difference ΔU, P_{PV} results in a voltage rise while the loads cause a decrease in voltage. The net load of the dwelling or node results in a net ΔU, if production exceeds the loads a voltage rise will be observed, this is what causes overvoltage during summer since the effects of all net energy generating dwellings are combined. Adding a consuming load then decreases the voltage differential again or could result in a negative voltage differential, this can be done by charging EES. Since only real power consumption is accurately measured (in the case and most situations) the omission of reactive loads makes a lot of sense resulting in simplifications on many fronts; only real power is relevant resulting in DC equations and the three phases are no longer essential. This reduces the number of voltage-related variables from 6 to 1 and results in much easier comprehendible results.

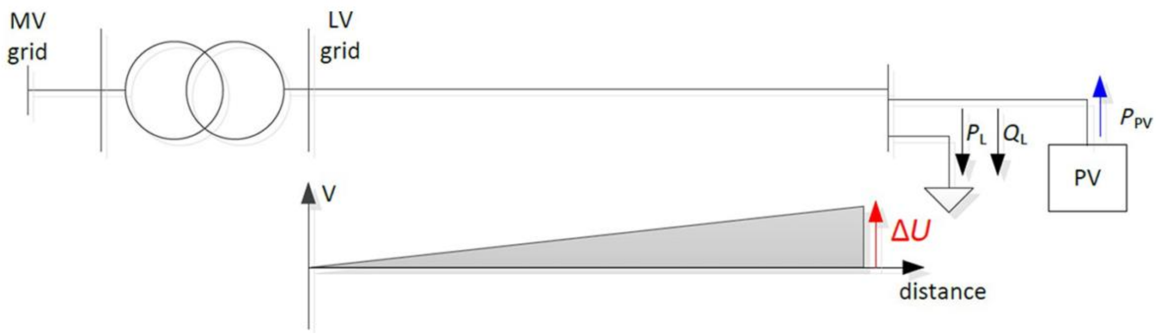

FIGURE 5: VOLTAGE RISING UNDER PV GENERATION LOADS (MARRA & YANG, 2015)

From Stedin we know the grid traditionally is set at a very high voltage like 420V. Then the least problems are expected at *the end of the street* so to say when loads cause a larger negative ΔU. As long as the voltages stay within 380V and 420V the operator is satisfied. The Dutch standards allow voltages between 360V and 440V but this is not allowed for longer than a certain short period and can be considered a poor performing grid that causes problems in appliances, just not instantaneous.

Last thing to learn from Marra (2015) is that the feeder losses can be modelled and benefits of EES to improve efficiency are interesting to observe. These feeder losses are the transmission cable losses incurred from supplying the neighbourhoods transformer. Losses in the transformer itself are about 2.5% but outside of the neighbourhood there are losses as well that can be avoided in summer by preventing reverse flow. Reverse flow could cause congestion in the medium voltage grid so preventing it is a double win situation. An average 3% of losses are added to bring a moderated 5.5% of loss in the transformer and higher voltage grids.

AC generators dictate the frequency of 50 Hz and in reality produce three phase shifted signals. Each signal is shifted 120 degrees or 1/3rd of a period. These three phases are the result of how a generator fundamentally works. The voltage between any of the two phases in the low voltage grid is 400 Volts. A regular dwelling connects to only one phase and ground and as a result the nominal voltage is 230V. Nevertheless the low voltage grid has all three phases present and dwellings are evenly distributed to the phases so loads are evenly applied to all three phases. Voltage quality control can be done by adding an inverse load where problems arise due to overloading of the infrastructure, in practice this only applies if the load is connected to the same phase as on which the power quality needs improvement and loading a different phase could result in creating new problems on a second phase. The model has been simplified as if all phases are combined into a larger one of 400V.

4.3.2 GIS implementation

GIS maps used in the form of shapefiles are sourced from OpenStreetMaps.org. GIS data is edited using QGIS. The grid was delivered as a pdf file which was converted to a raster file in form of an uncompressed tiff image. The maps from the shapefiles and grid were matched and the grid was traced by creating a new shapefile which contained the points that in the model are the nodes of the grid. Dwellings footprints are drawn as shapes from shapefile and their points are used as the connection to the grid. Finally the location of the transformer which is known from the grid design pdf is imported via a separate shapefile. The connection to the datasets containing the consumption patterns in summer and winter are made using an attribute for element in the dwelling-points shapefile. Results from the optimization are saved as a GIS points shape file, the storage configuration can always be exported or restored with the use of some procedures available in the model.

4.3.3 Demand pattern

In Wade (2010) data was used on a 30 minute resolution = 48 points per day to forecast user demand. A resolution appropriate to the functions that are assessed needs to be chosen or can be on the same resolution as the available data from the case. When dealing with daily fluctuations this resolution or smaller is appropriate, if seasonal fluctuations are addressed a larger timescale like a daily of weekly scale may be more appropriate. Dwellings in the model are assigned a demand pattern number as attribute in the GIS shapefile. This demand pattern number is used to later retrieve the demand pattern out of a CSV-file. The demand pattern is a CSV-file containing as many values as the model will run steps and the first value is the demand pattern number. The first item on the list in the CSV-file is removed using but-first and finally the list is loaded into a dwellings-own variable called demand-pattern during setup. Each value represents an average demand in Watts during the length of the time step.

4.3.4 Rendering grid

Nodes are drawn in QGIS as points and feature an attribute called “order” which indicates the order number of the node, this is used to identify the amount of outgoing links from each node. First all nodes are drawn, then starting at the transformers the grid is rendered by connecting to the nearest unpaired node. Then a node with incoming links but less links outgoing then its order will link to the in “order” set amount of nearest nodes and so forth until all nodes satisfy their order number. The backbone of the grid is now rendered. Then the dwellings are connected by asking all dwellings to create a link from the nearest node, the same goes for batteries. Finally dead ends are removed.

4.3.5 Battery management

EES is capable of acting as both a generator and a load. Voltage optimization and demand response are the most important functions for smart grids according to ENSG (2009) so these were the functions to be obtained in the model/case using events where they were compromised. Reverse flow into a feeder can be problematic but not always so only above a certain threshold it should be restricted, this is a parameter for the model. Overloading of a substation/feeder is also problematic, a threshold is used for the model to trigger EES response. Forecasting can be used to make an algorithm for the EES response at certain times, for instance being charged when forecasts indicates the battery needs to respond to an overpower situation and contrariwise.

Battery management

Marra (2015) offers a method for battery modelling. This is done by integration of the in- and outgoing energy, or when using discrete steps to add the net inflow of power times the length of time-step and efficiency of charge/discharge to the stored energy. As a result the energy stored in EES can be described in the following function:

$$E(t + \Delta t) = E(t) + \Delta t * P_{battery} * \eta_{(dis)charge}$$

Batteries are technically constraint in power they can supply and absorb. Any constraints in terms of power may be expressed as follows:

$$P_{discharge} \leq P_{battery} \leq P_{charge}$$

Constraints in stored energy or battery state can be expressed as follows where E_{min} and E_{max} are the minimum and maximum energy levels of the storage device, defining the usable energy window:

$$E_{min} \leq E(t) \leq E_{max}$$

SOC_{min} and SOC_{max} are the minimum and maximum SOC limits that should be set in relation to the application:

$$SOC_{min} \leq SOC(t) \leq SOC_{max}$$

As battery storage (or any other kind of storage) is cycled it is subjected to degradation. Assuming linear degradation the degradation can be calculated with the following equation:

$$DegradationLevel = \frac{NoOfCyclesEndured}{NoOfCyclesDeclared}$$

Degradation level can then be used to calculate the remaining capacity as follows:

$$RemainingCapacity = OriginalCapacity * 0.8 * DegradationLevel$$

With these functions battery performance is modelled more accurately. Also the estimated lifetime of the storage application can be assessed. In Ibrahim (2008) it is stated that life expectancy and total costs (investment, energy losses, and cycling fatigue) are the most important criteria in stationary EES applications. The cost per cycle could be the best way to evaluate the cost of an energy storage system designed for frequent charge–discharge applications.

BMS logic

There are different approaches for battery management. Three battery logics are implemented in the model, all three rely on the concepts of either applying peak shaving in winter or preventing reverse flow in summer. Shown in Figure 6 and Figure 7 are graphs that show the respective winter and summer demand patterns and when batteries should charge or discharge.

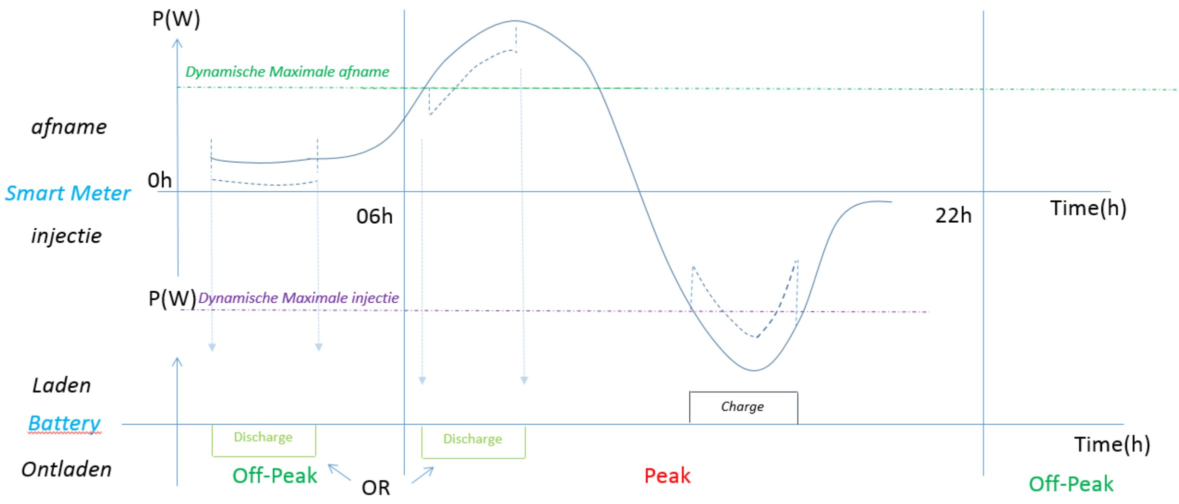

FIGURE 6: SUMMER BATTERY STRATEGY AND DEMAND PATTERN

The first concept is a reflection of the battery logic as it is applied in Hoog Dalem. As soon as net production occurs in summer batteries will charge at a fixed rate and then discharge during peak demand when demand exceeds production for peak shaving. In winter batteries charge during the night and are discharged when the morning demand peak starts. In the model this battery logic is named Compliance.

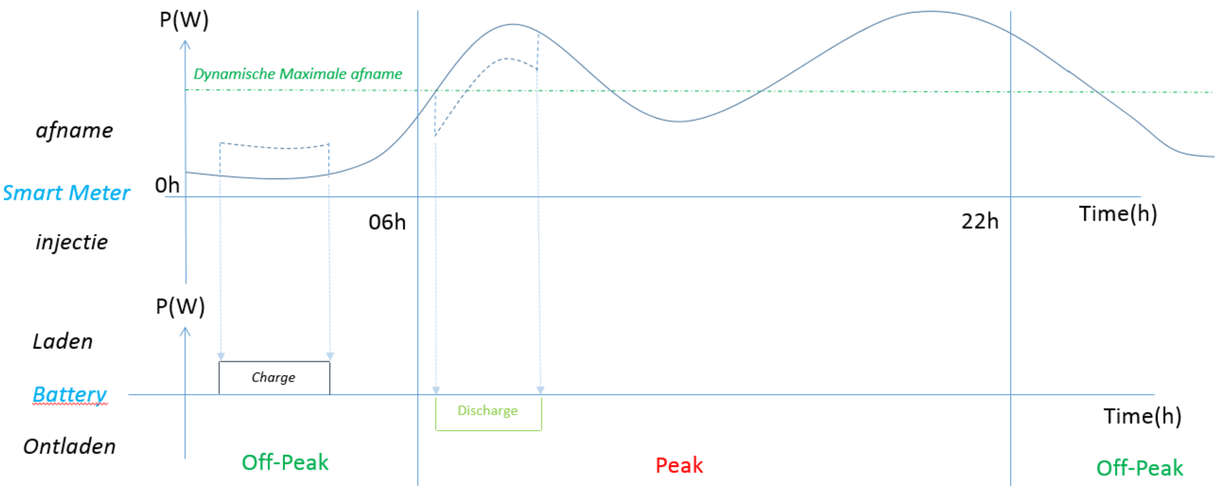

FIGURE 7: PEAK SHAVING BATTERY STRATEGY AND DEMAND IN WINTER

The second approach to battery management as proposed in this research extends on the first concept but instead charges only the surplus power that is being produced in summer and similarly for discharging, it is called the Smarter battery logic in the model. The third approach, the voltage controlled battery logic, will act on the same occurrences as the first two logics but only if the occurrence violates the technical restrictions that determine the performance of the grid. It works similarly to the Smarter battery logic and attempt to resolve the issue at minimum effort by the storage devices leaving a large capacity available to deploy in occurrences of power quality.

4.3.6 Financial model

Total Costs of Ownership are defined as:

$$TCO = CAPEX + OPEX$$

CAPEX or capital expenses are investment costs of the EES systems. In the model this is defined as the sum of the investment costs of all batteries (b_i) resulting in the following statement:

$$CAPEX = \sum_{b_0}^{b_i} InvestmentCosts$$

Operational costs are what OPEX consists of. Charging the battery costs money which is determined by the rate that is applicable at that moment for buying electricity. Operational costs are defined as the integral over the simulation time of energy expenses for each battery (b_i) plus additional yearly expenses. Discharging means selling energy or a negative battery demand and results in a negative operational expense at the then applicable rate, charging of a battery costs money and results in a positive operational expense. Since the model runs in discrete steps the integral can be replaced by a summation of the results in each step and the following function is defined:

$$OPEX =$$

$$\left(\sum_{t=0}^{t=n}\sum_{i=0}^{i=m} BatteryDemand(b_i) * EnergyRate\right) + \sum_{i=0}^{i=m} OPEX_{fixedyearlycosts}(b_i)$$

Energy losses result in a net operational expense over a full charge-discharge cycle, a more efficient battery is therefore cheaper to operate. The lithium battery is maintenance free since it is a solid state device. The Blue battery is not a final product yet and supposedly no maintenance is required over the expected life span of 15 years, however there is wear in the pumps and membranes which could require some maintenance. The HBr flow battery from Elestor requires yearly maintenance at an average price of 500 €/year.

4.3.7 Smart-grid-performance

In the model is a variable to monitor the performance of the smart-grid. Power quality constraints are given and each violation adds to the performance variable. A performance of 0 would be a perfectly compliant grid, in any case a lower value should represent a better performing grid.

Power quality limits are given by the network operator, voltages shouldn't exceed 420 Volts or dip below 380V. At times of voltage norm violation the following limitation is violated:

$$U_{min} \leq U \leq U_{max}$$

For every dwelling (d_i) that exceeds these voltage the difference in voltage squared is added to the performance variable. In case of over-loading of the infrastructure the following restriction is violated:

$$P_{transformer} \leq P_{transformermax}$$

For every transformer that exceeds the power limitation the difference in power is added to the performance variable. Results are integrated over the simulation time and since the model runs with discrete steps the integration can be replaced by a summation of the smart grid performance per time step and the following performance function is defined:

$$SmartGridPerformance =$$

$$\sum_{t=0}^{t=n}\left(\left(\sum_{i=0}^{i=m}\left(U(d_i) - U_{min/max}\right)^2\right) + \left(P_{transformer} - P_{transformermax}\right)\right)$$

4.3.8 Optimization algorithm

From Barton & Infield (2004) we are inspired to optimize storage capacity in terms of smallest size being able to achieve a certain goal (10 min of autarky for example) instead of optimizing for more complex scenarios. This helps us to not aspire a perfect solution but rather go for a (very) good solution. An optimization algorithm is developed since the solution space can be considered extremely complex and probably impossible to solve manually. There are: nodes, dwellings, different paths from and to each node, dwelling, the source. PV systems or EV's are added and the complexity of the grid layout enhances the size of the solution space further. Lastly there are three battery systems that can be applied and in any combination. Automated optimization is rather dumb and requires a lot of computing time, therefore the algorithm should only be used when manual solutions are not found or to verify the manual solutions.

The algorithm can allow non-perfect performance via a by the observer determined limit of performance so a rather good performaning solution is accepted. Optimization is done on the basis of an algorithm called Simulated Annealing. It allows small optimizations for each of the many variables until a local optimum is found. A "temperature" controls the annealing and the higher it is the larger the changes made to the configuration will be. Sometimes the model optimize in the wrong direction, in the beginning of the optimization this is allowed to allow escaping a local optimum. Accepting a decreased performance will occur at higher temperatures most of the time to explore the solution space. As the temperature decreases exponentially the chance of accepting a poorer solution decreases. Given that the solution space is huge the computation time to check all possible storage configurations is simply too long. Small incremental optimizations will be combined until no improvement can be found or the temperature reaches zero and the algorithm will report the outcome. Optimizations are done with the goal to decrease TCO while remaining within the restrictions of power quality known as Smart-grid-performance. A visual representation of how the optimization algorithm works is shown in Figure 27 of Appendix 8.2.

4.3.9 Interface

Shown in Figure 8 is the interface of the model in NetLogo. The left column the columns are graphs to monitor the performance of the grid. It shows power supplies into the neighbourhood, amount of energy stored, charging and discharging curves of the batteries, demand patterns of the dwellings before influence of EES and finally the voltages in the grid, maximum, minimum and mean voltages are displayed. The second column contains the model controls and some more performance indicators. Selections of scenarios can be made, turning on/off of batteries, selecting what kind of battery configuration should be rendered, selecting the battery logic, amount of batteries to create, the performance the grid should confirm to, energy costs and allows turning on the optimization algorithm. Furthermore the amount of batteries per type and in total are displayed.

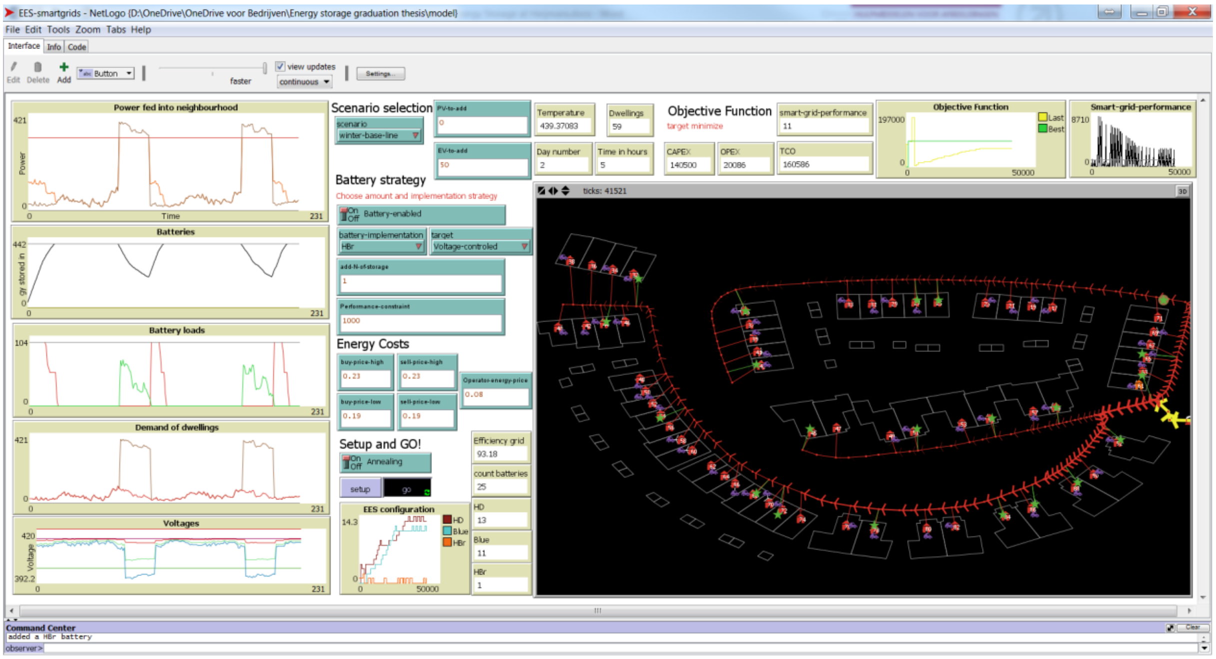

FIGURE 8: A SCREENSHOT OF THE INTERFACE

Above the world view are more monitors. Model time is shown, the amount of dwellings, temperature that constrains the algorithm operation, CAPEX, OPEX, TCO, performance of the grid is shown as well. Finally the automated optimization algorithm progress can be monitored via the objective function plot. The world monitor shows the project layout, grid layout, placement and types of batteries, placement of additional PV system or EV's. The thickness of the links in the grid represents the power they are displacing.

4.3.10 Output

In step one of the analysis the relation between amount of batteries and performance is determined using the NetLogo Behaviour Space tool. This tool covers a broad band of possible configurations given certain constraints. In this case it will determine the performance of the grid multiple times for each storage device and an increasing number of batteries added. Since the configurations are random every time and spatial distribution of storage and other loads may affect the results there are multiple runs for each combination of variables. Results are saved to a spreadsheet and table which contain the necessary information from which a relation between performance and configuration is determined.

The optimization algorithm used in step 2 uses TCO and Smart-grid-performance to determine a most cost-efficient design storage configuration. The best result is saved as a GIS file containing the locations and types of batteries used and the command centre of NetLogo is used to monitor the optimization progress textually. Besides the output the model finishes with the solution loaded for further research but thanks to the GIS output further research can be done at any time.

4.4 Model conclusions

A model was constructed to reflect a neighbourhood's energy supply system. Design choices were made on basis of insights into the case (chapter 5.1) and to maintain a balance between complexity and accuracy. Among the simplifications made the foremost simplification is that of disregarding the AC components and the resulting reactive power consumption of the neighbourhood. Due to a lack of insight in reactive power consumption in the case it was disregarded. Another AC simplification that was made is that of three phases that are present in such a network, a combined phase was modelled. These simplifications reduce complexity of the model and therefore make the results more comprehensible and reduces computation time. It was chosen to reduce the capacity of the network by disregarding parallel wires, this results in a grid that is more like an older infrastructural design.

The resultant model more closely resembles a DC grid with some cost savings of which the results will apply to AC grids as well. Insight into how problems develop are gathered from the many variables that are present in the model. Voltage quality can be monitored and insight is given to where power quality is poorest to understand why the grid is performing badly. The overall performance of the grid can be monitored through a performance function and this functions as an objective measure of how well the power supply system is working and is useful to assess the severity of the problems.

Electrical energy storage systems are accurately modelled including losses and capacity degradation, the inclusion of these phenomena allows determining problems with long-term operations of the systems. The software used to program the model, NetLogo, has proved capable of behavioural and weather simulations. The ability of adding these functions can make the model a universal tool that could potentially work without a data-input.

For a model demonstration please go to https://youtu.be/em6iU0Q3weU for a video demonstration, total playtime is less than 7 minutes.

5

Simulation results

Summer and winter scenarios reflect the current operations of the smart neighbourhood of Hoog Dalem. These scenarios function as the baseline on which both grid support functions are evaluated for their added value. Validation of the model is done on basis of both the winter and summer scenarios by checking if the simulated voltages are realistic. Then the baseline scenarios as they can be found today in the grid are expended by adding additional loads in winter and additional generation in summer and determine at which amount of added loads or generators the performance of the grid is adversely affected. The ability of the grid to maintain power quality is used as the basis to determine how well the grid is performing, for this a function is present in the model. As power quality related issues are present like overvoltage and overloading the performance function will increase indicating a decline in power quality. Then on the basis of a realistic worst-case scenario the performance is attempted to be restored by the means of EES and all battery-types with all battery logics are tested for their ability to improve power quality. Results show insight into how performance can be restored and show the location in which voltage-quality is compromised.

5.1 *Case: Hoog Dalem*

Hoog Dalem is a project in which 1400 dwellings are being built. The neighbourhood is full electric and all of its energy demand comes from electricity. Currently only a small portion of the project has been constructed but part of it is being used as an experiment for EES to support the grid and improve grid efficiency. A collaboration is held between the network operator Stedin, a power system supplier ABB, an information technology provider KPN and of course the contractor Heijmans. The aim of the project is for all parties to gain insights in how future services and products can be developed for energy supply transitioning and smart energy. Balancing energy flows within the neighbourhood is done using energy storage and demand management, during the project these functions will be optimized. To achieve the most insight into the performance of the grid a lot of data is recorded allowing very detailed analysis. Recorded data is highly detailed and covers the mayor energy consummators separately like the heat pump, dishwasher, washing machine, electric cooktop, overall consumption and also the power generation of the PV is measured on a per 15 minute basis. There are two data sources, the first one is from the smart meters which monitor consumption and production in and out of the house. The second data source is the cloud gate which gathers data from all different data sources and records them separately. All data has been anonymized to protect the privacy of the homeowners.

FIGURE 9: AERIAL PICTURE OF THE PROJECT (HTTP://WWW.HEIJMANS.NL/NL/NIEUWS/SMART-ENERGY-PROEFTUIN-HOOG-DALEM-VAN-START/)

Dwellings that are part of the experiment feature a cloud gate. The cloud gate allows homeowners to smart start high energy consuming appliances to start only when there is a surplus of energy in the dwelling or before a certain time is reached. Dishwasher and washing machine are both able to function this way and are programmed using a tablet computer. Having appliances turn on in a smart fashion introduces some noise in the measured data since they are not actually the demand pattern an inhabitant would mimic. This however will not interfere with the model analysis substantially, it lowers the requirement for storage to balance supply and demand. The alternative to balancing is demand management which is what technically is done already in most dwellings on a small scale, this indicates that there is less room for improvement via demand management. The sub-neighbourhood within the project Hoog Dalem that is used in this case study contains a total of 59 dwellings. During the collection of data that is available there was no EES present in the dwellings.

5.2 Scenarios and datasets

The model simulations starts at a baseline scenario of a winter and summer period to reflect the current state of operations. These scenarios are also used for calibration and validation of the model. This baseline provides a benchmark for the performance of the grid and is used to assess the power quality and the severity of power quality issues.

TABLE 4: OVERVIEW OF SCENARIOS

Scenario	**Demand**	**Generation**
Summer	Low	High
Winter	High	Low

As discussed in section 3.3 there is an electrification ongoing of appliances. The neighbourhood is already fully electric and no fossil fuels are consumed within the dwellings. As loads and generators are being added to the grid in the coming years trouble from a too large demand and over or under-voltage can be caused.

5.2.1 Summer

As a baseline for future summer scenarios an interesting period in the month June of 2015 is selected. During summer there is no heating demand while the cooling demand is relatively low, dwellings are not necessarily cooled and the need to do so is low thanks to the high performance of the thermal shell. Also the lighting is used less due to the longer days. A minority of dwellings is equipped with PV generation. The selected dataset contains a period of high solar intensity and low cloud coverage which results in large net production over an extended period in the summer scenario. As a result the voltage quality and reverse flow can be analysed.

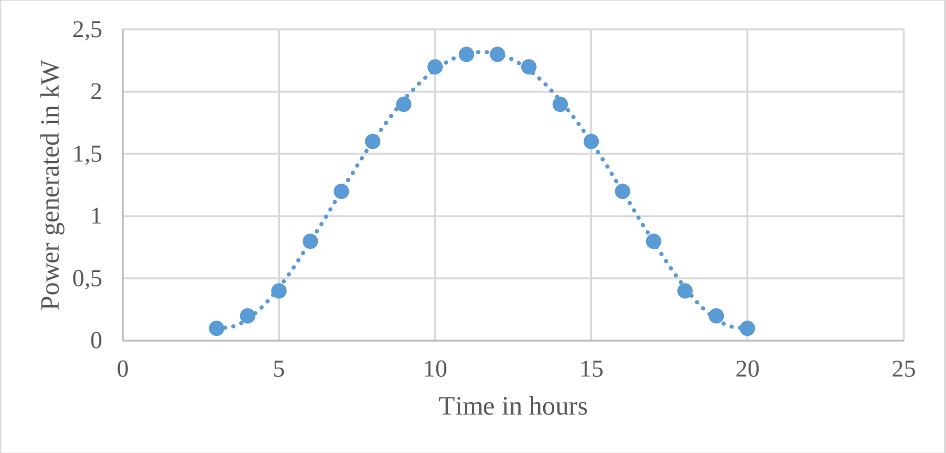

FIGURE 10: 5 KWP PV INSTALLATION'S DAILY POWER DISTRIBUTION

As the required investments for PV systems are decreasing while their efficiency increases there will most likely be an increase in PV-penetration in the coming years. 5 kWp installations of ~33 m² are about as large as they could be given the size of the dwellings and are used to determine the PV penetration at which voltage quality deteriorates. These 5kWp PV system's specifications and power distribution are acquired from Zonatlas; as shown in Figure 10 is a graph with hourly production capacity in kW during the most sunny month of 2015 June. As it's a modern neighbourhood the chances are that most people would want to achieve a maximum energy production. By adding PV installations the limits of the current grid are tested and any problems with having a very high installed capacity are attempted to be solved using EES.

EES is now deployed to improve performance and maintain power quality of the grid upon adding PV systems. A realist worst-case scenario is considered based on the trends in chapter 3.3. It is realistic that of the 59 dwellings 40 will feature a PV systems, there are already some systems present so we assume an additional 30 PV systems will be installed by 2025. This scenario contains 5 kWp systems although in reality 3 kWp systems are probably more likely for a residential application but since government incentives or other developments may encourage house owners to maximize their generation capacity the large ones are considered.

5.2.2 Winter

During winter when lighting and heating are used intensively demands are found to be highest, when peak-demands coincide there may be challenges to be faced. Electrification of appliances is ongoing and also applies to means of transportation, E-bikes, hoover-boards and foremost Electric Vehicles (EV's). EV's charging occurs at a very high rate, a little over 6 kW of charging power is what most domestic charging stations can provide. Chargers do not take into account power quality or peak shaving and can cause a tremendous increase in peak demand. The average commute by car is 22.6 km (Nederland heeft werk, 2015), at a typical power consumption of 0.25 kWh/km this means an energy consumption of about ~6 kWh. This results in a one hour demand of 6 kW. Typical charging of EV's coincides with the peak demand at 17 o'clock, as people come home from work.

Under-voltage might occur and most definitely the demand will exceed the preferred limits set forth while even the actual limit of 630 kVA may be reached. By adding EV's to the project the limitations of the grid are found, then EES is used to attempt to solve the issues. As far as worst case scenarios go it would be interesting to observe performance when most dwellings feature an EV which would charge during peak demand times. By 2025 most dwellings will most likely have a plug-in vehicle (as discussed in section 3.3) and so is chosen for a number of 50 EV's as a realistic worst-case scenario.

5.3 Validating the model

When designing electrical infrastructure for neighbourhoods, engineers use a combination of experience and calculations. The result are then assessed by calculating the voltages in the grid under extreme conditions. The design is optimized for minimal costs within specifications while maintaining a comfortable margin of error to ensure the risk of under-capacity in practice is minimal. Simulations of the base line scenarios of summer and winter are used to verify the voltages in the project are within the technical requirements and expectations.

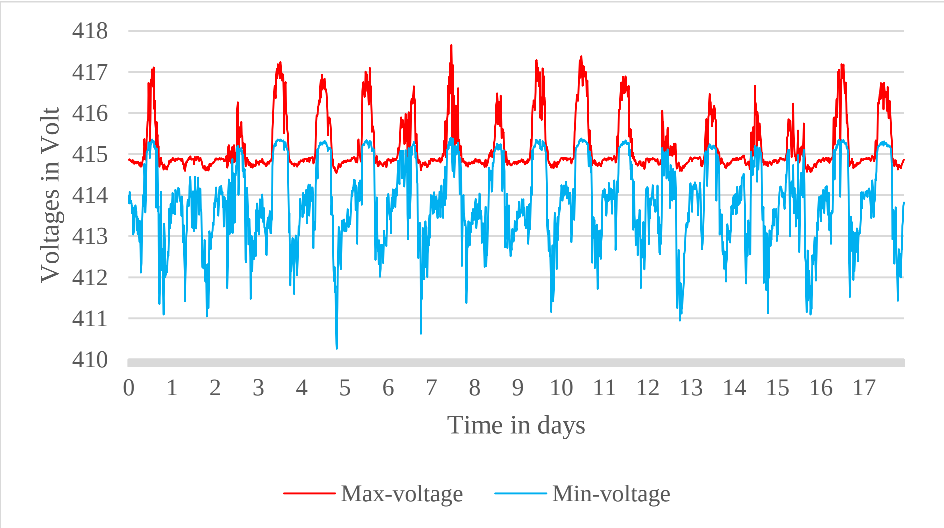

FIGURE 11: VOLTAGES IN GRID IN SUMMER SCENARIO OVER THE LENGTH OF THE SUMMER DATASET

The voltages in the grid are calculated on basis of basic physics laws and actual specifications from the infrastructure. Voltage of the transformer is set according to what the network operator estimates it would be set to in practice. Based on the dimensions of the cables in the neighbourhood a certain voltage bandwidth is available. Since modern infrastructure should be over-dimensioned to accommodate anything that might occur there should be a very large voltage bandwidth; the voltages are first checked if they are well within the restrictions. The transformer voltage is set to 415V to allow a very broad band for peak demand but also allowing net production. Running the base line summer scenario reveals the voltages stay under 418V so there are no issues there and a 80% increase in PV would be possible at first sight (dependent on relative placement in the infrastructure). When multiplying the demand patterns of dwellings by a factor 3 in the summer base line scenario the voltages reach as high as 423V, not too bad but since the winter voltages allow more room maybe the transformer voltage should be lowered by 3 of 4 Volts to be safe if it isn't already lower than 415V in the actual project (see discussion).

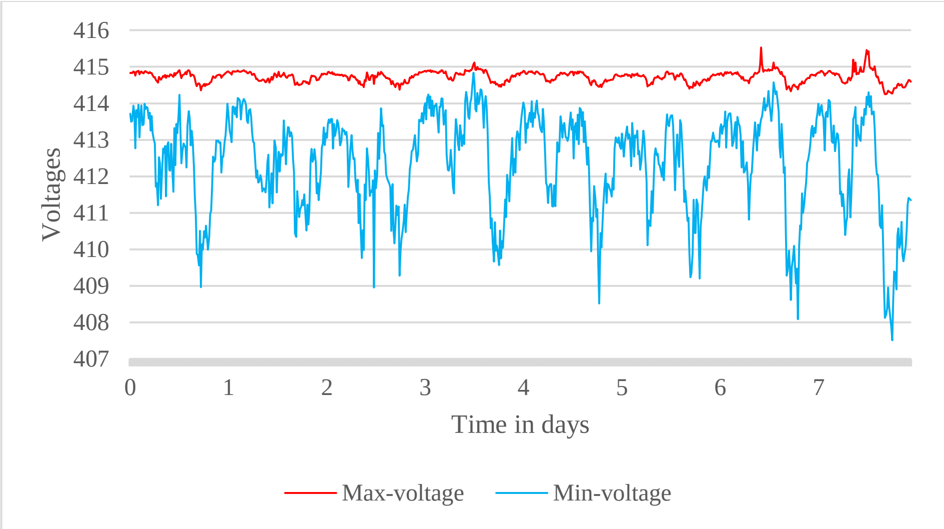

FIGURE 12: VOLTAGES IN GRID IN WINTER SCENARIO OVER THE LENGTH OF THE WINTER DATASET

In baseline winter scenario the voltage drops stay above 405V so copious within limits. Increasing all loads from the scenario by a factor 3 results in a minimum voltage of 395V. There still is 15V of room before the limits are reached. Multiplying demand by a factor of 6 results in under-voltage at 370 Volts and there the limits of the available bandwidth are found. As expected: the grid is very robust and sufficiently dimensioned to handle most developments. Voltage may be on the high side since there is a lot more room for loads than generators. Voltage bandwidths are slightly larger than in the actual project as was confirmed by the network operator. This is due to the design decisions made in the model in which there are no parallel grid connections while in reality there are. This results in an amplification of voltage quality problems due to a narrower bandwidth. This alternative grid design reflects an aged grid layout and results in more interesting results where voltage quality needs to be more closely guarded. A larger dimensioned grid allows bigger loads at the same voltage drops. So if a grid violates the voltage requirements while the transformer voltage is optimized already then the grid needs reinforcing or support otherwise. Voltages in summer are shown in Figure 11, winter voltages are shown in Figure 12.

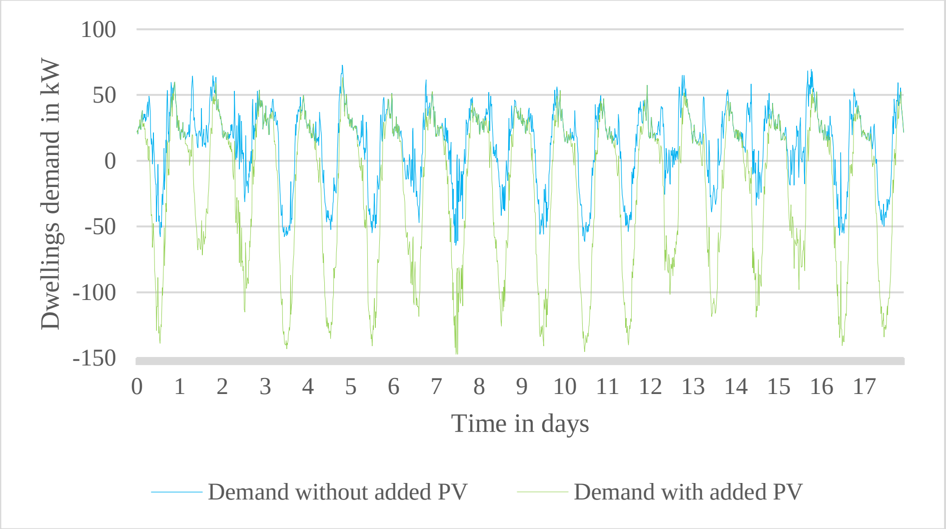

FIGURE 13: POWER SUPPLIED TO NEIGHBOURHOOD IN SUMMER SCENARIO IN KW OVER THE LENGTH OF THE DATASET

Without storage the cumulative demand pattern of the dwellings is equal to the supplied power to the grid. Voltages increase during times of net production but stay within the specified limits. At peak demand times the minimum voltages dip to around 411V which is absolutely no problem.

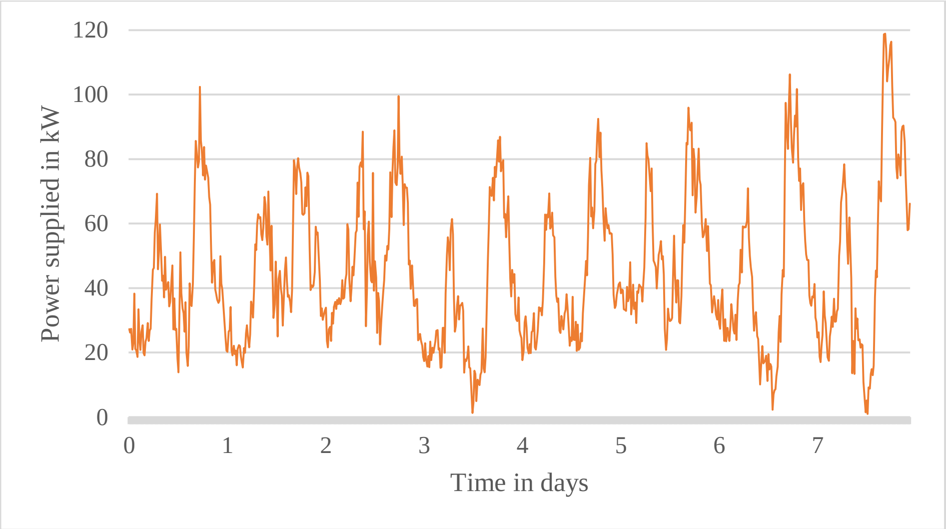

FIGURE 14: POWER SUPPLIED TO NEIGHBOURHOOD IN WINTER SCENARIO IN KW OVER THE LENGTH OF THE DATASET

5.4 Summer scenario

During summer an increased amount of net production by dwellings could result in overvoltage. Voltages rise and adding more generation capacity to the grid increases voltages even more. Today the grid is perfectly capable of coping with the generation capacity as was found during validation. However in the near future a 10 times increase in installed PV production is expected and the grid may face difficulties maintaining power quality.

5.4.1 *Grid performance with increased generation*

To determine the performance of the grid for future usage additional PV systems are added. Without storage the grid should be able to allow a lot of PV since during validation there was found a substantial margin voltage wise. PV systems are added to the grid according to Table 5 in which the performance results can also be found or in graphical form in Figure 15. Each number of added PV systems is simulated multiple times to determine the influence of spatial distribution on the performance and offers an indication of the severity of power quality issues in such scenarios. Performance is measured as how badly the power quality is affected and therefore a performance of 0 indicates a perfect power quality, the higher the performance figure the more severely power quality is affected.

TABLE 5: PERFORMANCE IN SUMMER WITH ADDED PV

No. of PV systems added	Repetitions	Best performance	Worst performance
0	5	0	0
4	5	0	0
8	5	0	0
12	5	0	0
16	5	0	66
20	13	1	481
22	8	21	472
24	13	4	2.174
26	8	140	6.615
28	13	13	11.159
30	33	97	10.471
32	13	863	18.558
34	8	2.487	21.538
36	13	1.135	22.807
38	8	6.086	19.166
40	38	7.632	60.624
42	8	17.074	36.916
44	13	13.021	53.720
46	8	42.734	66.693
48	13	37.506	77.665
50	8	49.731	75.541
52	13	62.408	112.312
54	8	72.208	119.411
56	13	83.513	135.538
58	8	116.090	137.604

As can be seen adding some of these large 5 kWp installations isn't any problem at all, until about 16 PV installations one could argue the performance may not be perfect yet it certainly performs well enough to be classified as acceptable with the worst performance being a mere 66. Upon addition of 20 PV systems the performance degrades but not in all cases, the best performance found may be acceptable while the worst is not. This difference in performance with the same amount of added PV installations is due to relative placement. Configurations with poor performance have a high concentration of PV in one place while another part of the grid is relatively vacant, a low resulting power quality in these locations is then the cause of the bad performance. Network operators are not able to influence the placement of PV installations so it must always considers a realistic worst case scenario. A section of the neighbourhood may be orientated particularly suitable for PV generation which would result in all dwellings to invest in PV systems leading to such a scenario. As the voltage increases the performance degrades more quickly, due to the quadratic performance function a 4V violation causes a 4 times as poor performance as a 2V violation. The degradation upon introducing more PV systems is therefore exponential as can be clearly seen in Figure 15.

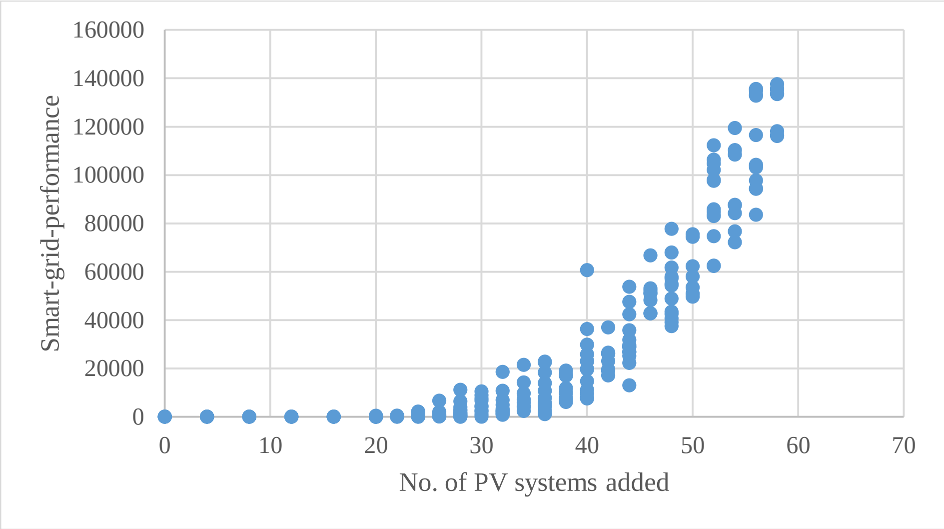

FIGURE 15: PERFORMANCE IN SUMMER WHEN ADDING PV

In the realistic worst-case summer scenario an additional 30 PV installations of 5 kWp will be added to the project. The model will simulate 25 random configuration with 30 PV systems added and their configurations are saved as a GIS file. The worst performing configuration will be used as the starting point for the worst-case simulations on which EES is assessed on its ability to restore power quality.

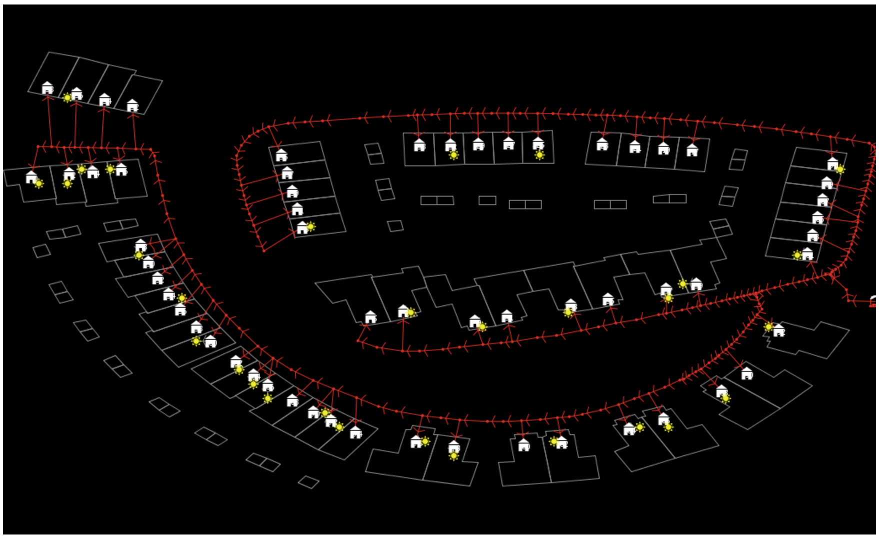

FIGURE 16: LOCATIONS OF THE 30 PV INSTALLATIONS

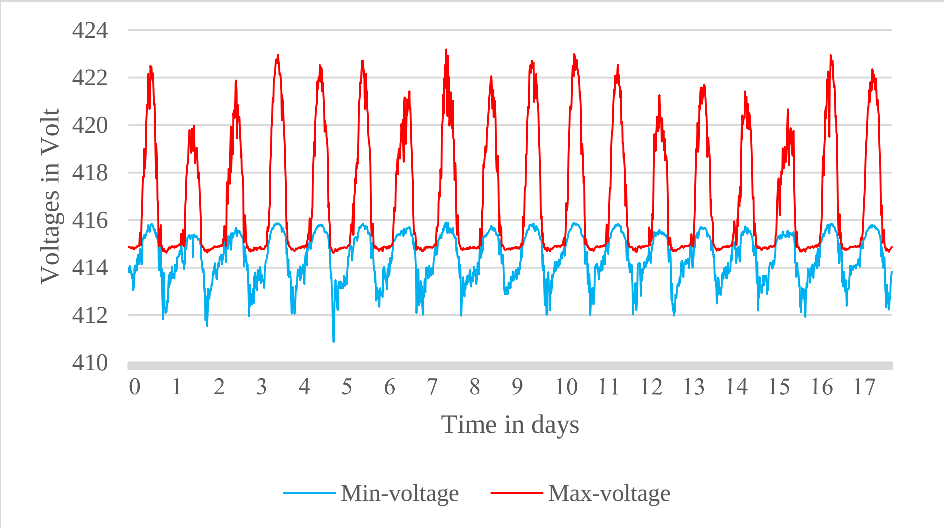

FIGURE 17: VOLTAGES IN GRID WITH 30 PV INSTALLATIONS

Shown in Figure 16 is the configuration that was found to perform the worst with 30 PV installations added. It can be seen that the majority of installations, displayed as yellow suns, are found in the same branch of the grid, namely the longer one at the bottom. Performance degradation is observed and as can be seen in Figure 17 this is due to over-voltage during peak-production. The resulting maximum combined net energy production of the neighbourhood is now close to 150 kW. The neighbourhood's energy demand in this scenario and the baseline scenario are both shown in Figure 18 and it differs only during daytime.

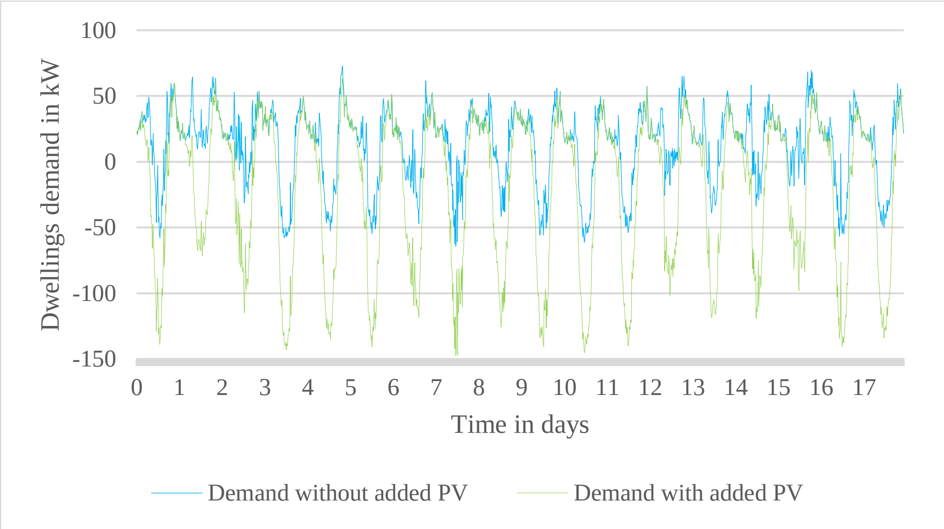

FIGURE 18:DEMAND WITH 30 PV INSTALLATIONS

5.4.2 Improving performance with EES

There are three types of batteries available and three types of battery management. First the currently applied lithium batteries are assessed for their potential to improve grid performance and potentially fully restoring power quality. Figure 19 shows the performance upon introducing HD batteries to the grid, voltage controlled battery logic (in grey) appears to deliver the best performance improvement while the compliance battery logic is worse in most cases and the smarter logic is definitely the worst approach to improving grid performance.

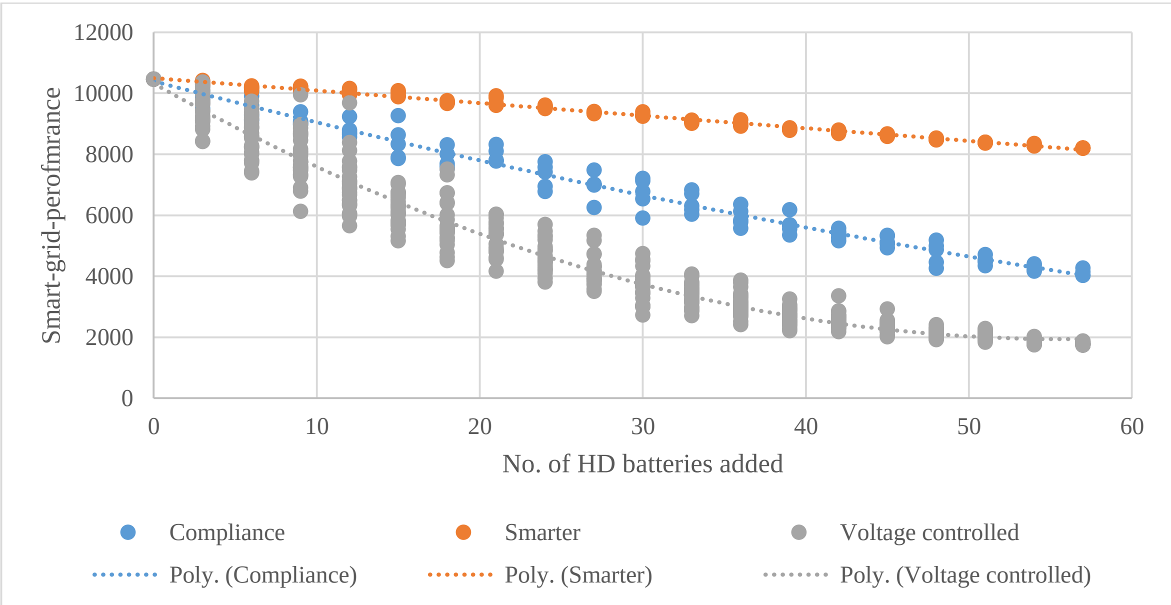

FIGURE 19: SMART GRID PERFORMANCE WITH HD BATTERIES IN SUMMER SCENARIO WITH 30 PV INSTALLATIONS ADDED

Interesting to observe is the spread in performance results for each battery logic. The smarter battery logic has a very small spread, this means that the placement of the systems in the neighbourhood does not strongly influence the performance. In case of the voltage controlled battery logic there is a very wide spread of performance which is smallest around the maximum and minimum amount of batteries installed, this is due to a lower amount of permutations available. For example at 9 added batteries the performance was found to be between 6.000 and 10.000, therefore the optimal placement of any number of HD batteries with voltage controlled battery logic needs to be carefully assessed. In conclusion the voltage controlled battery logic should be used in combination with the HD batteries but care must be taken on placement in the neighbourhood.

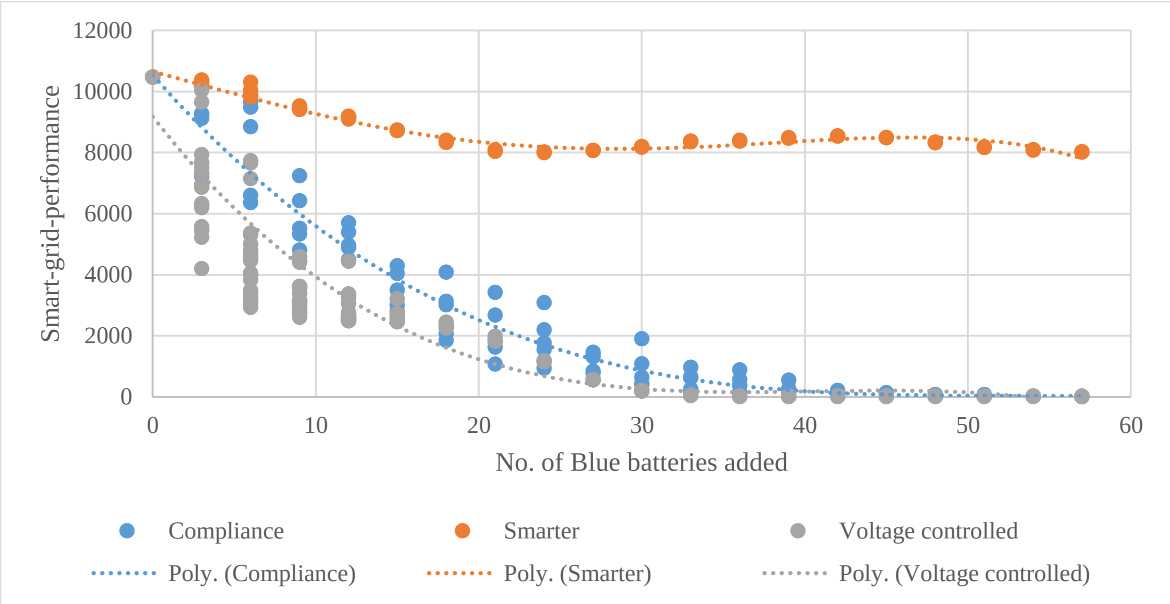

FIGURE 20: SMART GRID PERFORMANCE WITH BLUE BATTERIES IN SUMMER SCENARIO WITH 30 PV INSTALLATIONS ADDED

Performance of the grid upon addition of Blue batteries is similar to that of the HD batteries. As can be seen in Figure 20 the voltage controlled battery logic is the best performing while in this case the compliance battery logic is very similar although slightly poorer. Both the voltage controlled and compliance controlled Blue battery systems are able to improve the grid until perfect performance is reached. Again the spread in performances is largest with the voltage controlled battery logic and smallest with the smarter battery logic. It is interesting to discuss the differences between these functions at 21 and 24 batteries, they are very close together and the compliance strategy seems to be better in one case while on average the voltage controlled battery logic has a better performance and a smaller spread. The spread in performance of the voltage controlled battery logic is very large at small amounts of batteries installed while getting very small from a number of 15 batteries. The spread in performance is more constant with the compliance battery logic, as a result the spread is smaller than the voltage controlled battery logic at low number of batteries but larger from a number of 10 batteries or more.

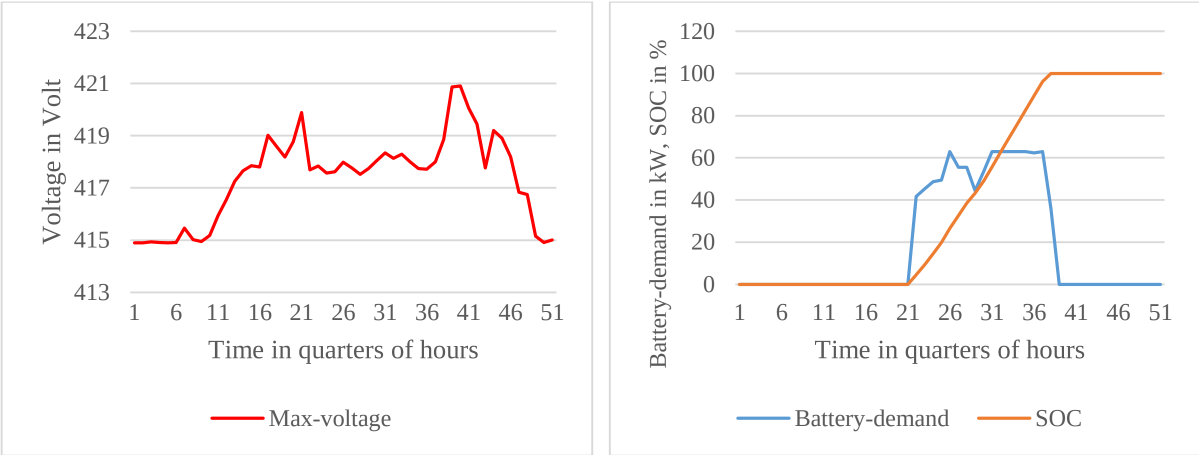

FIGURE 21 A/B: LEFT (A) THE VOLTAGES IN THE GRID WITH EES GRID SUPPORT AND SMARTER BMS LOGIC, RIGHT (B) THE OVERALL BATTERY RESPONSE AND STATE OF CHARGE

In conclusion the voltage controlled battery logic seems to perform better in most cases but there may be a better performance when using the compliance battery logic in some instances. The smarter battery logic is insufficient; batteries are not fully discharged leading to limiting the grid supportive capabilities the next day. Also the blue battery is a lot more powerful than the HD battery, unfortunately enough this combination of battery logic, powerful battery system and not fully discharged battery leads to a very high deployment of power in the first stage of net production and a full battery before the peak in production has been reached and a resultant very poor performance. This can be seen in Figure 21 A, as the PV generation increases the voltage follows. As the voltage reaches the upper limit the storage starts charging and the voltage drops to about 418 V indicating a too strong reaction of the storage than strictly necessary. As a result the storage is fully charged before the end of the generation period when the voltage can be seen to rise to 421 V.

TABLE 6: SMART GRID PERFORMANCE WITH HBR BATTERIES IN SUMMER SCENARIO WITH 30 PV INSTALLATIONS ADDED

	Best performance			Worst performance		
No. of HBr batteries added	Compliance	Smarter	Voltage-controlled	Compliance	Smarter	Voltage-controlled
0	10.471	10.471	10.471	10.471	10.471	10.471
1	0	3.721	123	10.471	8.675	10.471
2	0	7.679	2	7.828	9.681	6.821
3	0	7.934	2	6.582	9.017	11.010

Finally the HBr flow batteries performance improvement is assessed. Performance with this kind of battery is highly dependent on placement, due to the large power capacity it can introduce new problems or is just not able to resolve issues. The large differences in performance are shown in Table 6; adding one battery can improve performance to acceptable levels but it can also be seen that poor placement can result in no effect at all. Both compliance and voltage-controlled battery logic offer excellent performance although the compliance logic seems to perform the best by a small margin. Smarter battery logic performs very poorly and adding more than one battery even works contrarily.

5.5 Winter scenario

In winter the peak demand will cause overloading of the infrastructure, in specific of the transformer. As a result the relative placement of storage systems is not so much a factor as long as it doesn't introduce voltage problems. Starting with the baseline winter scenario additional loads by EV's are added to the neighbourhood to find the limitations of the grid. It may very well be that in a modern neighbourhood most homes will feature at least one plug-in EV or hybrid vehicle.

5.5.1 Grid performance under additional demand

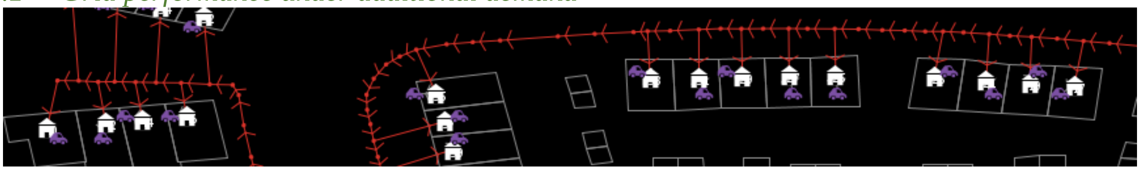

FIGURE 22: VIEW OF MODEL WITH EV'S

A large demand to the grid can result in under-voltage and overloading of the infrastructure or transformers. The latter seems to be the problem upon introduction of many EV's. The relative placement does not influence the results since the performance degradation is due to overloading of the transformer. The low power quality situation present in this situation is not directly impacting residences but is causing the feeder that is supplying power to be stressed beyond its limitations which could lead to power failure or voltage issues. Performance in over-loading situations is linearly related to the over-loading power observed, therefore a linear relation between overload and smart-grid-performance is found as shown in Figure 23. Performance of the grid upon introduction of EV's is shown tabularized in Table 7.

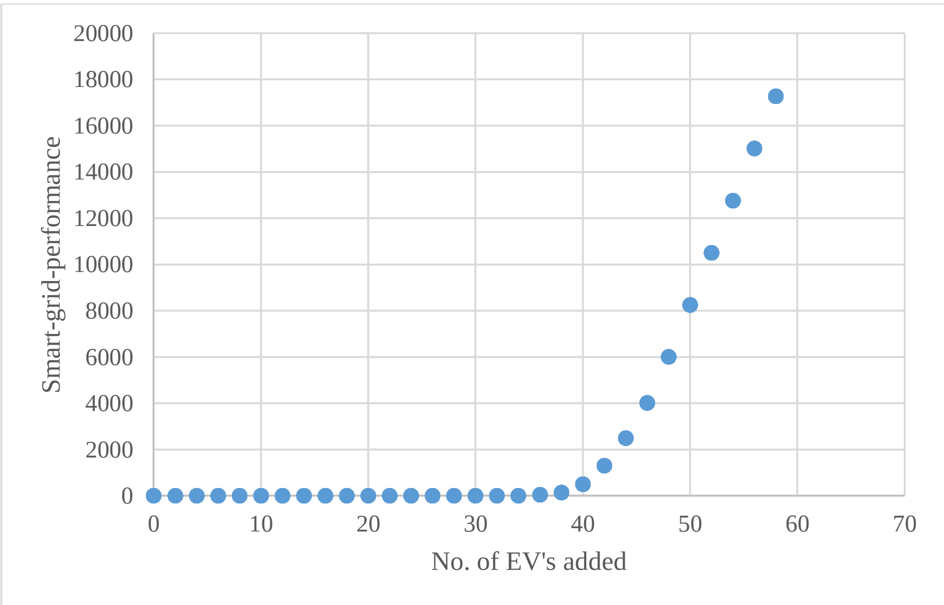

FIGURE 23: PERFORMANCE IN IN WINTER WHEN ADDING EV'S

Performance degradation occurs upon introduction of 34 EV's although substantial performance degradation does not occur before 42 EV's are added. A performance of over 8.000 is observed in the realistic worst-case scenario of 50 EV's added to the grid which can be seen more easily in Table 7. 25 random simulations were done for each amount of EV's added and performance is not influenced by the placement location of the loads since there was no variance in the performance. Since the relative placement of these EV's is not of influence on the performance the model will randomly place them for each scenario, only if voltage-quality related performance issues are observed this statement will be revisited. EV's are represented as purple cars in the model as shown in Figure 22 and in the realistic worst-case winter scenario 50 of them are added to the project.

TABLE 7: PERFORMANCE IN WINTER WITH ADDED EV'S

No. of EV's added	Repetitions	Performance
< 32	25	0
34	25	10
36	25	40
38	25	141
40	25	499
42	25	1.310
44	25	2.499
46	25	4.014
48	25	6.012
50	25	8.249
52	25	10.505
54	25	12.761
56	25	15.071
58	25	17.273

5.5.2 Improving performance with EES

There are three types of batteries available and three types of battery management. First the currently applied lithium batteries are assessed for their potential to improve grid performance. Figure 24 shows the performance upon introduction of HD batteries into the grid. A linear relation between all of the battery logics can be seen, the compliance battery logic performs the worst while the smarter and voltage-controlled battery logic fair comparably well. Neither of the battery logics is able to restore performance to below 3500 in combination with the HD battery type but in any case adding batteries somewhat improves performance.

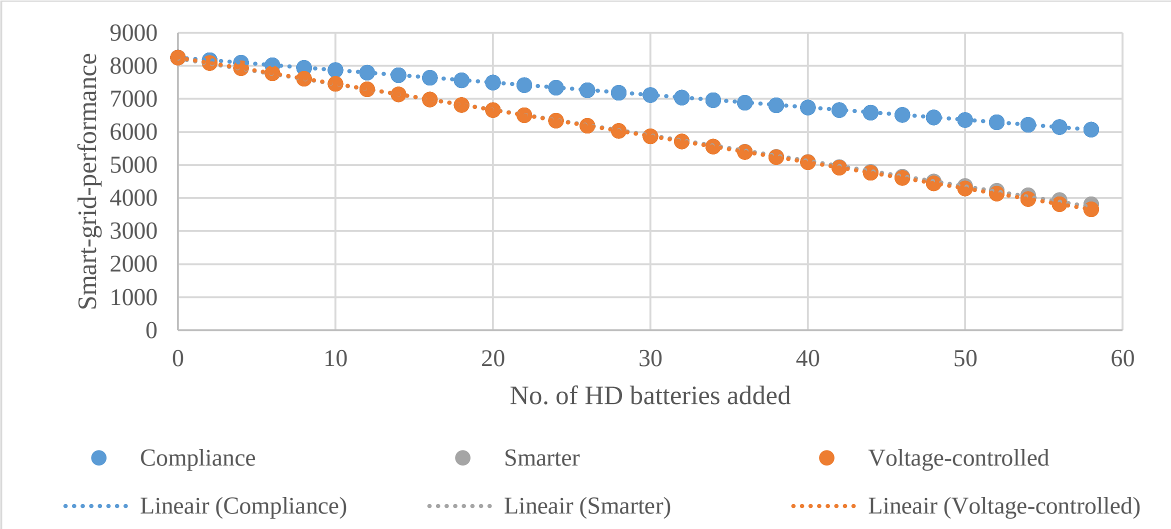

FIGURE 24: SMART GRID PERFORMANCE WITH HD BATTERIES IN WINTER SCENARIO WITH 50 EV'S ADDED

Blue batteries are then assessed. As can be seen in Figure 25 a linear relation between performance improvement and the amount of batteries is found to exist until a certain limit is reached. The performance in case of the compliance logic performs the poorest. Initially the Smarter and Voltage-controlled battery logic perform equally until about 12 batteries performance starts differing. Performance with the Smarter battery logic is limited to about 1.700 but with the Voltage-controlled battery logic a performance of 0 can be achieved.

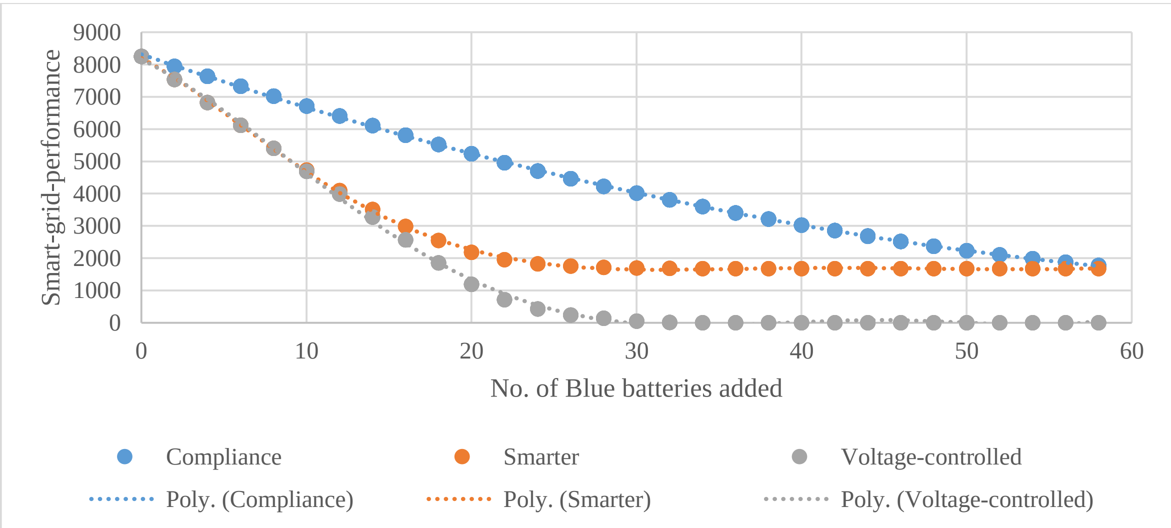

FIGURE 25: SMART GRID PERFORMANCE WITH BLUE BATTERIES IN WINTER SCENARIO WITH 50 EV'S ADDED

The difference in performance between the smarter and voltage-controlled logics are because of over deployment of grid-support. The smarter logic will deploy much more power leading to an overcompensation while the voltage controlled logic only supports as much as needed to achieve conformity to the upper limits of power supply. In this regard the voltage-controlled battery logic is much easier to program than in the summer scenario where a voltage drop compensation needs to be adjusted with a power that has to be determined for each situation. In case of the winter scenario the support needed is simply the excess demand of energy beyond limitations of the grid that should be delivered from the storage devices in order to restore performance.

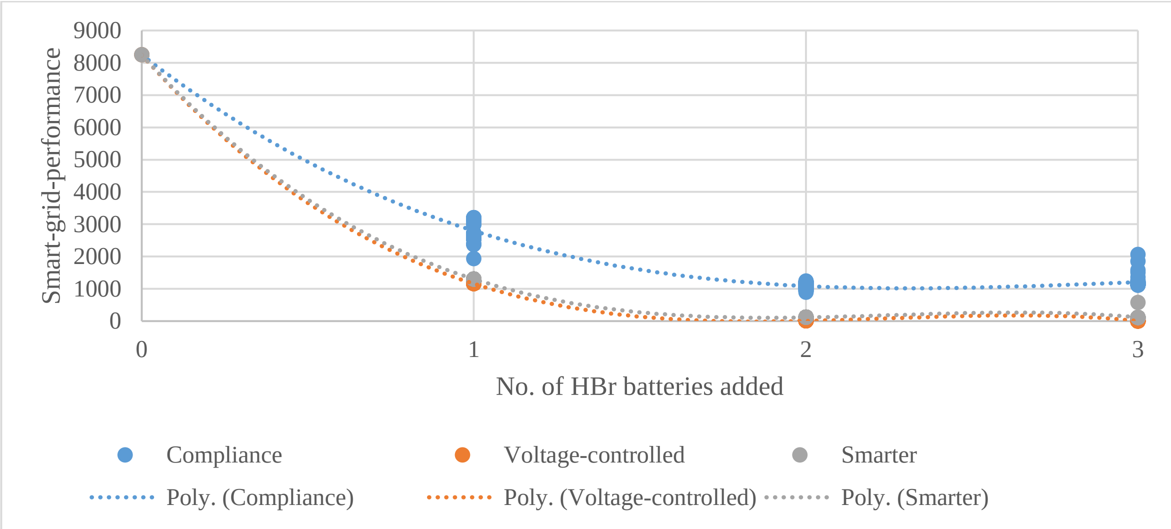

FIGURE 26: SMART GRID PERFORMANCE WITH HBR BATTERIES IN WINTER SCENARIO WITH 50 EV'S ADDED

Lastly the HBr batteries are assessed on their ability to restore performance in a situation of excess demand. Seen in Figure 26 are the performances when adding HBr batteries; the compliance battery logic performs the poorest and shows a spread in the achieved performance for each amount of batteries added due to newly introduced voltage-quality problems. The voltage-controlled and Smarter battery logic perform very similarly and about one of these large batteries is found to be close to sufficient to restore performs to acceptable levels. Placement of the battery with Smarter and Voltage-controlled battery logics is irrelevant, with Compliance battery logic the placement does seem to matter.

5.6 Discussion

Simplifications of the grid resulted in a less robust grid than is used in the actual project and amplification of performance degradation. However the simplifications are made to reflect significant cost reduction of the infrastructure and resulted in excellent performance now and in the near future. Only in the more distant future like the 2025 scenarios problems will occur with grid performance, these results are more interesting since the actual grid is over-dimensioned by such an extent that performance will not degrade and there will not be any resultant performance degradation to resolve. The project itself is therefore not accurately modelled, the model reflects the situation of a renovation project that has modern building performance in combination with aged grid infrastructure.

Overvoltage in summer occurs while no under-voltage occurs in winter. This leads to the conclusion that lowering the voltage in the transformer could reduce or even resolve the problems without causing new problems. However the results do not reflect the three phases that are actually present in the grid and under-voltage may very well be another problem in practice when loads are concentrated on a single phase. Simplification of three phases into a combined one may be much simpler but foremost it reduces the complexity of the results. Separate (AC) phases can each have voltage quality issues and among them leading to six voltages to monitor and optimize. This problem is less applicable for generation related scenarios, if generation comes online it will do so evenly distributed on all phases since the generation does not depend on behaviour of the inhabitants but on the local weather conditions which are of course very similar given the small size of the neighbourhood.

Another simplification made in the model is that of only using real power consumed and supplied. AC grids have complex currents and there is reactive power being transported through the grid causing additional voltage differentials to occur. Due to a lack of data on reactive power consumption in dwellings only the real power was modelled. DC grids would not be bothered by three phases and reactive power. DC grids offer additional benefits in low voltage grids. It is highly probable that DC grids are used in the foreseeable future, the simplifications made in this model more accurately describe such a DC grid.

Battery logic was found to be of great influence on the performance of the grid. More research into this topic is most definitely required to obtain a better battery logic and to optimize utilization of the storage devices. A whole research could be done on battery logic algorithms, for instance forecasting of generation and demand would greatly benefit the grid support functions while reducing battery wear. Optimization of the EES controlling logic for an each specific configuration is probable able to yield a substantial performance improvement.

Risks are considered as an important parameter to make design choices, this is why grids are over-dimensioned for realistic worst-case scenarios. EES can offer the chance to take more risks since problems can be resolved by adding EES where needed. Here is the most important of the problems with grid design; network operators design and operate the grids but the investment costs are paid by the dwelling owners. Therefore TCO is not of interest to the grid operator, operating costs are the main costs a network operator is faced with.

Operational costs include replacing costs, labour costs and possibly rental costs for the location. Blue batteries may be more cost-efficient when considering the lower investment and maintenance costs but they are to be placed in dwellings or require a system to combine them into a larger battery. An HBr battery will feature higher total costs of ownership when only considering technical operation costs and bare investment costs. When considering multiple visits to all dwellings and the separate installation costs the resultant TCO is different and may result in an alternative best solution. In any case the network operator will choose to minimize operation costs which may very well be in favour of a more centralized solution. Solid state EES will incur less operating costs than an EES system with moving parts, however a plain copper wire will not have any operational costs except for some discernible energy losses.

Dutch net-metering laws are expected to change in 2020. When this happens a price differential between buying and selling of energy will occur and the grid can no longer be used as a perfect EES device. When this happens the profitability of PV systems will most likely be reduced. Battery technology is developing at an enormous rate and with it the investment costs per kWh are decreasing. At some point in the future EES will make a PV system more profitable by storing energy for later use to prevent losing money due to the price differential.

6

Conclusion

6.1 Scientific relevance

A model was developed to determine the technical benefits of electrical energy storage (EES) for application in neighbourhoods in the functions of voltage-control and peak-shaving. It has been able to provide a better insight in the mechanics that cause grids to be adversely effected by foreseeable developments like a high integration rate of photovoltaics (PV) and electric vehicles (EV). The tools' insights can be used to predict where problems occur and how to solve them using either traditional reinforcement or more innovatively by applying EES. The tool is therefore most useful to determine the long term grid performance developments and plan EES intervention at by then more cost-effective investment. Although EES was capable of functioning in the aforementioned functions their functionality was limited by the battery logic which needs calibration for each specific configuration. Most importantly: EES can be used to restore performance without mayor reinforcement of the grid and therefor allowing a higher number of VRES generation.

A high concentration of PV installations in the same branch of the grid causes overvoltage, particularly in the extremities of longer sections. The addition of Electric Vehicles is causing an increased peak demand resulting in overloading. Unlike in the summer scenario there is no relation between placement of these loads and the performance of the grid, adding loads causes overloading of parts of the infrastructure namely in the transformer/feeder. Under-voltage was expected to occur during peak demand but during simulations this has not been found to cause issues confirming the non-existing relation between placement of loads and performance of the grid.

" Which Electric Energy Storage method is most suitable for application within the scale of a neighbourhood for voltage control and peak shaving? "

Foremost it was found that improving grid performance is possible by means of EES. Three battery types were researched of which a solid state Lithium battery (HD battery), a salt water flow battery (Blue battery) and a Hydrogen Bromide flow battery (HBr battery). These batteries were tested in combination with three battery control logic concepts. The HD battery with its small capacity proofs less effective per installed unit, the Blue battery with its larger size is able to perform better at a lower number of batteries while the very large HBr battery shows that a centralized battery is also capable of improving performance in contrast to the decentralized nature of the other battery types.

Battery control logic was found to be essential to optimize utilization of the batteries' capabilities of which the Voltage-controlled battery logic was found to perform best. All three battery concepts have been found to work effective in some combination of scenario, battery type, relative placement and battery logic. There are many variables in play and an abundance of battery placement configurations available which caused the battery logics to be programmed to benefit performance in most situations but hampering battery utilization potential. When using this model as a design guide for EES the battery logic can be tuned for the chosen configuration in order to perform optimal.

In summer the localized origins of performance degradation caused by a high PV concentration in the extremities can be most effectively resolved by placing EES in these same extremities. Such a relation was not found for the winter scenario where the loads' placement is not of influence of the performance, batteries should then be placed where they benefit the grid in summer scenarios.

Capital costs of a modern traditional grid are below 1000 €/dwelling, the grid in this project is therefore not more expensive than €60k and after simplifications a lower investment would even be required. Than looking at the costs of the EES systems there are about 22 Blue batteries required to resolve the future summer scenario, costing by itself already €77k. From an economic standpoint it is therefore not feasible to use EES to replace traditional grid over-dimensioning. On the other hand when existing grids do fail the costs of reinforcing the underground infrastructure for a whole neighbourhood may be more cost-intensive than adding above ground storage devices. And when EES is used the stacking of benefits or combination of functions can result in the creation of more value than the levelized costs of storage. Although at the current state of technology and investment costs it will not be through price arbitration or as a means to improve on a potential deterioration of net-metering legislation as was calculated in section 3.5.4. As the need for smart grids rises further and the generation capacity will increasingly be from variable renewable source there will come a time where storage is more needed, in the meantime storage is becoming cheaper and therefore somewhere in the future it will be a profitable and therefore sustainable alternative to the traditional means.

6.2 Societal relevance

This research shows the possibilities of using EES for maintaining power quality in future smart grids that are capable of managing energy efficiently and more reliably. Other power supply systems' problems resulting from the ongoing energy transition like balancing demand and supply can be partially solved by the smart grid EES systems when they are not required for their core tasks. During days of fluctuating VRES generation the EES systems can be applied to restore balance in energy supply and demand. If such multifunctional energy storage systems are integrated into the grid they allow a higher level of VRES without requiring fossil fuelled balancing capacity, this should lead to reduced emissions and lower energy generation costs. Emissions reduction and a more sustainable energy supply system decrease our dependence on foreign resources and lower energy costs stimulate economic growth.

7

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8

Appendices

Please note that the report, final presentation, model, videos, results and most data can be downloaded from a public Dropbox folder. Due to confidentiality of the data-sets used they are not included, datasets are required to perform simulations and should be provided by yourself.

https://www.dropbox.com/sh/9hvcldkay1j4ll5/AADBOMa8eNT-2ldEXdafylJba?dl=0

8.1 Smart city concepts literature study

The first concept of a smart city is by Weening (2006) in which telecommunication plays the main role. There are two distinct sub-types of smart cities, in the first there is a central role for services and the second where this role is given to infrastructure. Part of these services are informational services like providing real-time information regarding for example (cultural) activities, hotel room availability, weather, public transportation schedules and municipal services like applying for permits. Networks and ‘community networks’ which are part of the smart city concept do the following according to Schuler (1996, as quoted in Weening, 2006) : *“(...) to help revitalize, strengthen, and expand existing people-based community networks much in the same way that previous civic innovations have helped communities historically”*. These networks offer the opportunity to restore the lack of social contact due to the digitalization of society. Also they enable some groups of people to better partake in the community through emancipation and empowerment. These community networks then help in developing a smart city socially.

The ‘wired city’ and ‘intelligent city’ are subsets of smart city concepts revolving around an extensive ICT network of data and economic connections in an integration with public and private parties. This approach of the infrastructure centred smart cities focusses on creating economic growth by attracting investments or creating job/economic opportunities by improving connectivity to areas. Caragliu (2011) recognizes the main role of ICT infrastructure in the smart city policies followed by socio-economic capital like education. According to Gold (1990 as quoted in Weening 2006); having a decent ICT infrastructure can make economies flourish because of cost reduction and improved accessibility of handicapped personnel. Lazaroiu & Roscia (2012) agree on both the social and economic characteristics of a smart city model which should embody technology which is in service to the inhabitants and to economic and social life quality improvement. Need be noted there are concerns that an intelligent city can result in a privacy violations because of unwanted user-data usage (ExtremeTech, 2015).

Weening (2006) [T]: *“A smart city project is a project in which a city is equipped with ICT infrastructure and electronic services to enhance social-economic development.”* In this definition a city is considered a distinct and separable area in which people live, work and recreate which can be on different scales like a village, neighbourhood or even a country. The ICT infrastructure mainly consists of physical broadband (>10Mb/s) connection, electronic services are informational, interactional and transactional. And Caragliu (2011) points out that the rapid innovations in ICT can cause forerunning cities to lose their edge, developments in ICT should be maintained constantly and is an endless pursuit. It was found that large human capital accelerates urban innovations since innovations are driven by skilled entrepreneurs.

More qualitatively described a smart city is a ‘bigger, faster, easier’ city of the future (NEC Corporation, 2014). It needs the integration of platforms, products and processes with city infrastructure and the urban space such as buildings, parks and roads. You could say an integration between digital and physical. This integration should improve efficiency, better use capacity and reduce congestion which means for instance waiting times are lower, less traffic jams occur and power supplies are more stable. The analogies between Weening and NEC are present in their focus on infrastructural facilities but the integration between physical and digital is added which is also considered by Batty et al. (2012) indicating the infrastructure is integrated into the city, data mining is applied to help a more organised and more efficient delivery of services and improved quality of life. A truly integrated city can be defined with the more ambiguous Planetary Nervous System in which everything is connected to everything at all times. Smart cities are a perspective of the idea that ICT is used to operate a city. A smart city can be decomposed into the following categories: economy, people, governance, mobility, environment and living which is all done smartly.

8.2 Simulated annealing logic flow chart

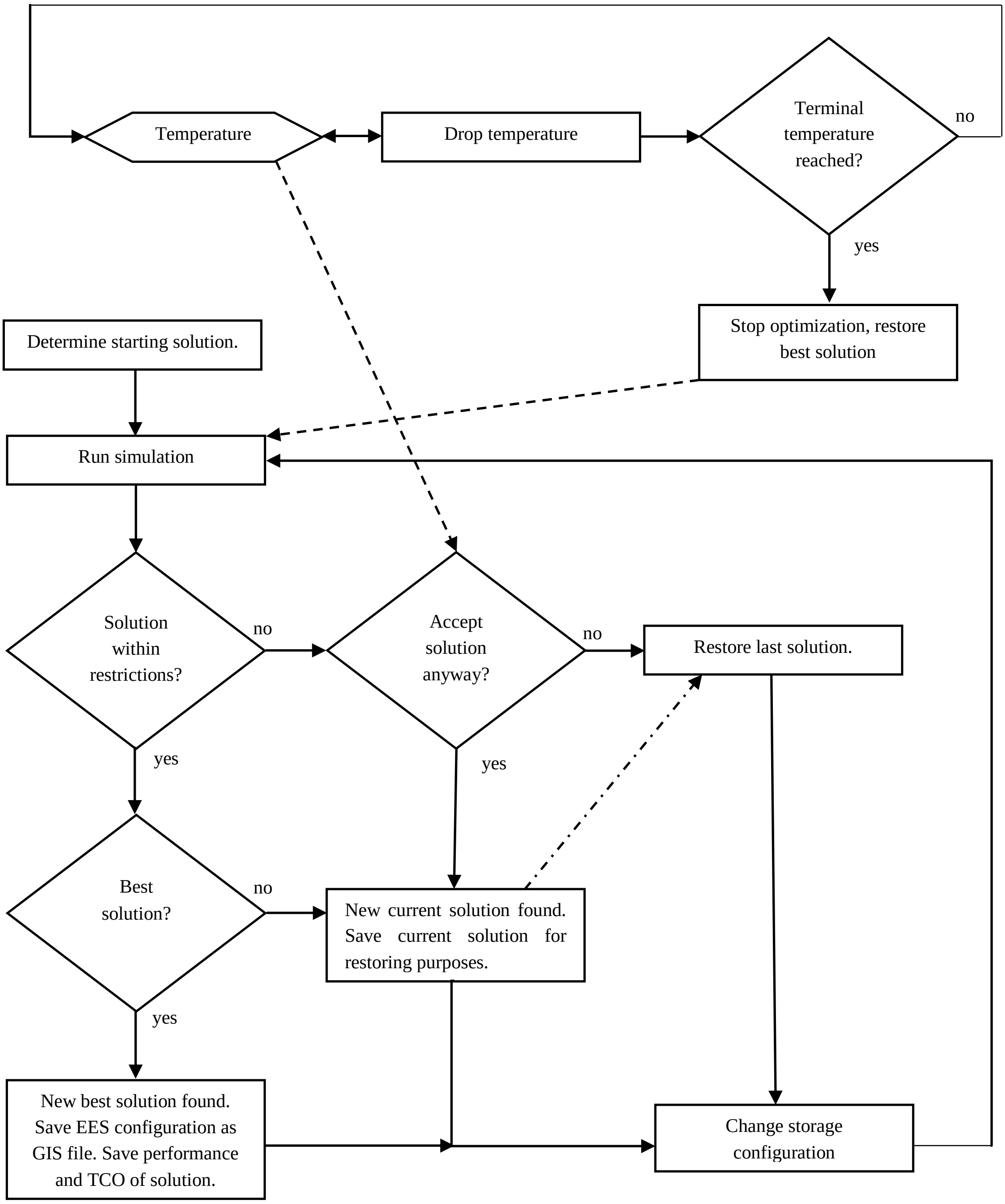

FIGURE 27: SIMULATED ANNEALING OPTIMIZATION ALGORITHM

8.3 Globals

8.3.1 Globals in code

Global variable	Function
best-solution	Saving best TCO in simulated annealing process(SA-P)
last-solution	Saving last TCO in SA-p
last-configuration	Saving last configuration of storage in SA-p
best-configuration	Saving best configuration of storage in SA-p
pv-configuration	Helper variable for saving PV configuration
best-performance	unused
last-performance	unused
high-bandwidth	unused
temperature	Controls SA-p
temperature-start	Determines length of SA-p and quality of solution
i	Helper variable for SA-p
resistance-per-km	Resistance of cables in grid, used in links
TCO	Total costs of ownership
CAPEX	Capital expenses
OPEX	Operational expenses
smart-grid-performance	Variable to monitor performance of smart grid
energy-wasted	Monitors energy losses in the grid
energy-supplied	Monitors amount of energy supplied by transformers
energy-consumed	Monitors net energy consumed in dwellings
reverse-power-supplied	Monitors amount of reverse energy supplied by trans.
building-footprints	Helper variable for GIS displaying of dwellings
dwellings-points-gis	Helper variable for GIS displaying of dwelling-points
nodes-gis	Helper variable for GIS displaying of nodes
terminal-nodes-gis	unused
transformers-gis	Helper variable for GIS displaying of transformers
deltaT	unused
demandprofiles	Helper variable to load profiles into dwelling-agents
temp	Helper variable to load profiles into dwelling-agents
quarter	helps to keeps track of model time
hours day	helps to keeps track of model time
pv-pattern	Production pattern of additional PV systems
ev-pattern	unused

8.3.2 Choosers

These globals are used to choose alternative scenarios, battery implementations and battery logics.

Global variable	Options
Scenario	winter-baseline summer-baseline
battery-implementation	HD Blue HBr Random none
target	Compliance Smarter Voltage-controlled

8.3.3 Switch

These globals are used to turn on and off functionality in the model

Global variable	**Options**
Battery-enabled	On/off
Annealing	On/off

8.3.4 Input

These globals are used to input numerical values

Global variable	**Integer or double**
PV-to-add	integer
EV-to-add	integer
add-N-of-storage	integer
Performance-constraints	integer
buy-price-high	double
buy-price-low	double
sell-price-high	double
sell-price-low	double
Operator-energy-price	double

8.4 Agents

```
links-own [
	linkpower
	delta-v
	energyloss
	dimensions
]

breed [ dwellings dwelling ]
breed [ nodes node ]
breed [ transformers transformer ]
breed [ batteries battery ]
breed [ evs ev ]
breed [ pvs pv ]

dwellings-own [
	demand
	pv-production
	demand-inhouse
	dwellings-voltage
	demand-pattern
]

nodes-own [
	nodepower
	nodevoltage
	order
]

transformers-own [
	powersupply
	max-power-supply
	supplyvoltage
]

pvs-own [
	production
]

evs-own [
	charging-demand
]

batteries-own [
	capital-costs
	operational-expenses
	energy-stored
	min-energy
	max-energy
	min-energy-designed
	max-energy-designed
	max-power-charge
	max-power-discharge
```

```
        battery-demand
        batteries-voltage
        Nc
        Nd
        SOC
        battery-type
        count-cycles
        declared-cycles
        wear-level
]
```

8.5 Setup procedure

```
to setup
    clear-all

    set deltaT 0.25 ; uren

    set-default-shape dwellings "house"
    set-default-shape nodes "dot"
    set-default-shape transformers "factory"
    set-default-shape batteries "star"
    set-default-shape evs "car"
    set-default-shape pvs "sun"

    set pv-pattern CSV:from-file "consumption-patterns/pv-5kwp.CSV"

    ;;;;;;;;;;;;;;;;;;;;;
    ;;;;; GIS stuff ;;;;;

    set building-footprints gis:load-dataset "GIS/building-footprints.shp"
    set dwellings-points-gis gis:load-dataset "GIS/points.shp"
    set nodes-gis gis:load-dataset "GIS/nodes.shp"
    set transformers-gis gis:load-dataset "GIS/transformers.shp"
    gis:set-world-envelope  (gis:envelope-union-of  (gis:envelope-of  building-
footprints) (gis:envelope-of transformers-gis) (gis:envelope-of nodes-gis))

    display-structures
    display-buildings
    display-transformers
    display-grid

    render-grid

    if battery-implementation = "HD" [ask n-of add-N-of-storage dwellings [add-a-
battery-hd]]
    if battery-implementation = "Blue" [ask n-of add-N-of-storage dwellings [add-a-
battery-blue]]
    if  battery-implementation  =  "HBr"  [ask  n-of  add-N-of-storage  nodes  [add-a-
battery-hbr]]
    if battery-implementation = "Random" [
        ask n-of (random add-N-of-storage) dwellings [add-a-battery-hd] ask n-of
(random add-N-of-storage ) dwellings with [any? batteries-here = false] [add-a-
battery-blue] ask n-of random 2 nodes [add-a-battery-hbr]]

    calculate-flows
    calculate-delta-v


    if PV-to-add > 0 and (scenario = "summer-baseline" or scenario = "summer-worst-
case") [
      ask n-of PV-to-add dwellings [
        ask min-one-of patches with [count turtles-here = 0 and distance myself >
0.5] [distance myself][
          sprout-pvs 1 [
          create-link-from min-one-of dwellings [distance myself]
          set color yellow
```

```
          set size 0.8
          ]
        ]
      ]
    ]

    if EV-to-add > 0 and (scenario = "winter-baseline" or scenario = "winter-worst-
case") [
      ask n-of EV-to-add dwellings [
        ask min-one-of patches with [count turtles-here = 0 and distance myself >
0.2] [distance myself][
          sprout-evs 1 [
          create-link-from min-one-of dwellings [distance myself]
          set color violet
          set size 0.8
          ]
        ]
      ]
    ]

    set energy-wasted 0
    set energy-supplied 0
    set energy-consumed 0
    set CAPEX sum [capital-costs] of batteries
    set OPEX sum [operational-expenses] of batteries
    set TCO CAPEX + OPEX
    set smart-grid-performance 0
    set temperature-start 100000
    set temperature temperature-start
    set best-solution 0
    set last-solution 0
    set best-performance 0
    set last-performance 0
    set high-bandwidth 0
    set resistance-per-km 0.206
    set i 0

    file-close
    reset-ticks

    set hours floor ((i - floor (i / 96 ) * 96) / 4)
    set day   floor (i / 24 / 4 )


end
```

8.6 GIS related procedures

```
to display-structures

  gis:set-drawing-color grey
  gis:draw building-footprints 1

end

to display-buildings

  gis:set-drawing-color red
  gis:draw dwellings-points-gis 1

  foreach gis:find-features dwellings-points-gis "ADDR_STREE" "Ruigenhoek"
  [
    let location gis:location-of (first (first (gis:vertex-lists-of ?)))
    if not empty? location
    [
      create-dwellings 1
      [
        let nr gis:property-value ? "profilenr"
        set  demandprofiles  CSV:from-file    word  word  word  word  "consumption-
patterns/"scenario "/" nr ".CSV"
        set temp but-first item 0 demandprofiles
        set xcor item 0 location
        set ycor item 1 location
        set label gis:property-value ? "ADDR_HOUSE"
        set color white
        set demand-pattern temp
        ]]]
end

to display-transformers

  foreach gis:feature-list-of transformers-gis
  [
    let location gis:location-of (first (first (gis:vertex-lists-of ?)))
    if not empty? location
    [
      create-transformers 1
      [
        set xcor item 0 location
        set ycor item 1 location
        set supplyvoltage 415
        set color red
        set max-power-supply 315
        ]
      ]
    ]
end

to display-grid

  foreach gis:feature-list-of nodes-gis
  [
```

```
    let location gis:location-of (first (first (gis:vertex-lists-of ?)))
    if not empty? location
    [
      create-nodes 1
      [
        set xcor item 0 location
        set ycor item 1 location
        set order gis:property-value ? "Order"
        set color red set size 0.5
        ]]]
end

to restore-last-configuration
  ask batteries [die]
  foreach gis:find-features last-configuration "battery-type" "hd"
  [
    let location gis:location-of (first (first (gis:vertex-lists-of ?)))
    if not empty? location
    [
      create-batteries 1
      [
        set xcor item 0 location
        set ycor item 1 location
        set color white
        set energy-stored 1.8
        set max-energy (2 * energy-stored) set min-energy (energy-stored / 0.9 * 0.2)
        set nc 0.97 set nd 0.97 set declared-cycles 2000
        set max-energy-designed max-energy set min-energy-designed min-energy
        set max-power-charge    max-energy / 4
        set max-power-discharge max-power-charge
        set batteries-voltage 400
        set capital-costs 2500
        set battery-type "hd"
        create-link-from min-one-of nodes [distance myself] [set color white]
        ]
      ]
    ]

  foreach gis:find-features last-configuration "battery-type" "blue"
  [
    let location gis:location-of (first (first (gis:vertex-lists-of ?)))
    if not empty? location
    [
      create-batteries 1
      [
        set xcor item 0 location
        set ycor item 1 location
        set color white
        set energy-stored 5
        set max-energy (2 * energy-stored) set min-energy 0
        set nc 0.9 set nd 0.9 set declared-cycles 5000
        set max-energy-designed max-energy set min-energy-designed min-energy
        set max-power-charge    3
        set max-power-discharge 3
        set batteries-voltage 400
```

```
        set capital-costs 3000
        set battery-type "blue"
        create-link-from min-one-of nodes [distance myself] [set color white]
        ]
      ]
    ]

    foreach gis:find-features last-configuration "battery-type" "hbr"
  [
    let location gis:location-of (first (first (gis:vertex-lists-of ?)))
    if not empty? location
    [
      create-batteries 1
      [
        set xcor item 0 location
        set ycor item 1 location
        set color white
        set energy-stored 125
        set max-energy (2 * energy-stored) set min-energy 0
        set nc 0.9 set nd 0.9 set declared-cycles 8000
        set max-energy-designed max-energy set min-energy-designed min-energy
        set max-power-charge    50
        set max-power-discharge 50
        set batteries-voltage 400
        set capital-costs 75000
        set battery-type "hbr"
        create-link-from min-one-of nodes [distance myself] [set color white]
        ]
      ]
    ]
end

to restore-best-configuration
  ask batteries [die]
  foreach gis:find-features best-configuration "battery-type" "hd"
  [
    let location gis:location-of (first (first (gis:vertex-lists-of ?)))
    if not empty? location
    [
      create-batteries 1
      [
        set xcor item 0 location
        set ycor item 1 location
        set color white
        set energy-stored 1.8
        set max-energy (2 * energy-stored) set min-energy (energy-stored / 0.9 * 0.2)
        set nc 0.97 set nd 0.97 set declared-cycles 2000
        set max-energy-designed max-energy set min-energy-designed min-energy
        set max-power-charge    max-energy / 4
        set max-power-discharge max-power-charge
        set batteries-voltage 400
        set capital-costs 2500
        set battery-type "hd"
        create-link-from min-one-of nodes [distance myself] [set color white]
        ]
```

```
      ]
    ]

  foreach gis:find-features best-configuration "battery-type" "blue"
  [
    let location gis:location-of (first (first (gis:vertex-lists-of ?)))
    if not empty? location
    [
      create-batteries 1
      [
        set xcor item 0 location
        set ycor item 1 location
        set color white
        set energy-stored 5
        set max-energy (2 * energy-stored) set min-energy 0
        set nc 0.9 set nd 0.9 set declared-cycles 5000
        set max-energy-designed max-energy set min-energy-designed min-energy
        set max-power-charge    3
        set max-power-discharge 3
        set batteries-voltage 400
        set capital-costs 3000
        set battery-type "blue"
        create-link-from min-one-of nodes [distance myself] [set color white]
        ]
      ]
    ]

    foreach gis:find-features best-configuration "battery-type" "hbr"
  [
    let location gis:location-of (first (first (gis:vertex-lists-of ?)))
    if not empty? location
    [
      create-batteries 1
      [
        set xcor item 0 location
        set ycor item 1 location
        set color white
        set energy-stored 125
        set max-energy (2 * energy-stored) set min-energy 0
        set nc 0.9 set nd 0.9 set declared-cycles 8000
        set max-energy-designed max-energy set min-energy-designed min-energy
        set max-power-charge    50
        set max-power-discharge 50
        set batteries-voltage 400
        set capital-costs 75000
        set battery-type "hbr"
        create-link-from min-one-of nodes [distance myself] [set color white]
        ]
      ]
    ]
end

to restore-pv-configuration
  ask pvs [die]
```

```
  foreach gis:feature-list-of gis:load-dataset "PV/pv-configs-30.shp"
  [
    let location gis:location-of (first (first (gis:vertex-lists-of ?)))
    if not empty? location
    [
      create-pvs 1
      [
        set xcor item 0 location
        set ycor item 1 location
        create-link-from min-one-of dwellings [distance myself]
        set color yellow
        set size 0.8
        ]
      ]
    ]
end
```

8.7 Grid related procedures

```
to render-grid
  ask links [die]
  stop-inspecting-dead-agents

  ask transformers [
    create-link-to min-one-of nodes [distance myself] [set color red]
  ]

  while [any? nodes with [count my-in-links = 0]][
   ask nodes with [count my-in-links = 1 and count my-out-links != order]
      [create-links-to min-n-of order nodes with [distance myself > 0 and count my-
in-links = 0][distance myself][set color red set dimensions 1]]
  ]

  ;;; connect dwellings and batteries to nodes
  ask  dwellings  [set  dwellings-voltage  400  create-link-from  min-one-of  nodes
[distance myself] [set color red]]

  while [any? nodes with [not any? my-out-links]][
    ask nodes with [not any? my-out-links] [die]
  ]
end

to calculate-flows

  ask links with [not member? end2 batteries][set linkpower "unset"]
  ask links with [member? end2 dwellings] [set linkpower [demand] of end2]
  ask links with [member? end2 pvs] [set linkpower -1 * [production] of end2]
  ask links with [member? end2 evs] [set linkpower [charging-demand] of end2]

  while [any? links with [linkpower = "unset"] ] [
    ask nodes with [count my-in-links = 1 and not any? my-out-links with [linkpower
= "unset"]] [
      set nodepower sum [linkpower] of my-out-links ask my-in-links [set linkpower
[nodepower] of end2] ]
  ]

  ask transformers [set powersupply (sum [linkpower] of my-out-links)]
end

to calculate-flows-batteries
  ask links with [member? end2 batteries] [set linkpower [battery-demand] of end2 /
[count my-in-links] of end2]
end

to calculate-delta-v

;                         (resistance per m )   (amperage     )   (length of link in
m)
  ask links [set delta-v  -1 * resistance-per-km * dimensions * linkpower / 415 *
(link-length * 4.31)] ;;;; 0.206 / 1000 is the resistance per m ;; 4.31 is the
correction factor for the link length  ;;; linkpower / 415 * 100 is the current in
the link in A
```

```
  ask nodes [set nodevoltage "unset"]
  ask transformers [ask [end2] of one-of my-out-links [set nodevoltage
[supplyvoltage] of myself + sum [delta-v] of my-in-links]]

  while [any? nodes with [nodevoltage = "unset"] ] [
    ask nodes with [nodevoltage != "unset"] [
      ask my-out-links with [not member? end2 dwellings and not member? end2
batteries] [
        ask end2 [set nodevoltage [nodevoltage] of [end1] of one-of my-in-links +
[delta-v] of myself]
      ]
    ]
  ]
  ask links     [set energyloss -1 * linkpower / sum [supplyvoltage] of transformers
* delta-v]
  ask dwellings [set dwellings-voltage mean [delta-v] of my-in-links + [nodevoltage]
of [end1] of one-of my-in-links]
  ask batteries [set batteries-voltage sum [delta-v] of my-in-links + [nodevoltage]
of [end1] of one-of my-in-links]

  let bw [dwellings-voltage] of max-one-of dwellings [dwellings-voltage] -
[dwellings-voltage] of min-one-of dwellings [dwellings-voltage]
  if bw > high-bandwidth [
    set high-bandwidth bw
  ]

end
```

8.8 Battery related procedures

```
to add-a-battery-hd ;;; currently used battery in Hoog Dalem by Victron
  ;;;; can only run in agent/turtle context. Designed for node in particular. Patch
should work too.
    ask patch-here [sprout-batteries 1 [
        set color white
        set energy-stored 0
        set max-energy 2.4
        set min-energy 0
        set max-energy-designed max-energy
        set min-energy-designed min-energy
        set max-power-charge    max-energy / 4
        set max-power-discharge max-power-charge
        set nc 0.97 set nd 0.97 set declared-cycles 2000
        set batteries-voltage 400
        set capital-costs 2500
        set battery-type "hd"
        create-link-from min-one-of nodes [distance myself] [set color white]]];]
end

to add-a-battery-blue ;;;blue battery salt water
  ;;;; can only run in agent/turtle context. Designed for node in particular. Patch
should work too.
    ask patch-here [sprout-batteries 1 [
        set color white
        set energy-stored 0
        set max-energy 10
        set min-energy 0
        set max-energy-designed max-energy set min-energy-designed min-energy
        set max-power-charge    3
        set max-power-discharge 3
        set nc 0.9 set nd 0.9 set declared-cycles 5000
        set batteries-voltage 400
        set capital-costs 3000
        set battery-type "blue"
        set shape "star-blue"
        create-link-from min-one-of nodes [distance myself] [set color white]]];]
end

to add-a-battery-hbr ;;;hbr battery
  ;;;; can only run in agent/turtle context. Designed for node in particular. Patch
should work too.
    ask patch-here [sprout-batteries 1 [
        set color white
        set energy-stored 0
        set max-energy 250
        set min-energy 0
        set max-energy-designed max-energy set min-energy-designed min-energy
        set max-power-charge    50
        set max-power-discharge 50
        set nc 0.9 set nd 0.9 set declared-cycles 8000
        set batteries-voltage 400
        set capital-costs 75000
```

```
        set battery-type "hbr"
        set shape "star-brown"
        create-link-from min-one-of nodes [distance myself] [set color white]]];]
end

to battery-ifthenelse

  if battery-enabled = true [

    if target = "Compliance" and (scenario = "summer-baseline" or scenario = "summer-
worst-case") [
      battery-logic-regular-summer
    ]

    if target = "Smarter" and (scenario = "summer-baseline" or scenario = "summer-
worst-case")[
      battery-logic-smarter-summer
    ]

    if target = "Voltage-controled" and (scenario = "summer-baseline" or scenario =
"summer-worst-case")[
      battery-logic-voltage-summer
    ]

    if target = "Compliance" and (scenario = "winter-baseline" or scenario = "winter-
worst-case") [
      battery-logic-regular-winter
    ]

    if target = "Smarter" and (scenario = "winter-baseline" or scenario = "winter-
worst-case")[
      battery-logic-smarter-winter
    ]

    if target = "Voltage-controled" and (scenario = "winter-baseline" or scenario =
"winter-worst-case")[
      battery-logic-voltage-winter
    ]

    ;;; constraints the battery should comply to:
    ;
    ;   Max-power-supply <= battery-demand <= Max-power-charge
    ;   min-energy <= Energy-stored <= max-energy
    ask batteries [
    ;;;; limiting power
    if battery-demand > max-power-charge            [set battery-demand max-power-
charge]
    if battery-demand < ( - max-power-discharge) [set battery-demand (- max-power-
discharge)]

    ;;; limiting capacity
    if battery-demand > 0 and (energy-stored + 0.25 * battery-demand * Nc) > max-
energy [set battery-demand (max-energy - energy-stored) * 4 / Nc]
    if battery-demand < 0 and (energy-stored + 0.25 * battery-demand * Nd) < min-
energy [set battery-demand (min-energy - energy-stored) * 4 / Nd]
```

```
    ]
  ]

  if battery-enabled = false [ask batteries [set battery-demand 0]]

end

                                 ;;;;;;;;;;;;;;;;;;;;;
                                 ;;;;;          ;;;;;
                                 ;;;;;   Winter   ;;;;;
                                 ;;;;;   Regular  ;;;;;
                                 ;;;;;          ;;;;;
                                 ;;;;;;;;;;;;;;;;;;;;;

to battery-logic-regular-winter

    if hours = 6 or hours = 15 or hours = 0 [
      ask batteries [set battery-demand 0]
    ]

    if hours >= 0 and hours < 6 [
      ask batteries with [battery-demand = 0][
        set battery-demand (max-energy - energy-stored) / (5 - hours)
      ]
    ]

    if (hours >= 6 and hours < 15) [
      ask batteries with [sum [demand] of dwellings-here > 0 and battery-demand = 0][
        set battery-demand (min-energy - energy-stored) / 3 / (23 - hours)
      ]

      ask batteries with [[nodepower] of [end1] of one-of my-in-links > 0 and battery-
demand = 0][
        set battery-demand (min-energy - energy-stored) / 3 / (23 - hours)
      ]
    ]

    if (hours >= 15 and hours < 23) [
      ask batteries with [sum [demand] of dwellings-here > 0 and battery-demand = 0][
        set battery-demand (min-energy - energy-stored) / (23 - hours)
      ]

      ask batteries with [[nodepower] of [end1] of one-of my-in-links > 0 and battery-
demand = 0][
        set battery-demand (min-energy - energy-stored) / (23 - hours)
      ]
    ]

end


                                 ;;;;;;;;;;;;;;;;;;;;;
                                 ;;;;;          ;;;;;
                                 ;;;;;   Summer   ;;;;;
                                 ;;;;;   Regular  ;;;;;
```

```
                                ;;;;;           ;;;;;
                                ;;;;;;;;;;;;;;;;;;;;;;

to battery-logic-regular-summer
  let supply-temp sum [powersupply] of transformers

    if hours = 6 or hours = 18 [
      ask batteries [set battery-demand 0]
    ]

    if hours >= 6 and hours < 17 [
      ask batteries with [sum [demand] of dwellings-here < 0 and battery-demand = 0][
        set battery-demand (max-energy - energy-stored) / (17 - hours)
      ]
      if supply-temp < 0 [
        ask batteries with [battery-demand = 0] [
          set battery-demand (max-energy - energy-stored) / (17 - hours)
        ]
      ]
    ]

    if (hours >= 18 and hours <= 23) or ( hours >= 0 and hours < 6) [
      ask batteries with [sum [demand] of dwellings-here > 0 and battery-demand = 0][
        set battery-demand (min-energy - energy-stored) / 10
      ]

      ask batteries with [[nodepower] of [end1] of one-of my-in-links > 0 and battery-
demand = 0][
        set battery-demand (min-energy - energy-stored) / 10
      ]
    ]

end


                                ;;;;;;;;;;;;;;;;;;;;;;
                                ;;;;;           ;;;;;
                                ;;;;;   Summer  ;;;;;
                                ;;;;;   Smarter ;;;;;
                                ;;;;;           ;;;;;
                                ;;;;;;;;;;;;;;;;;;;;;;
to battery-logic-smarter-summer
  let supply-temp sum [powersupply] of transformers
  let total-energy-stored sum [energy-stored] of batteries - sum [min-energy] of
batteries
  let total-capacity-available  sum [max-energy] of batteries - sum [energy-stored]
of batteries

  ifelse supply-temp < 0 and total-capacity-available > 0 [
    ask batteries with [soc < 100] [
      set battery-demand -1 * supply-temp * (max-energy - energy-stored) / total-
capacity-available
    ]
  ]
  [
```

```
   ifelse ((hours >= 17 and hours < 24) or (hours >= 0 and hours <= 9) )and total-
energy-stored > 0[
      ask batteries with [soc > 0] [
        set battery-demand -1 * (0.7 + 0.3 * soc / 100) * supply-temp * (energy-
stored - min-energy) / total-energy-stored
      ]
   ]
   [
      ask batteries [
        set battery-demand 0
      ]
    ]
  ]
end



                                 ;;;;;;;;;;;;;;;;;;;;;;
                                 ;;;;;           ;;;;;
                                 ;;;;;   Winter   ;;;;;
                                 ;;;;;   Smarter  ;;;;;
                                 ;;;;;           ;;;;;
                                 ;;;;;;;;;;;;;;;;;;;;;;
to battery-logic-smarter-winter
  let supply-temp sum [powersupply] of transformers
  let supply-max  sum [max-power-supply] of transformers

  if hours > 0 and hours < 6 [
    ask batteries with [SOC < 100][
      set battery-demand max-power-charge
    ]
  ]
  if supply-temp > supply-max [
    ask batteries with [SOC > 0][
      set battery-demand -1 * max-power-discharge
    ]
  ]
end
                                 ;;;;;;;;;;;;;;;;;;;;;;
                                 ;;;;;           ;;;;;
                                 ;;;;;   Summer   ;;;;;
                                 ;;;;;   voltage  ;;;;;
                                 ;;;;;           ;;;;;
                                 ;;;;;;;;;;;;;;;;;;;;;;
to battery-logic-voltage-summer
  let supply-temp sum [powersupply] of transformers
  let total-energy-stored sum [energy-stored] of batteries - sum [min-energy] of
batteries
  let total-capacity-available  sum [max-energy] of batteries - sum [energy-stored]
of batteries

  ifelse [dwellings-voltage] of max-one-of dwellings [dwellings-voltage] > 420 and
total-capacity-available > 0 [
    ask batteries with [soc < 100] [
      set battery-demand -0.5 * supply-temp * (max-energy - energy-stored) / total-
capacity-available
```

```
    ]
  ]
  [
   ifelse ((hours > 18 and hours < 24) or (hours >= 0 and hours <= 9) ) and total-
energy-stored > 0[
      ask batteries with [soc > 0] [
        set battery-demand -0.4 * max-power-discharge
      ]
   ]
   [
      ask batteries [
        set battery-demand 0
      ]
    ]
  ]
end

                                 ;;;;;;;;;;;;;;;;;;;;;;
                                 ;;;;;            ;;;;;
                                 ;;;;;   Winter   ;;;;;
                                 ;;;;;   voltage  ;;;;;
                                 ;;;;;            ;;;;;
                                 ;;;;;;;;;;;;;;;;;;;;;;
to battery-logic-voltage-winter
  let supply-temp sum [powersupply] of transformers
  let supply-max  sum [max-power-supply] of transformers
  let total-energy-stored sum [energy-stored] of batteries - sum [min-energy] of
batteries
  let total-capacity-available  sum [max-energy] of batteries - sum [energy-stored]
of batteries

  ifelse supply-temp > supply-max and total-energy-stored > 0[
    ask batteries with [soc > 0] [
      set battery-demand (supply-temp - supply-max) * (min-energy - energy-stored) /
total-energy-stored
    ]
  ]
  [
   ifelse (hours >= 0 and hours < 6) and supply-temp < supply-max [
      ask batteries with [soc < 100] [
        set battery-demand supply-max - supply-temp
      ]
   ]
   [
      ask batteries [
        set battery-demand 0
      ]
    ]
  ]
end

to battery-maths

  ask batteries with [battery-demand > 0] [set energy-stored (energy-stored + 0.25 *
battery-demand * Nc)]  ;;want to use globals instead of 0.25?
```

```
  ask batteries with [battery-demand < 0] [set energy-stored (energy-stored + 0.25 *
battery-demand * Nd)]

  ask batteries [
    set SOC (energy-stored - min-energy) / (max-energy - min-energy) * 100
    set count-cycles (count-cycles + 0.5 * abs battery-demand * 0.25 / (max-energy -
min-energy))
    set wear-level count-cycles / declared-cycles * 100
    set max-energy max-energy-designed * (1 - 0.2 * wear-level / 100 )
    set min-energy min-energy-designed * (1 - 0.2 * wear-level / 100 )

    ifelse hours >= 7 and hours <= 22 [ ;;;high price
      ;set operational-expenses operational-expenses + abs battery-demand * (1 - Nc
+ 1 - Nd) / 2 * buy-price-high this is already in calculated in the following prices

      ifelse battery-demand > 0[
        set  operational-expenses  operational-expenses  +  battery-demand  *  0.25  *
Operator-energy-price
      ]
      [
        set  operational-expenses  operational-expenses  +  battery-demand  *  0.25  *
Operator-energy-price
      ]
    ]
    [
      ifelse battery-demand > 0[
        set  operational-expenses  operational-expenses  +  battery-demand  *  0.25  *
Operator-energy-price
      ]
      [
        set  operational-expenses  operational-expenses  +  battery-demand  *  0.25  *
Operator-energy-price
      ]
    ]
  ]

end
```

8.9 Go procedure

```
to go
  set i i + 1

  if temperature = 0 or (annealing = false and i = length temp) [
    print "This is the end"
    stop
  ]

  set temperature temperature-start * exp (-0.1 * ticks / length temp)

  ;;;;  simulated annealing stuff
  if i = length temp [

    simulated-annealing

    ask batteries [
      set operational-expenses 0
      set energy-stored 0
      set count-cycles 0
    ]

    set energy-wasted 0
    set energy-supplied 0
    set energy-consumed 0
    set CAPEX 0
    set OPEX 0
    set TCO 0
    set smart-grid-performance 0
    set i 0
  ]
  set quarter i - day * 24 * 4 - hours * 4
  set hours floor ((i - floor (i / 96 ) * 96) / 4)
  set day   floor (i / 24 / 4 )

  ifelse hours >= 18 and hours <= 23 [
    ask evs [
      set charging-demand 6
    ]
  ]
  [
    ask evs [
      set charging-demand 0
    ]
  ]

  ask pvs [
    set production item 0 item (i - day * length pv-pattern) pv-pattern / 1000
  ]

  ask dwellings [
    set demand-inhouse item i demand-pattern / 1000
    set demand demand-inhouse + sum [linkpower] of my-out-links
```

```
    ]

  ask links with [ member? end2 batteries][set linkpower 0]

  calculate-flows
  calculate-delta-v

  battery-ifthenelse

  calculate-flows-batteries
  calculate-flows
  calculate-delta-v

  battery-maths
;
;  calculate-flows
;  calculate-delta-v

  ask dwellings with [demand < 0] [set color green]
  ask dwellings with [demand = 0] [set color white]
  ask dwellings with [demand > 0] [set color red]

  ask links with [not member? end2 pvs ][set color red set thickness abs linkpower /
100]
  ask links with [linkpower < 0] [set color green]
  ask links with [linkpower = 0] [set color white]

  ask nodes                      [set color red]
  ask nodes with [nodepower < 0] [set color green]
  ask nodes with [nodepower = 0] [set color white]

  ask batteries with [battery-demand > 0] [set color red]
  ask batteries with [battery-demand < 0] [set color green]
  ask batteries with [battery-demand = 0] [set color white]

  ask links with-max [abs linkpower] [set color yellow]
  ask dwellings with-max [abs (dwellings-voltage - 400)][set color orange]

  foreach [energyloss] of links [set energy-wasted energy-wasted + abs ? * 0.25]
  set energy-wasted energy-wasted + 0.055 * 0.25 * abs sum [powersupply] of
transformers ;;;;;; + energy wasted in storage? in kwh
  set energy-consumed energy-consumed + sum [demand] of dwellings * 0.25

  set energy-supplied energy-supplied + sum [abs powersupply] of transformers * 0.25

  if sum [powersupply] of transformers < 0 [set reverse-power-supplied reverse-power-
supplied + abs sum [powersupply] of transformers * 0.25]

  ask dwellings with [dwellings-voltage > 420] [set smart-grid-performance smart-
grid-performance + (dwellings-voltage - 420) ^ 2]
  ask dwellings with [dwellings-voltage < 380] [set smart-grid-performance smart-
grid-performance + (dwellings-voltage - 380) ^ 2]
```

```
  ask transformers with [powersupply > max-power-supply] [set smart-grid-performance
smart-grid-performance + (powersupply - max-power-supply)]
 ; ask transformers with [powersupply < 0] [set smart-grid-performance smart-grid-
performance + abs powersupply]


  set CAPEX sum [capital-costs] of batteries
  ifelse scenario = "summer-baseline" or scenario = "summer-worst-case" [
    set OPEX sum [operational-expenses] of batteries * 15 * 10.7 * 0.7 ;;;; 0.7 is
the correction for the cycling of storage gets used less in may and september etc.
they are either half cycles, full cycles or something in between and length of dataset
is 17 days of the half year so 10.7 times the opex
  ]
  [
    set OPEX sum [operational-expenses] of batteries * 15 * 26 * 0.9  ;;;;; 7 days
in dataset so times 26 and not always there will be these full cycles so corrected
by 0.9
  ]
  set OPEX OPEX + count batteries with [battery-type = "hbr"] * 500 * 15 ;;; about
500 per year in maintainance required * 15 years
  set TCO CAPEX + OPEX

  tick
end
```

8.10 Simulated annealing procedure

```
to simulated-annealing

  if temperature < 2 [
    set temperature 0
    stop
  ]

  if last-solution = 0 [
    print word "Found starting solution at tick " ticks
    print word "The TCO is " TCO
    print word "The performance of the grid is " round smart-grid-performance

    set last-solution TCO
    set last-performance smart-grid-performance
    ifelse any? batteries [
      set last-configuration gis:turtle-dataset batteries
    ]
    [
      set last-configuration 0
    ]
  ]

  if smart-grid-performance < performance-constraint and best-solution = 0[
    print word "Found initial solution!! At tick " ticks
    print word "The TCO is " TCO
    print word "The performance of the grid is " round smart-grid-performance

    set best-solution TCO
    set best-performance smart-grid-performance
    ifelse any? batteries [
      set best-configuration gis:turtle-dataset batteries
      gis:store-dataset best-configuration word word word "solutions/" scenario "/"
best-solution
    ]
    [
      set best-configuration 0
    ]
  ]


  ifelse TCO <= last-solution and smart-grid-performance < performance-constraint [
    print word "Found new solution at tick " ticks
    print word "The TCO is " TCO
    print word "The performance of the grid is " round smart-grid-performance

    set last-solution TCO
    set last-performance smart-grid-performance
    set last-configuration gis:turtle-dataset batteries

    if last-solution < best-solution [
      print word "Found (new) best solution!! At tick " ticks
      print word "The TCO is " TCO
```

```
      print word "The performance of the grid is " round smart-grid-performance

      set best-solution TCO
      set best-performance smart-grid-performance
      set best-configuration gis:turtle-dataset batteries
      ifelse any? batteries [
        set best-configuration gis:turtle-dataset batteries
        gis:store-dataset best-configuration word word word "solutions/" scenario "/"
best-solution
      ]
      [
        set best-configuration 0
      ]
    ]
  ]
  [
    ifelse exp(-(TCO - last-solution) / temperature) > random-float 1 [
      print word "Accepting poorer solution at tick " ticks
      print word "The TCO is " TCO
      print word "The performance of the grid is " round smart-grid-performance

      set last-solution TCO
      set last-performance smart-grid-performance
      ifelse any? batteries [
        set last-configuration gis:turtle-dataset batteries
      ]
      [
        set last-configuration 0
      ]
    ]
    [
      print word "Rejecting poorer solution at tick " ticks
      print word "The TCO is " TCO
      print word "The performance of the grid is " round smart-grid-performance

      restore-last-configuration
    ]
  ]

  ;;;;;;;;;;;; changing the configuration, smartly: if the restictions are met remove
one of batteries, if restrictions are not met add batteries
  ifelse last-performance < performance-constraint [

    let amount 1 + random 3 + temperature / 100000 * random 6

    if amount > count batteries[
      set amount count batteries
    ]

    ask n-of (amount) batteries [print word "Removed a battery of type " battery-
type die]
  ]
  [
    let bat-add random 3
```

```
    if bat-add = 0 [
      ask n-of (1 + temperature / 100000 * random 5) dwellings [
        add-a-battery-hd
        print "added a HD battery"
      ]
    ]

    if bat-add = 1 [
      ask n-of (1 + temperature / 100000 * random 3) dwellings [
        add-a-battery-blue
        print "added a Blue battery"
      ]
    ]

    if bat-add = 2 [
      ask n-of 1 nodes [
        add-a-battery-hbr
        print "added a HBr battery"
      ]
    ]
  ]
end
```