Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Electric Power Engineering

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Model Development for coordination of flexibility resources in grid connected Local Energy Communities

Master's thesis in Energi & Miljø
Supervisor: Hossein Farahmand
Co-supervisor: Dmytro Ivanko
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Preface

This master thesis concludes a five year study program at the study program *Energi & Miljø* at NTNU, Trondheim. The work has been conducted at the Department of Electric Power Engineering with the supervision of Professor Hossein Farahmand and co-supervision of the postdoctoral researcher Dmytro Ivanko.

Firstly, a big thanks is issued towards my supervisors, especially to Dmytro Ivanko for assisting my throughout my work, in particular with the coding work in this thesis. This work would not have been concluded without him.

Another big thanks has to be given to all classmates and fellow students who have made the last five years a fantastic experience. Lastly, I would like to thank all my friends and family who have been of great support throughout my study period.

Trondheim, November 15, 2022
Jørgen K. Pedersen

Abstract

With a rapid increase of intermittent energy resources in the European power mix, the need of new ways to control the market are present. These new renewable assets have a great effect on the environmental aspects of the power generation but can be stressful both for the market operators and the grid itself. Implementing flexibility assets can be of great help in reducing this stress.

Firstly, this thesis will perform an analysis based on the current literature about the different flexibility assets currently available. With flexibility resources present in the power market new actors come in to play, and these will also be described, and their contribution will be explained.

During the work on this thesis a model to simulate the effects of introducing flexibility assets in a Local Energy Community has been created. The way this model has been implemented and what it can do will be explained.

To showcase the model's capabilities, a case study has been created and carried out. This case study with is firstly presented before the results of the simulations are presented and discussed. The results shows that the model can simulate the effects of the integration of flexibility assets in a Local Energy community, and that it can be a useful tool when deciding which flexibility asset is most useful for a given grid.

Sammendrag

De siste tiårene har det vært en rask økning i mengden ikke regulerbare energiressurser i den europeiske kraftmiksen, noe som har ført til et behov for nye måter å kontrollere kraftmarkedet på. Disse nye kraftressursene har en stor positiv effekt på klimaet, men kan være belastende for både nettverksoperatør og kraftnettet å håndtere. Implementering av fleksibilitetsressurser kan være til stor hjelp for å redusere denne belastningen.

Denne masteroppgaven vil først gjennomføre en undersøkelse basert på den nåværende litteraturen om de forskjellige tilgjengelige fleksibilitetsressursene. Innføringen av disse ressursene i kraftmarkedet fører til at nye aktører kommer på banen, disse vil bli presentert og deres roller vil bli forklart.

I arbeidet med denne oppgaven har det blitt laget en modell for å simulere effektene av å introdusere fleksibilitetsressurser i et Lokalt Energi Samfunn (LEC). Hvordan denne modellen er laget, og dens formål vil bli beskrevet.

For å vise frem hva modellen er i stand til, er det laget og gjennomført et eksempelstudie. Dette studiet vil først bli presentert, før resultatene vil bli gjennomgått og diskutert. Resultatene viser at modellen er i stand til å simulere effektene av fleksibilitetsressursene i et Lokalt Energi Samfunn, og at modellen kan være et nyttig verktøy for å avgjøre hvilken fleksibilitetsressurs som er til størst nytte for et gitt kraftnett.

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1 Introduction

To reach the climate goals issued by the United Nations within 2030, an increase in renewable power generation is pivotal. Renewable energy sources like wind and solar are intermittent, meaning that they only produce when the weather conditions are correct or optimal. It can be difficult to secure reliable power supply in a power system with a high percentage of intermittent power generation. Flexibility resources distributed across the grid will have a big impact in securing supply and to avoid expensive grid upgrades. In this thesis the flexibility resources that will be investigated are flexible generation and batteries installed in the low voltage grid. In the rest of this chapter the motivation behind-, the scope of-, the objective of- and the structure of this thesis will be presented.

1.1 Motivation

There has been a great increase in the power demand both in Norway and in the rest of the world in the past decades. This increase puts stress both on the power generation capacities in areas as well as on the grid infrastructure. To reduce this stress the implementation of flexibility resources in the low voltage grid can be highly beneficial. This again creates the need for clearing a market with actors that previously have not existed. The biggest motivation for this thesis is to develop a model that can simulate a market with all these new actors, and which can optimize the market clearing to minimize costs.

1.2 Objective

The objective this thesis is to develop a model capable of simulating the effects of introducing different flexibility resources into the low voltage grid. The model should be able to simulate entire Local Energy Communities (LEC) in connection to the distribution grid, and to showcase the effects the different flexibility resources have on the economical dispatch in the system. In addition, the thesis will aim to investigate the effects a grid tariff on all power purchased into a LEC will have on both the market and how it effects the amount of power the LEC generates itself and chooses to import.

1.3 Structure

This thesis will be divided into eight chapters, this section will give a quick introduction to what each chapter will be about and its contribution to the thesis. The first chapter is the introduction which will introduce and define the problem which will be investigated.

The second chapter will review the different flexibility assets available, and how they can be used as problem solvers in the grid.

The third chapter explores the coordination of the flexibility market and its participants. Furthermore, the choice of the model used in this thesis will be justified here.

The fourth chapter is the method chapter. This includes the mathematical formulations for the model, which forms the basis for the entire work.

The fifth chapter will introduce the case study which has been conducted. A description of each scenario, and all premises for the simulation will be explained here.

The sixth chapter will present all results from the simulation on the scenarios presented in chapter five.

The seventh chapter will discuss all results from the sixth chapter and explore whether the objectives presented in last section were met.

The eighth chapter is conclusion and further work, this will conclude the thesis by answering if the objectives of the work was met as well as suggesting further work that can be conducted.

2 Flexibility analysis

Historically the power system in Norway has been built up by a few big power producers, and many small or medium-sized consumers. The main power producers in Norway are either fossil or hydropower stations, meaning that production can be adjusted to meet the demands of the consumers. With the rapid integration of non-consistent renewable energy sources such as wind and solar, combined with aging grid infrastructure, there is a need for a new way to operate the power system (2). The grid upgrades is extremely expensive and mainly necessary to cover peak energy demand for short time periods throughout the day (3). In these conditions, the utilization of flexibility assets from the consumer side to reduce peak energy demand in the grid looks like a much more promising and cost-efficient alternative that can postpone upgrading existing grids and building new ones.

In this section, we will look at the different flexibility resources, how they are operated, and what kind of services they can provide. The new way of operating the local flexibility market will also be presented. In addition, it will be explained which party in the flexibility market is responsible for which role, and who controls the production of flexibility resources. We will also investigate local energy communities (LECs) as a source of flexibility and how they are built and operated.

2.1 Flexibility resources

Flexibility resources in the power grid are energy resources distributed across the grid, often operated by what before was recognized as consumers. There are several reasons for their implementation. From the consumer side, revealing flexibility assets will allow us to lower energy bills or get additional discounts for electricity use. From the side of the grid operator, flexibility resources are a powerful instrument for reducing operating costs and avoiding expensive upgrades to the grid (4).

In this section, different flexibility resources will be presented, with pros and cons, and examples of implementation.

2.1.1 Energy storage systems

In an energy market with a high percentage of variable renewable energy sources energy storage systems (ESS) are a very effective way of increasing flexibility. With various production throughout the day and week, and with a mismatch in peak production and peak consumption, the effects of storing away the surplus energy during time slots with high production is key to having a functional and effective energy market (5).

ESS is a collective term for many different technologies with the most prolific ones being battery storage, pumped hydro, hydrogen, and thermal and compressed air storage. The main properties of ESS are storage capacity, charge and discharge rate, efficiency, and response time.

From the grid's perspective, the ESS can be viewed both as a consumer or a producer, depending on its current situation. The services it provides to the grid are voltage control, supply reserve, and congestion management. ESS will also be beneficial in terms of peak-shaving, especially if there is a very high short-period peak in the system. From the battery owners perspective the battery can be used as a trading device, i.e., that it can be used to buy energy when the prices in the market are low, and subsequently sell the energy when the prices are high (6).

One example of an implemented ESS is with electric ferries. They need a very large amount of power in a short period of time which can be extremely difficult for the grid to cope with, especially since the docks often are placed in the outskirts of the grid. With an ESS placed nearby the docks, the load needed to supply this ferry can be spread more evenly throughout the day (7).

2.1.2 Dispatchable power plants

Where most of the newer renewable power sources has variable production, the fossil power plants are dispatchable, meaning they can increase or reduce production on command from a system operator at any given time. (8) Although the aim is to reduce the usage of these power sources as much as possible, the necessity of having a decent capacity reserve of dispatchable power in a market is paramount. However, the dispatchable capacities does not have to be fossil, but can come from low or zero emission sources such as hydro power or hydrogen plants.

The main properties of DPP are their size (maximum output), the variability of production (if it only can be on/off or anything in between) and their location in the grid. Depending on size and location DPP can be used for congestion management, upping voltages in the outer parts of the grid and increasing security of supply.

In Europe's energy market Norway with its hydro power capacity acts sort of like a DPP for other countries, being able to deal with fluctuations in the wind and solar production in Denmark and Germany. (9)

2.1.3 Demand side responses

Demand side responses (DSR) include all the flexibility measures that can be taken on the demand side to allow for various production in the market. These measures are described in the list below.

Load shifting

So far we have mostly discussed the flexibility actions that can be taken by the supply side in order to meet the demands during the peak hours. Another way to increase the flexibility in a market is to have shift-able loads. This means that the load complies to the generation instead of the other way around(10). One example of this is tap-water heating or space heating, which can be turned on and off depending on the available power. New electronic devices often comes with a timer, meaning that the consumer can decide to run its dishwasher or washing machine at off-peak hours, which will be of benefit both for the grid, and for the consumer itself. Although an interesting flexibility asset, load shifting will not be investigated in the case study part of this thesis.

Real-time pricing/Time-of-use

Real-time pricing in a system is when the energy price given to the customers varies throughout the day, allowing the customers to reduce their consumption when the prices are high, and increase it when prices are low. Although real-time pricing is not really a flexibility resource, having this pricing mechanism in the system can be of great benefit if the consumers are aware of it. This is very comparable to load-shifting, or even a form of it, but rather than having loads in the system that can consume only when needed, this happens automatically from prices being high during peak hours and low during the off-peak hours.

Load shedding

Although not really a flexibility asset, load shedding can be considered a final remedy to avoid dangerously low voltages in the system (11). It should only be used when no other options are viable. In these cases, it is necessary for the network operator to know which loads are possible to shed, and the costs of shedding each of these loads. Load shedding differs from load shifting in the term that you fully neglect the given load or a part of it instead of just changing the time it's active.

2.2 Flexibility resources as a problem solver in the grid

In this section we will investigate the different problems that occur in the power system and how flexibility resources aim to solve them. We will look at voltage and congestion problems, as these are the problems that will be investigated further in the thesis.

2.2.1 Voltage problems

Whenever power flows through a line with a given resistance a voltage drop between the nodes will occur. If the loads in a system is greater than what the lines in the system are designed for, the voltage at the receiving node can become so low that the connected electronic devices can be damaged. The same applies if the voltage at a given node becomes too high.

For example, in a rural part of the grid, a long distance from the nearest power generation, the voltages may fall under the accepted limits. One way of solving this problem is to install a DPP in these exposed areas to boost the voltage away from the danger zones.

2.2.2 Congestion problems

Congestion problems in the grid occur either when the total load in the system is too big to handle energy consumption in peak hours or when for some reason a line goes fault and either dysfunction as a whole or its capacity gets reduced drastically.

One way to manage these peak hours is to either have a capacity of stored energy (ESS) in the grid, a capacity of DPP or a combination of both. In terms of line faults, if the flexibility capacity is big enough it can also support the required loads until the problem gets resolved.

2.3 Local energy communities

A local energy community (LEC) can be defined as a small subsystem in the grid that tries to be self-sustained with both production and flexibility resources. However, LECs can be independent (disconnected) from the gird as well, in this case it must be self-sustained. (12) In this study, we will only focus on the grid connected LECs. From the grids point of view the LEC as a whole can be seen as either a producer or consumer in the grid, depending on whether it produces more or less than its own consumption.

A local energy community can be the size of a small neighbourhood, or the size of a small city. In this thesis we will focus on relatively small LECs. The way they are organized is that the parties in the community work together to reduce the amount of energy purchased into the system as much as possible.(13) The incentives for the participants in the community are lower prices for their energy as well as reducing their own carbon footprint. For the grid operators and the owners of the grid (often state or county owned) there are also incentives in form of reduced maintenance costs. Figure 1 is a model of a small LEC consisting of five residential homes, all with solar panels on the roof. Two of the homes have Electric vehicles which can act as ESS's for the LEC. With no other energy source in place this LEC will have to purchase energy during the night and on cloudy days.

Figure 1: A small LEC with solar production and car batteries as ESS, from (1)

In Norway there is an added tax to each kWh that is bought which goes to the grid operators to cover parts of the maintenance and upgrade costs of the grid.(14) One incentive for LECs is that this tax will be avoided for all energy produced within the LEC, and will only be paid for the energy transferred into it. The effects of an implementation of a grid tariff will be looked at in the case study section of this thesis, and the effects it has on the usage of the flexibility resources in the grid will be discussed in chapter 7.

3 Flexibility market coordination

This section will provide the basis for which the model used in this thesis is built upon. The choices made when choosing the optimization algorithms for the different market entities will be described and justified. Furthermore, the different actors in a flexibility market will be introduced and their roles and responsibilities in the market will be explained. Section 3.1 will describe the different participants in the market and section 3.2 will explain the basis of which the model is built upon.

3.1 The market participants

The energy market consists of several different participants with different roles and objectives. In this section we will investigate the most important ones for this thesis and which role they play in coordinating and regulating the market efficiently.

3.1.1 From consumers to prosumers

In the past the consumers in an energy market have played a passive role, being considered loads for the DSO, which it needs to supply. Now however, with more and more consumers offering distributed energy resources to the market, the situation has changed drastically. A lot of buildings have installed generation capacities of their own, for example in the form of rooftop mounted solar panels. These installations will be used to supply the buildings themselves primarily, but when they produce more than the building consume this will be sold back into the grid. This creates a bidirectional flow in the grid, which can be difficult for the grid to cope with.

3.1.2 DSO as Balancing responsible party

The balancing responsible party (BRP) is responsible for balancing production and consumption in the market, i.e, to manage the different flexibility resources in the system depending on current production and demand. (15). In this system, the natural BRP will be the DSO as they are the grid owner, and ultimately the one responsible for answering to a higher entity (TSO) in the power system.

3.1.3 Aggregators role in a flexibility market

In a flexibility market, an aggregator acts as a broker for energy transactions between the flexibility owners, often the prosumers in the market the BRP and the DSO.(16) An aggregator is typically either the utility company itself or commercial aggregators. Their main objective is to enable the prosumers or other flexibility owners in the market to participate in the market so that they can transact their flexibility at the correct prices in the market.

A key technology for the aggregators is smart metering and real-time communication with these systems. As of 2019 all houses in Norway were required to install such a smart meter, which can provide essential information to the aggregator.(17)

One example of a resource that an aggregator can control is all the electric vehicles in a parking garage. These cars and their batteries are connected to the grid, and together they provide a significant ESS that the rest of the grid can benefit from. Every single car owner cannot be bothered to buy and sell the energy inside their vehicle on their own, but an aggregator can take this responsibility for them.

3.2 Flexibility market modeling

This section aims to provide reasoning and justification for the choices of market clearing methods used in the thesis. The mathematical formulations in the chapter 4 is built on the choices described in this section.

Optimal power flow (OPF) is a powerful tool when optimizing the flow and generation in a system. It helps reduce costs and losses in the system and helps to determine the optimal usage of generation (if plural) in the system in accordance with the given restrictions.

In this thesis the OPF will not only be solved once, but 96 times (each 15 minutes), and the OPF for each time step will be dependent on the rest, as it is the total cost all time steps combined that is of interest. This means that the system requires information about the pricing for the entire day when deciding the OPF for a given time step.

It exists different ways to conduct OPF, and there are some important factors to consider when choosing the one best suited for one specific problem. The most important factors being the grid topology (meshed/radial), the ratio between the resistance and the impedance

(R/X ratio) in the system and whether there is distributed generation in the system or not. For this thesis there will be conducted OPF on both a medium voltage distribution grid and plural low voltage communities.

Both the distribution grid and the low voltage grids in this thesis are radial grids, and there will be distributed generation in the system. This causes the OPF problem in this thesis to be non-convex, and therefore some kind of relaxation to the OPF algorithm is necessary. There are different methods of relaxing the OPF problem, but many of them is inapplicable to this problem. For example, DC OPF does not take reactive losses into account, and this being a medium and low voltage problem the results will be too imprecise. AC OPF will have problems converging due to the problem being non-convex. The choices to solve the OPF can be narrowed down to either Second order-cone programming (SOCP) or semi-definite programming (SDP). As SDP requires substantially more computational time per iteration compared to SOCP, the option chosen to solve the OPF in this thesis was SOCP-ACOPF approach.

3.2.1 Market clearing with the SOC-ACOPF approach

This grid in this thesis will be a medium voltage distribution grid with two low voltage grids connected to it. In this section the market clearing in this grid will be described and the means of which this is done will be explained.

To solve the OPF for the entire system, the problem was divided into one OPF for the distribution grid and one for each of the low voltage grids. To save computational time it is beneficial to solve them separately, but still dependent on each other and in the same iteration. The way this problem was decomposed was by using the ADMM method. ADMM uses augmented Lagrangian relaxation to divide convex optimization problems into smaller sub-problems, in this case the OPF for the distribution grid and the low voltage grids alone. This method allows all sub-problems to be solved in parallel, meaning that each iteration solves the entire system. The way it does this is by using the LECs variables as constants in the DSOs OPF and vice versa. Firstly, it solves the OPF in the DSO, and uses the resulting shadow prices and generation to solve the OPF in the LECs. The results from the LECs OPF are then again used in the DSO OPF, and this cycle will run until the system reaches convergence. This happens simultaneously for all time steps, and the end result is the multi-period OPF for the entire system.

4 Method for DSO/LEC coordination

The main part of the thesis is the work on the DSO/LEC coordination model. The model is built on previous work from Ole Kjærland Olsen, Damian Sieraszewski (18) and Ine Solsvik Vågane (19), which both investigated TSO/DSO (DC/AC) coordination, with one TSO and multiple DSO´s in the system. The main objective of this thesis was to translate this model to model the power flow in a system with one DSO and plural LECs. This section consists of two sub chapters, in the first the day ahead market clearing model will be presented, and in the second the flexibility market clearing model will be presented.

4.1 Day ahead market clearing

The objective of this model is to minimize the total cost of power supply in a system consisting of one distribution grid with multiple LECs connected to it. The objective function for the optimization problem can be seen in equation 1. ($P_n^{G,DSO}$) and (($P_m^{G,LEC}$) is the production in each node of the DSO and the LEC respectively. ($c_n^{G,DSO}$) and ($c_n^{G,DSO}$) is the cost of production in these nodes. The rest of this sub chapter will go into each of the restrictions, to explain their purpose and contribution.

The SOC-ACOPF constraints (2-8) determine the power flow restrictions and applies both for the DSO and for the LECs in the problem. Equation 9 is the connection constraint between the DSO and a LEC, which makes the power transferred from the DSO to the LEC looks like a load from the DSOs perspective, as seen from the resemblance to the active power flow restriction (2). The variable explanation for all variables used in the formulas below are given in Appendix (A).

Model Formulation:

DG SOC-ACOPF variables: $u_n, R_{nj}, I_{nj}, P_n^{G,DG}, Q_n^{G,DG}$

LEC SOC-ACOPF variables: $u_m, R_{mj}, I_{mj}, P_m^{G,LEC}, Q_m^{G,LEC}$

Minimize :

$$\sum_{n=1...N} P_n^{G,DSO} * c_n^{G,DSO} + \sum_{m=1...M} P_m^{G,LEC} * c_m^{G,LEC} \tag{1}$$

Subject to SOC-ACOPF constraints:

$$P_m^L - P_m^G = -\sqrt{2}u_m \sum_{j\epsilon k(m)} G_{mj} + \sum_{j\epsilon k(j)} G_{mj} * R_{mj} - B_{mj} * I_{mj}, \qquad m = 1, ..., M \tag{2}$$

$$Q_m^L - Q_m^G = -\sqrt{2}u_m \sum_{j\epsilon k(m)} B_{mj} + \sum_{j\epsilon k(j)} B_{mj} * R_{mj} + G_{mj} * I_{mj} \qquad m = 1, ..., M \tag{3}$$

$$2u_m u_j \geq R_{mj}^2 + I_{mj}^2 \qquad \text{for all mj lines} \tag{4}$$

$$R_{mj} \geq 0, \qquad \text{for all mj lines} \tag{5}$$

$$u_1 = V_1/\sqrt{2}, u_m \geq 0, \qquad m = 2, ..., M \tag{6}$$

$$P_m^{G,min} \leq P_m^G \leq P_m^{G,max} \qquad m = 1, ..., M \tag{7}$$

$$Q_m^{G,min} \leq Q_m^G \leq Q_m^{G,max} \qquad m = 1, ..., M \tag{8}$$

Subject to DSO/LEC connection constraint:

$$P_n^{G,DSO} - P_m^{G,LEC} = -\sqrt{2}u_n * \sum_{j\epsilon k(n)} G_{nj} + \sum_{j\epsilon k(j)} G_{nj} * R_{nj} - B_{nj} * I_{nj} \tag{9}$$

4.2 Flexibility market model

This sub chapter will present how the model handles the flexibility resources added to the system. The objective of the model is to minimize the cost of production and flexibility resources combined (10), where ($P_{m,t,u}^{G,Flex}$) is the flexible generation at node M, in hour t and unit u. ($P_{m,t,u}^{charge}$) and ($P_{m,t,u}^{disch}$) are the amount of power either charged or discharged from a battery at node m in hour h and unit u. ($P_{m,t,u}^{LS}$) is the amount of power shedded in the node at each time step, and ($c_{m,t,u}^{G,Flex}$), ($c_{m,t,u}^{batt}$) and ($c_{m,t,u}^{LS}$) are the costs respectively.

The SOC-ACOPF constraints (11-15) determines the power flow restrictions of the model, and the most obvious change to the last model is that the flexibility variables has become a part of the active flow constraint (equation 11). The connection constraint (equation 16) remains similar to the one in the day ahead model, except for the addition of time steps. The flexible generation constraint (equation 17) makes sure that the flexible generation at each node is between the minimum and maximum levels for that particular node at that particular time step. The load shedding constraint (equation 18) makes sure that the amount of shedded power at one node is not bigger than the original load at that node in the same time step. Lastly the battery constraints (equation 19 - 25) dictates the behaviour of the batteries in the system. One noteworthy implementation for the batteries is that they have to finish each day on the same state of charge ($P_{m}^{SoC,init}$) as they started the day with. Again, all variables with their explanation can be found in Appendix (A)

Multi-Period DG/LEC Optimization Model Formulation

DG SOC-ACOPF variables: $u_{n,t,u}, R_{nj,t,u}, I_{nj,t,u}$

LEC SOC-ACOPF variables: $u_{m,t,u}, R_{mj,t,u}, I_{mj,t,u}$

Flexibiliy variables: $P^{G,Flex}_{m,t,u}, P^{L,Flex}_{m,t,u}, P^{SoC}_{m,t,u}, P^{charge}_{m,t,u}, P^{disch}_{m,t,u}$, $P^{LS}_{m,t,u}$

Minimize:

$$\sum_{m=2..M}\sum_{t=1...T}\sum_{u=1...U}(P^{G,Flex}_{m,t,u} * c^{G,Flex}_{m,t,u} + (P^{disch}_{m,t,u} - P^{charge}_{m,t,u}) * c^{batt}_{m,t,u}) - P^{LS}_{m,t,u} * c^{LS}_{m,t,u} \tag{10}$$

Subject to SOC-ACOPF constraints:

$$\begin{aligned} P^{L,LEC}_{m,t,u} - P^{G,LEC}_{m,t,u} - P^{G,Flex}_{m,t,u} + P^{charge}_{m,t,u} - P^{disch}_{m,t,u} = \\ -\sqrt{2}u_m \sum_{j\epsilon k(m)} G_{mj} + \sum_{j\epsilon k(j)} G_{mj} * R_{mj} - B_{mj} * I_{mj} \end{aligned} \tag{11}$$

$$Q^{L,LEC}_{m,t,u} - Q^{G,LEC}_{m,t,u} = -\sqrt{2}u_{m,t,u} \sum_{j\epsilon k(m)} B_{mj} + \sum_{j\epsilon k(j)} B_{mj} * R_{mj,t,u} + G_{mj} * I_{mj,t,u} \tag{12}$$

$$2u_{m,t,u}u_{j,t,u} \geq R^2_{mj,t,u} + I^2_{mj,t,u} \qquad \text{for all mj lines} \tag{13}$$

$$R_{mj,t,u} \geq 0, \qquad \text{for all mj lines} \tag{14}$$

$$u_1 = V_1/\sqrt{2}, \quad u_m \geq 0, \qquad m = 2, ..., M \tag{15}$$

Subject to DSO to LEC connection constraint:

$$P^{G,DSO}_{n,t,u} - P^{G,LEC}_{m,t,u} = -\sqrt{2}u_{n,t,u} * \sum_{j\epsilon k(n)} G_{nj} + \sum_{j\epsilon k(j)} G_{nj} * R_{nj,t,u} - B_{nj} * I_{nj,t,u} \tag{16}$$

Subject to flexible generation constraint:

$$P^{G,FLex,min}_{m,t,u} \leq P^{G,Flex}_{m,t,u} \leq P^{G,Flex,max}_{m,t,u} \tag{17}$$

Subject to Load shedding constraint:

$$P_{m,t,u}^{LS} \leq P_{m,t,u}^{L,LEC} \tag{18}$$

Subject to battery constraints:

$$P_{m,t,u}^{SoC,min} \leq P_{m,t,u}^{SoC} \leq P_{m,t,u}^{SoC,max} \tag{19}$$

$$P_{m,t,u}^{charge,min} \leq P_{m,t,u}^{charge} * (1 - \delta_{m,t,u}) \leq P_{m,t,u}^{charge,max} \tag{20}$$

$$P_{m,t,u}^{disch,min} \leq P_{m,t,u}^{disch} * \delta_{m,t,u} \leq P_{m,t,u}^{disch,max} \tag{21}$$

$$P_{m,1,1}^{SoC} = P_{m}^{SoC,init} + P_{m,1,1}^{charge} * \eta^{charge} - \frac{P_{m,1,1}^{disch}}{\eta^{disch}} \tag{22}$$

$$P_{m,t,u}^{SoC} = P_{m,t,u-1}^{SoC} + P_{m,t,u}^{charge} * \eta^{charge} - \frac{P_{m,t,u}^{disch}}{\eta^{disch}} \tag{23}$$

$$P_{m,t,1}^{SoC} = P_{m,t-1,U}^{SoC} + P_{m,t,1}^{charge} * \eta^{charge} - \frac{P_{m,t,1}^{disch}}{\eta^{disch}} \tag{24}$$

$$P_{m,T,U}^{SoC} = P_{m}^{SoC,init} \tag{25}$$

With the finished model in place, it is possible to determine the best use of flexibility in a system given the required parameters. The rest of the thesis will focus on testing this model with a use case to showcase its performance.

5 Case study

In order to test the model developed in this thesis it is necessary to develop a test-grid with desired properties. As a part of the HONOR-project, which this thesis contributes to, the grid chosen is one being used in different HONOR projects as well. The grid consists of a distribution grid (Medium voltage) with two identical low voltage grids (LECs) connected to it. Both the low and medium voltage parts of the grid are Ding0 grids and are also part of the same network.

Costs of production and flexibility

For the flexible generation the pricing is randomized to cost between 120 and 150% of the cost of the power purchased from the distribution grid. The batteries have a usage price, i.e there is a fee paid for both charging and discharging the batteries. The cost of generation, flexible generation and battery charge/discharge can be seen in figure 2. Furthermore, in the model there will be a possibility to shed some of the load to maintain voltage levels at all buses. As this should only be a last resort solution the price for load shedding has been set to 20 000 EUR/MWh. This price is not realistic but is set very expensive in the model to make sure that it tries to avoid it by all means.

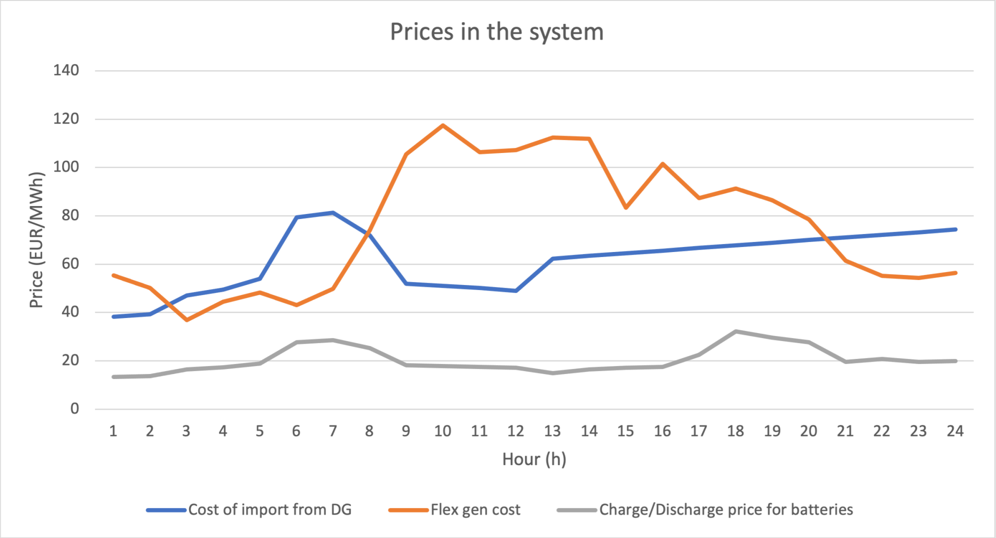

Figure 2: The cost of importing power from the distribution grid compared to flexible generation cost and battery charge/discharge costs.

5.1 Grid development

The grid's purpose is to test the developed model and its performance. In theory, all MV loads in the distribution grid represent a low voltage grid, which can be seen as a community, but as each additional LEC requires a lot of extra computation time, it was decided that two LECs is sufficient to determine the model's performance. Figure 4 shows the grid in its entirety without any flexibility resources added in the LECs.

The distribution grid (MV) consists of 38 buses, where 14 of these are loads. The reference voltage in the Distribution grid is 31,4 kV, and it is connected to the LECs at bus 23 and 33 (figure 4). Each LEC consists of 23 buses, where of 11 are loads. The reference voltage in the LV grid is 400V. There are two different load types in the LECs, agricultural and residential. The agricultural loads are at buses 3, 5, 7 and 9, the rest of the loads are residential. The load profiles used in the simulations can be seen in figure 5, and have been collected from (**?**).

In order to make this grid interesting to test the model, some up scaling of the loads had to be made. The loads still follow the same curve as in figure 5, but have been scaled up in order to make the total load a challenge for the grid infrastructure to cope with. Figure 3 shows the original total load demand in one of the LECs compared to the modified, up scaled one used in the simulations.

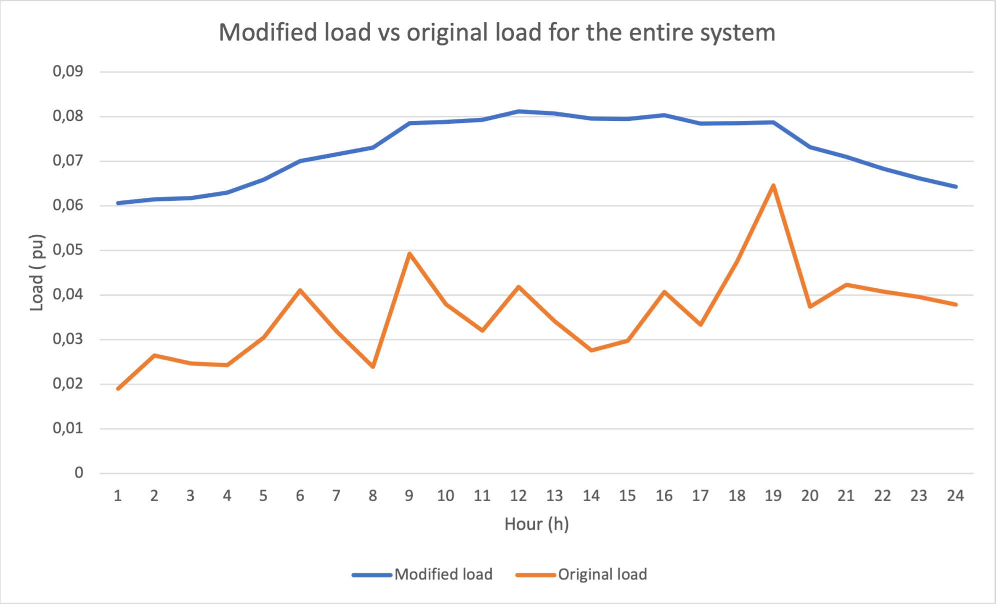

Figure 3: The original total load in the system compared to the modified load used for the simulations.

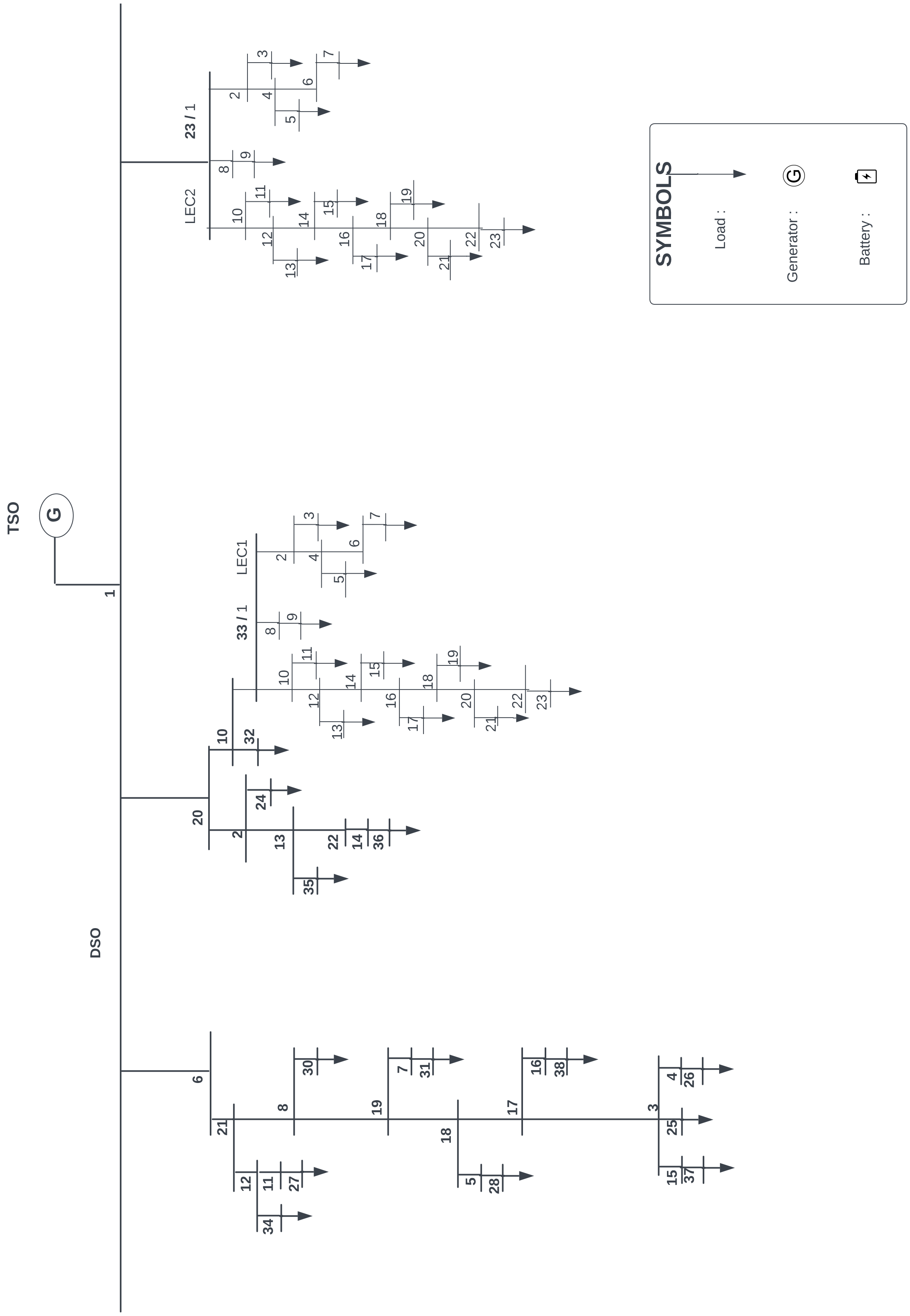

Figure 4: The grid used for the simulations, with no flexibility added.

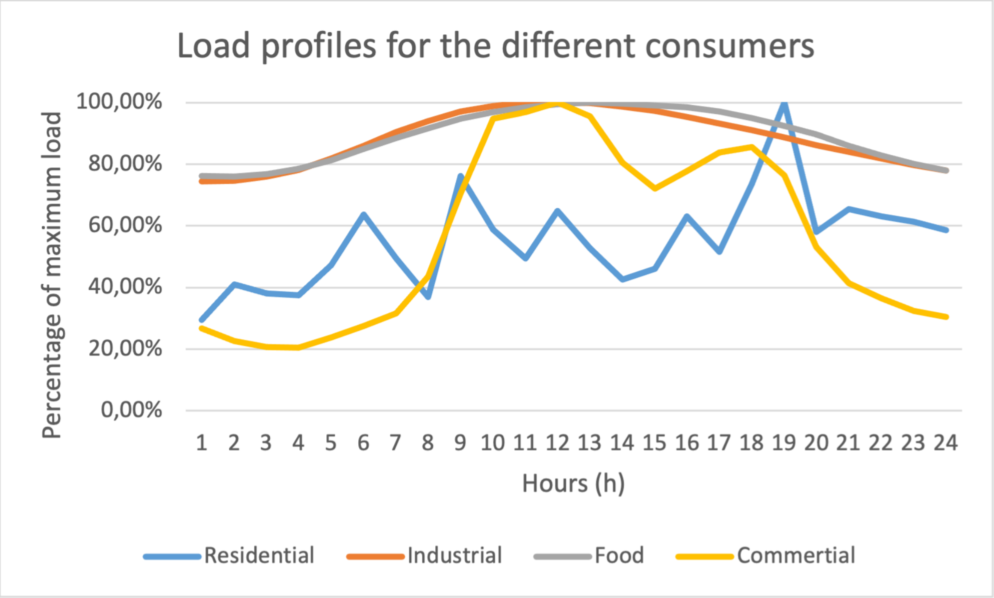

Figure 5: Load profiles for the different load types, industrial and commercial loads are not in either of the LECs, but are sub parts of some of the MV loads.

5.2 Scenario development

To see the full range of the model's performance four different scenarios was created, each one to utilize a different feature in the model to the one prior. In this section each scenario will be described, but a rough overview can be seen in table 1.

Scenario	Flexible generation	Batteries	Grid tariff
1	-	-	-
2	X	-	-
3	X	X	-
4	X	X	X

Table 1: The set up for the four different scenarios

Voltage regulations

As described in section 2.2.1 electrical equipment can be damaged or lose functionality if exposed to a different voltage level than it is designed for. To make sure that the voltage levels at all buses are within the desired limits, voltage regulation can be implemented to the model. This makes sure that the voltage at all buses will stay below 1.1 pu and above 0.9 pu. All scenarios will be run both with and without voltage regulations in place.

5.2.1 Base case

The base case scenario is the grid in its original form, with no flexibility resources added. In this scenario the grid is exactly as described in figure 4. This scenario will act as a reference point for the other scenarios to see how much of an impact the different additions make to the results.

5.2.2 Flexible generation added

For the second scenario flexible generation was added to bus 5 and 21 in both LECs. Both these buses are close to the end buses in their respective branch, and therefore, both these buses and the ones further down their branches are exposed for voltage drops when the loads are high. Table 2 shows the introduced generators in the system.

Flexible generation

Bus Number	Maximum Production
5	0.03 pu (3MW)
21	0.02 pu (2MW)

Table 2: The flexible generation in the LECs

5.2.3 Including the batteries

The batteries were installed at bus 5 and 19 in the LECs, both to show that they can be installed at a bus with and without a generator already in place, and because these buses are crucial in voltage management due to the reasons mentioned in last section. The specifications of the installed batteries can be seen in table 3. The reason for the size difference in these batteries is that the agricultural loads at and around bus 5 is significantly bigger than the residential loads at and close to bus 19. The grid as it looks after all flexibility is added can be seen in 6.

Installed batteries

Bus Number	Capacity	Maximum discharge	Maximum charge	Initial state
5	0.06 pu (6MWh)	0.01 pu (1MW)	0.01 pu (1MW)	0.03 pu (3MWh)
19	0.002 pu (0.2MWh)	0.0003 pu (30kW)	0.0003 pu (30kW)	0.001 pu (0.1MWh)

Table 3: Specifications for the installed batteries

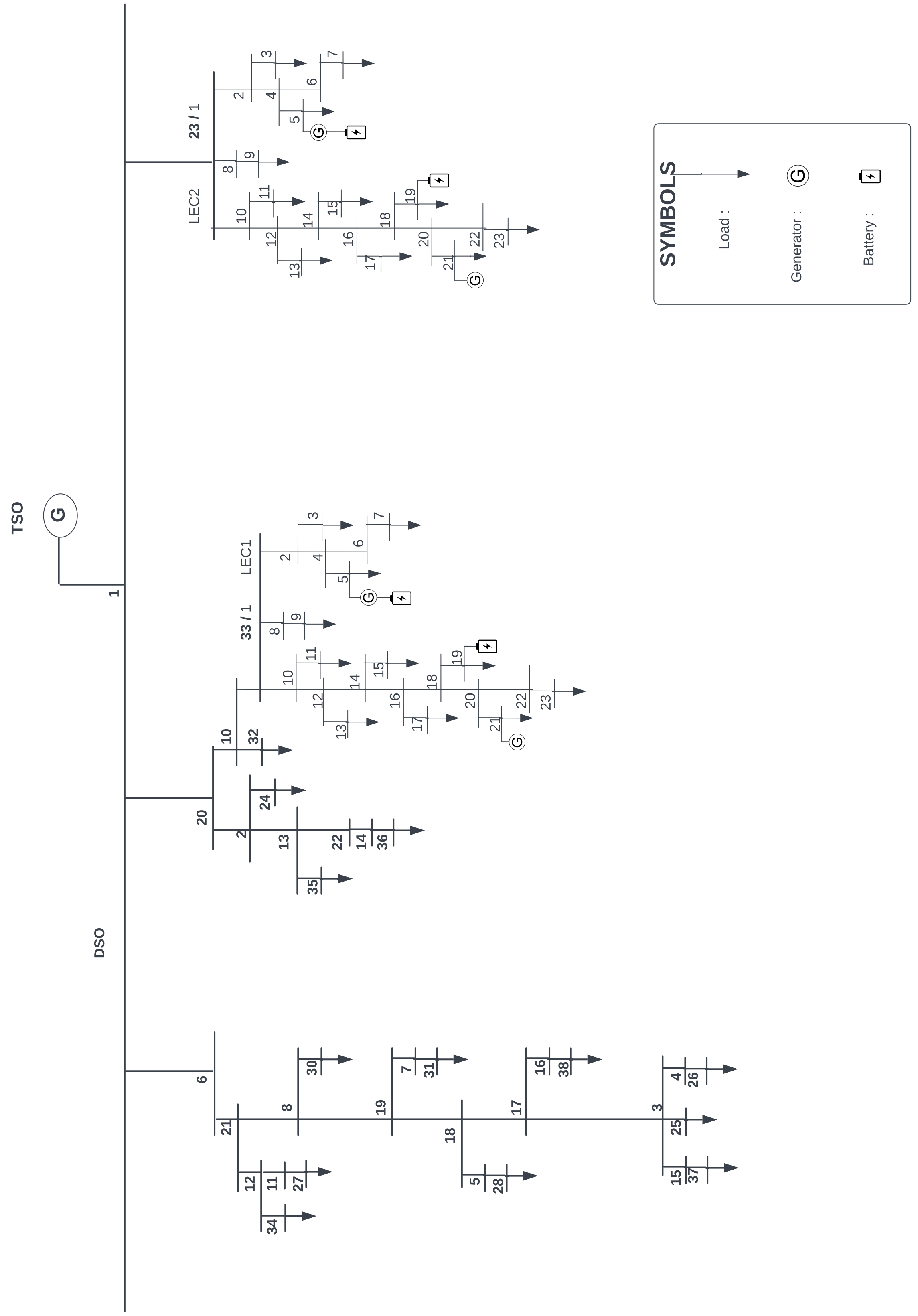

Figure 6: The grid used for the simulations, with all flexibility resources added.

5.2.4 Tariff

As discussed in section 2.3, grid tariff can be a crucial incentive to install or increase flexibility. In order to apply this to the model, all energy imported from the DSO to the LECs is taxed with an additional fee. Numbers from NVE shows that the average grid tariff in Norway per 1st of June 2022 is 51.73 øre/kWh.(20) It was therefore chosen a tariff of 0.05 EUR for this model. The purpose of adding this scenario is to see how it effects the already installed flexibility resources in the system, and to what extent it changes the usage of them.

6 Results

This section will present the results from the simulations on the case study in last section. Firstly, all scenarios will be presented alone, and lastly there will be comparative results which will help to see the differences between the scenarios more clearly. All figures presented in this chapter are from LEC 1 in the case study. As the LECs are identical, the resulting figures are close to identical as well.

6.1 Base case

For the base case scenario, the most important values to look at is the voltages at the exposed buses in the LEC, figure 7 presents the voltages at bus 4,5,6 and 7 in LEC 1 throughout the simulated day. If the voltage graph is inspected with the load graph (figure 3) in mind, one can see that there is a connection between the sized of the loads in the system and the drops in voltage.

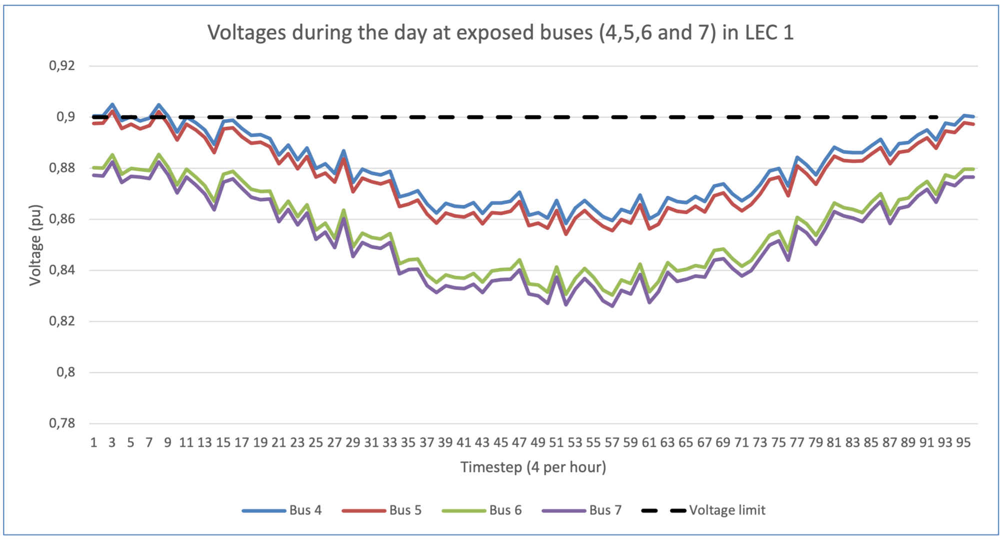

Figure 7: The voltages at bus 4,5,6 and 7 throughout the day, base case no voltage regulations.

Figure 8 shows the voltage at the same buses when the voltage regulations are in place. If compared to the same graph without voltage regulations, it becomes clear that the system has had to shed some of the load in order to maintain voltages over 0.9 pu.

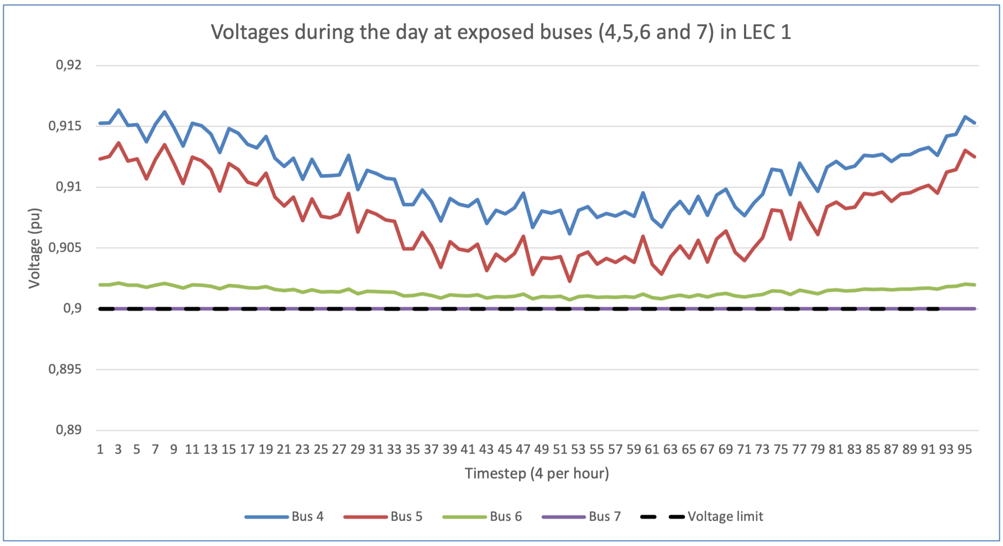

Figure 8: The voltages at bus 4,5,6 and 7 throughout the day, base case with voltage regulations.

All load shedding happened at bus 7 in the LEC, figure 9 shows the amount of load shedded in comparison to the entire load demand at bus 7 throughout the day. The graph shows that the bigger the load was, the bigger part of it had to be shedded, this is because the other loads at the same branch had similar peaks (all loads on this branch are agricultural).

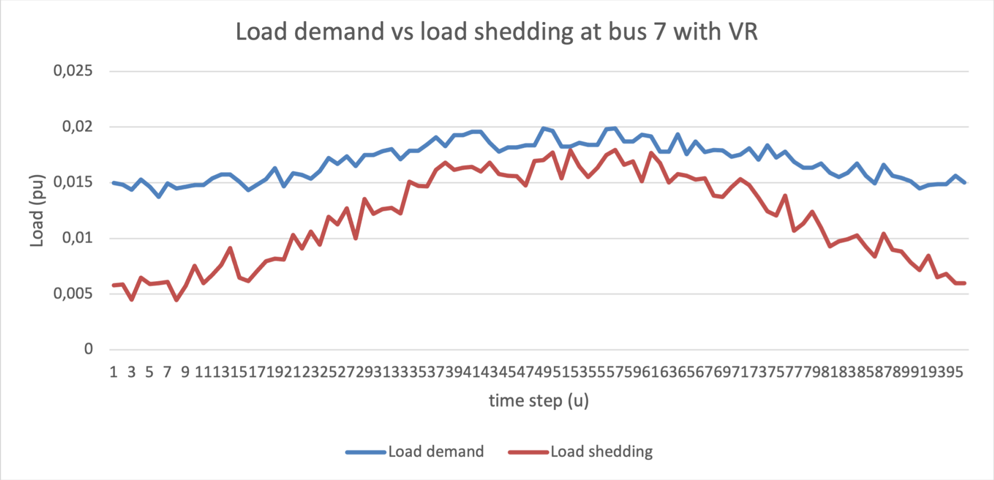

Figure 9: The load demand and the amount of load shedded throughout the day, base case with voltage regulations.

Table 4 shows the total amount of load shedding at both LEC 1 and LEC 2, and the cost for this. As mentioned in the previous chapter, the cost of load shedding was set to be extremely expensive in this model, as it is not considered a flexibility asset, but something that should be avoided at all costs.

LEC Number	Amount shedded	Cost of shedding
LEC 1	0.2834 pu (28.34 MWh)	**566 733 EUR**
LEC 2	0.2834 pu (28.34 MWh)	**566 733 EUR**

Table 4: The total amount of load shedded, and cost of shedding at bus 7 in LEC 1 and 2 with voltage regulations in place.

6.2 With flexible generation

When the flexible generation at bus 5 and 21 is added, the voltages at the exposed buses in LEC 1 behaves accordingly to figure 10. If this graph is considered alongside the price graph from the previous chapter (figure 2) it is clear that the dip in voltages occur (time step 33, and hour 8) when the price for importing energy into the LEC becomes lower than the cost of producing energy inside the grid.

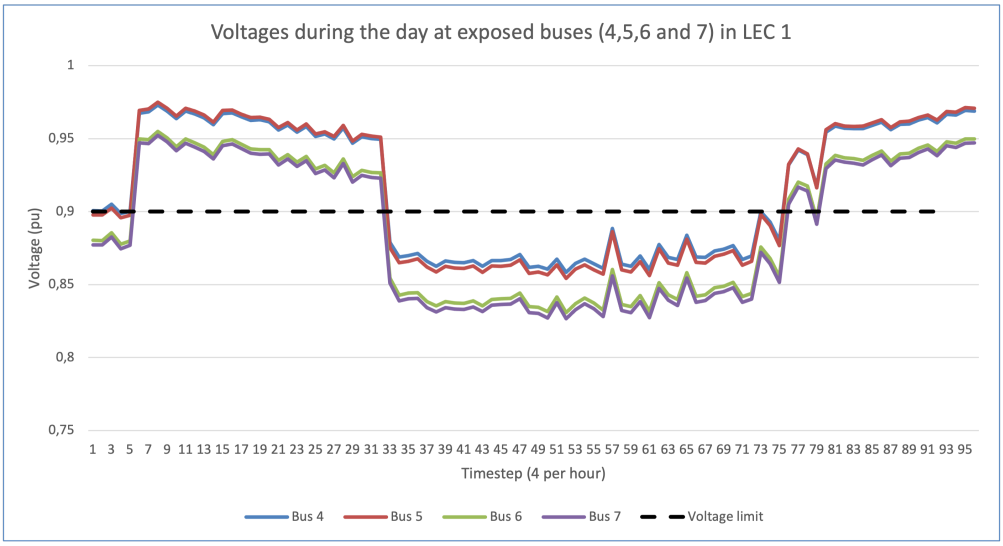

Figure 10: The voltages at bus 4,5,6 and 7 throughout the day, with flexible generation but no voltage regulations.

When the voltage regulations were implemented (figure 11), the system was now able to maintain voltages over 0.9 pu without shedding any load. The dips in voltage occur at the same time steps as without voltage regulations, due to them stops at 0.9 pu.

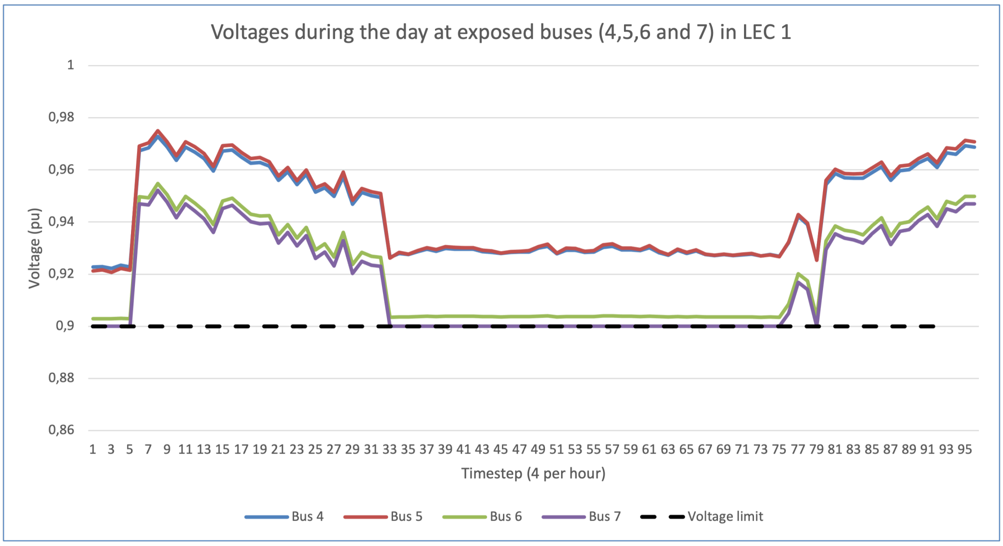

Figure 11: The voltages at bus 4,5,6 and 7 throughout the day, with flexible generation and voltage regulations.

With flexible generation added, it is necessary to see how much and for which periods of the simulated day these generators produce. Figure 12 shows the flexible generation at bus 5 and 21 during the day. If compared to the prices in the system (figure 2) it can be seen that the flexible production is at its maximum for all time steps when it is cheaper than to purchase from the outside grid. The reason it still produces some even when the flexible generation prices are higher is that the losses are greatly reduced when producing in the LEC.

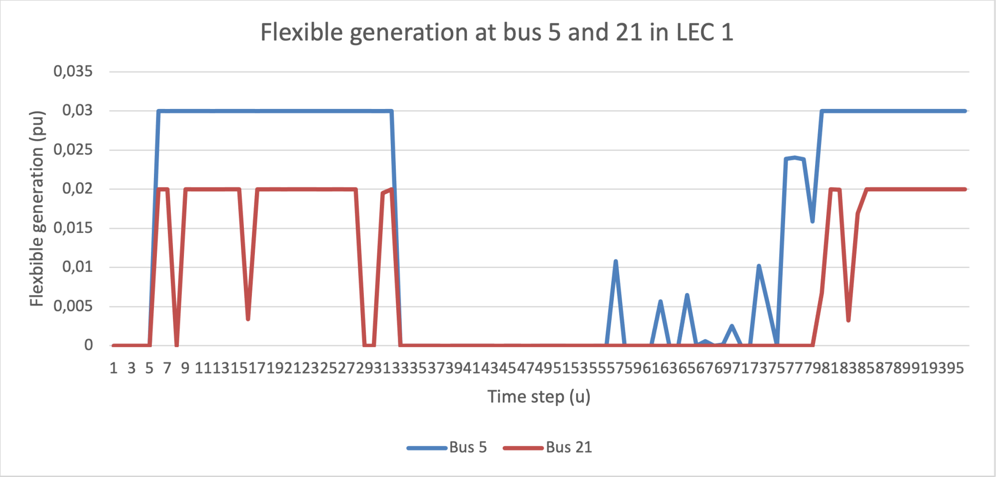

Figure 12: The flexible generation at bus 5 and 21 throughout the day, no voltage regulations.

Figure 13 shows the flexible generation during the with voltage regulations in place. To maintain the voltages above 0.9 pu, there is now a need to keep up the flexible generation at bus 5 even though it is more costly than importing the power from the grid.

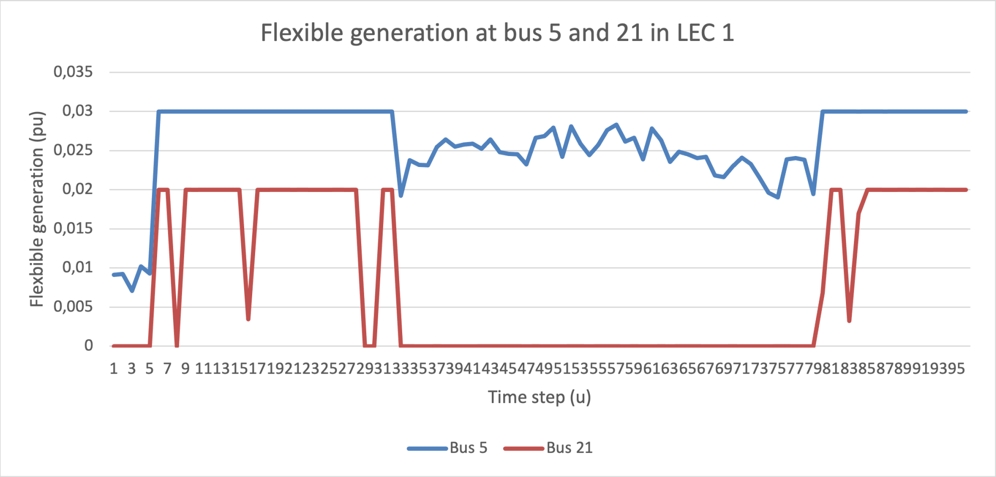

Figure 13: The flexible generation at bus 5 and 21 throughout the day, with voltage regulations.

6.3 Adding the batteries

There has now been added two batteries to the LECs, one at bus 5 with 6 MWh capacity and one at bus 19 with 0.2 MWh capacity. As for the previous scenarios, the voltages at bus 4,5,6 and 7 is presented in figure 14. This graph looks very similar to the one without the batteries, the only exception is when the batteries are charging the voltages dips, and when they are discharging there is an increase.

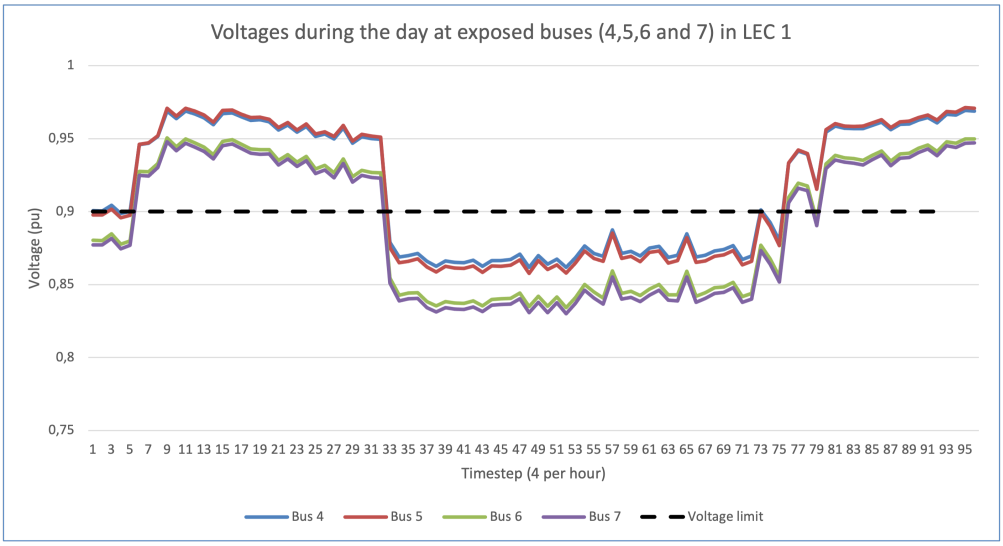

Figure 14: The voltages at bus 4,5,6 and 7 throughout the day, with flexible generation and batteries, no voltage regulations.

The same as above yields for the voltages with the restrictions active, which can be seen in figure 15.

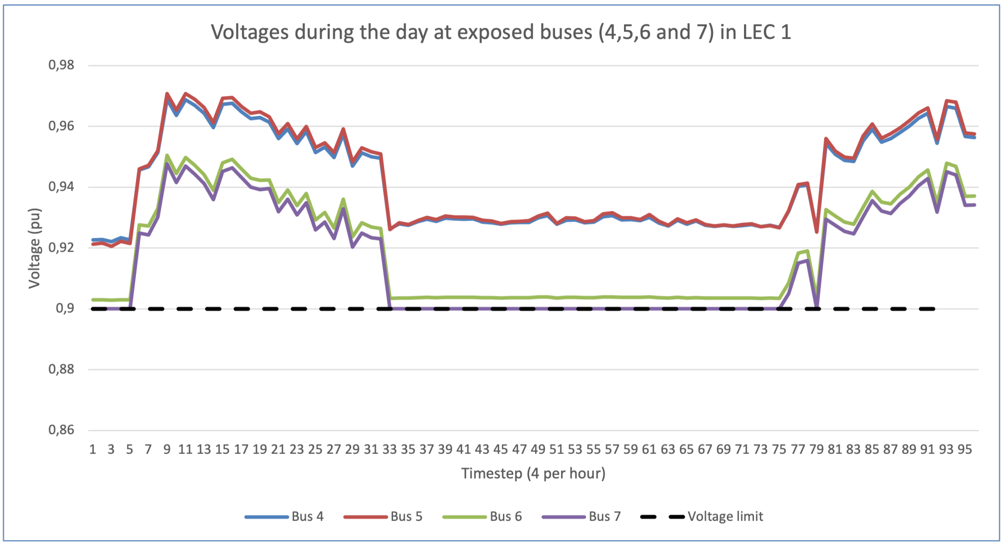

Figure 15: The voltages at bus 4,5,6 and 7 throughout the day, with flexible generation and batteries, with voltage regulations.

The flexible generation at bus 5 and 21 can be seen in figure 16, this is also very similar to the flexible generation in the system without the batteries in place.

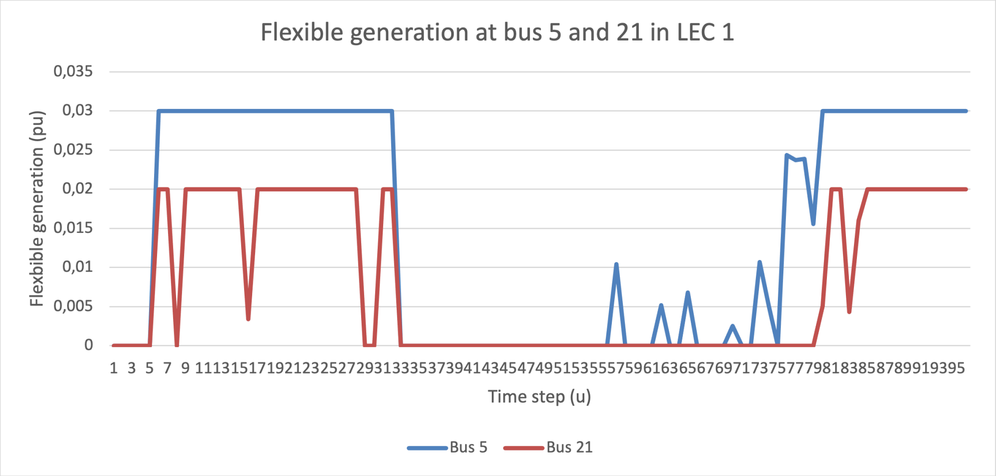

Figure 16: The flexible generation at bus 5 and 21 throughout the day after the batteries were introduced, no voltage regulations.

When the voltage restrictions are applied, the benefits of the batteries becomes clearer. The system now requires less flexible generation during the expensive period to maintain the voltages above 0.9 pu. For example, at time step 46 (when the price difference is at its biggest), the difference in the flexible generation is almost 0.1 pu with and without the batteries.

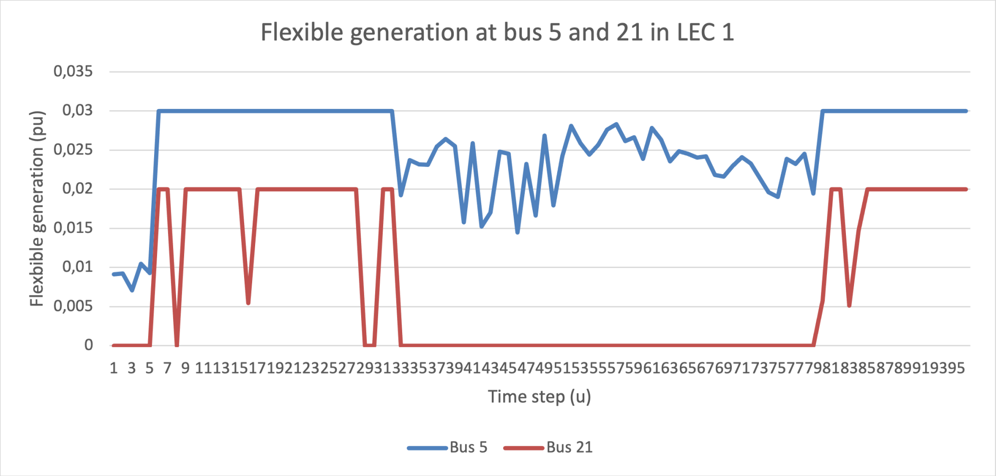

Figure 17: The flexible generation at bus 5 and 21 throughout the day after the batteries were introduced, with voltage regulations.

With the batteries in place, it is important to see how they have been used throughout the simulated day. Figure 18 shows the state of charge of the batteries at bus 5 and 19 during the day. The batteries charge at the beginning of the day when the prices are low and are discharged when the prices of flexible generation are high later on the day. As there is a cost of charging and discharging the batteries, the model decides that the cheapest alternative is to never discharge the batteries completely.

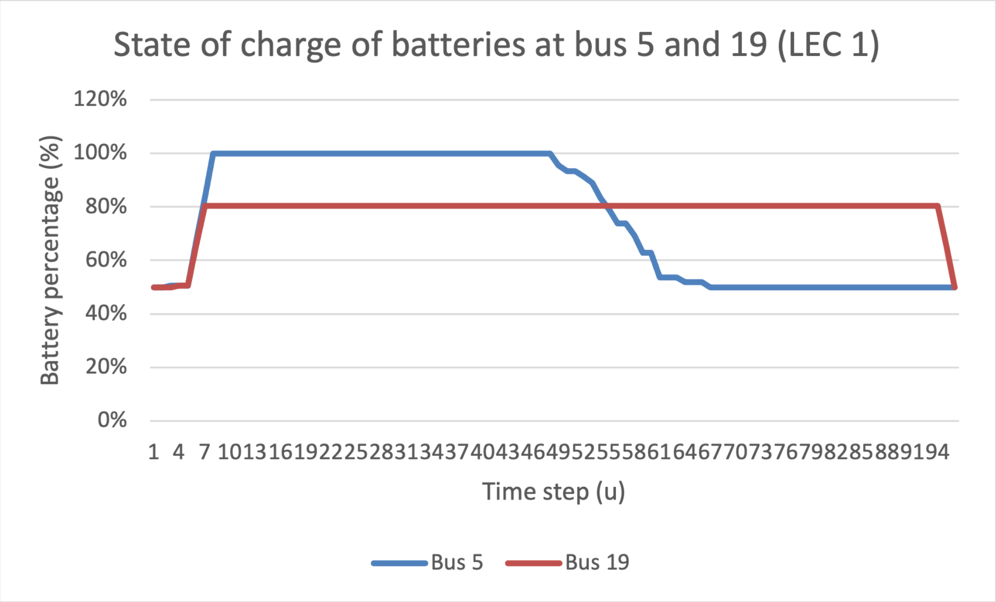

Figure 18: The state of charge of the batteries in the system throughout the day, no voltage regulations.

With the voltage restrictions enabled, the batteries usefulness increases. This is because the LEC no longer can purchase all the needed power from the distribution grid. Figure 19 shows that the model now benefits from the full capacity of the batteries, and that it is discharged during the time when the price difference is at its greatest.

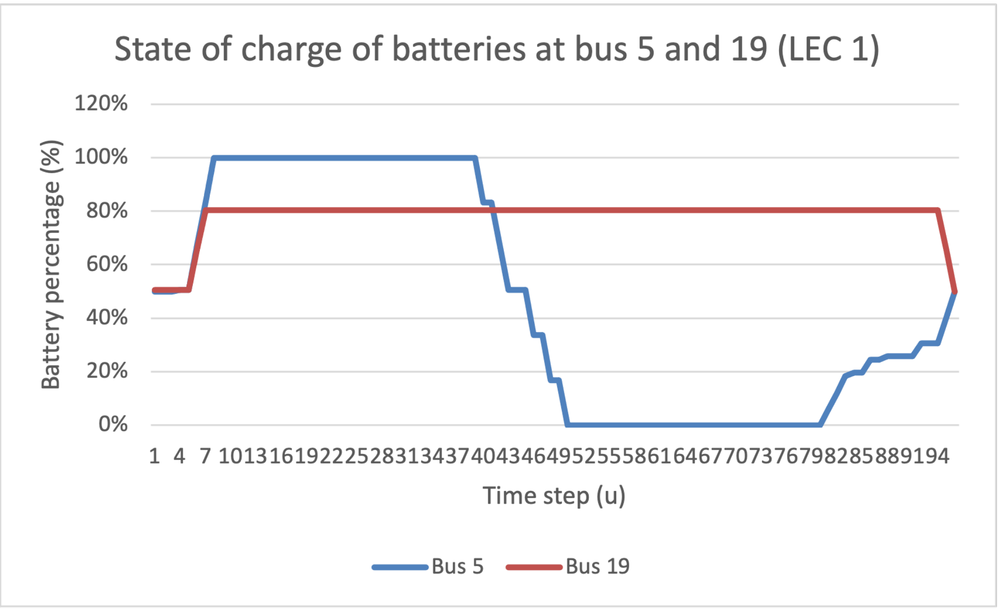

Figure 19: The state of charge of the batteries in the system throughout the day, with voltage regulations.

6.4 Including the grid tariff

A grid tariff of 0.05 EUR/kWh (50 EUR/MWh) has now been added to the system. In the price graph (figure 2) in last section it can be seen that the maximum price difference between the flexible generation and the energy purchased from the distribution grid is about 70 EUR/MWh, which it is around hour 9 in the simulation. This will of course contribute to making internal generation in the LEC more lucrative.

After implementing the grid tariff to the power imported to the LEC, the resulting voltage profiles can be seen in figure 20. It is clear that the implementation of the voltage restrictions will impact this scenario less than the previous ones, as the voltage only dips below 0.9 pu during a small period of the day, when the cost of the external power with the added tariff still is cheaper than the flexible generation is.

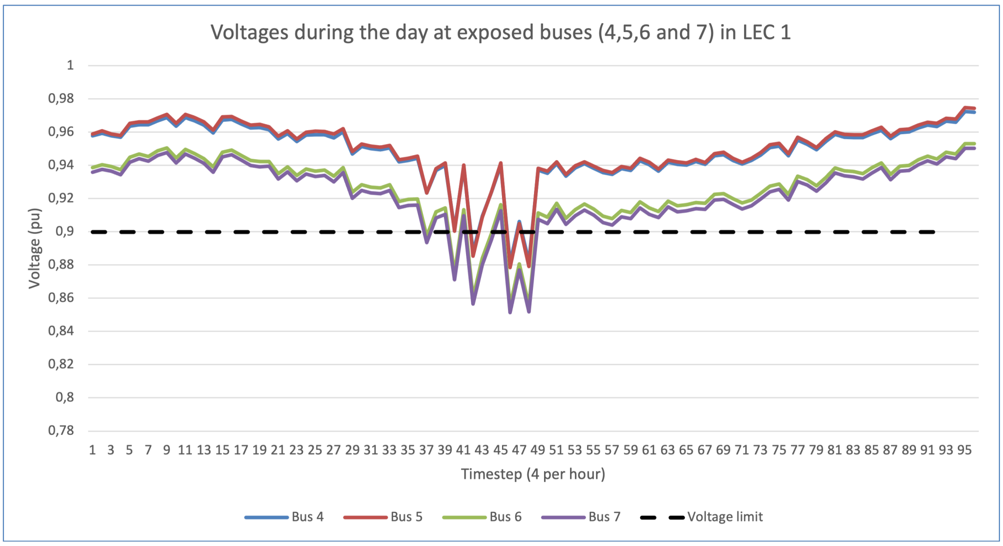

Figure 20: The voltages at bus 4,5,6 and 7 throughout the day after the grid tariff was implemented, no voltage regulations.

After the voltage regulations is added the flexible generation must increase slightly in order to maintain the voltages above 0.9 pu. Figure 21 shows that the voltages now only slightly touches the 0.9 pu-line at a few time steps during the day. This contrasts with the previous scenarios where the voltage at bus 7 were stationary at 0.9 pu from time step 33 to 75.

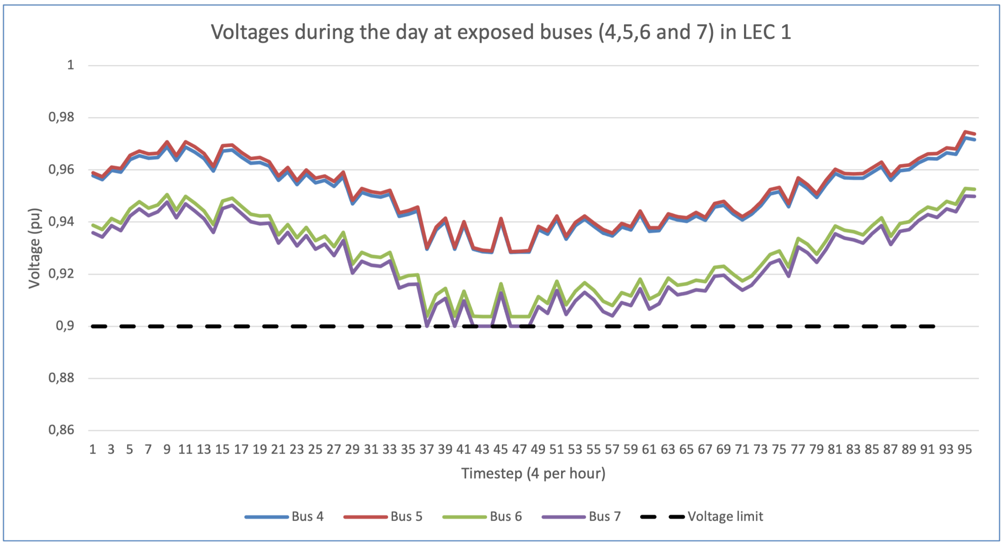

Figure 21: The voltages at bus 4,5,6 and 7 throughout the day after the grid tariff was implemented, with voltage regulations.

Figure 22 shows the flexible generation at bus 5 and 21 after the tariff was implemented. As seen from the voltage graph, it was obvious that the amount of flexible generation at bus 5 had to increase drastically compared to the previous scenarios for the voltages to remain over the 0.9 pu-line for the most of the day.

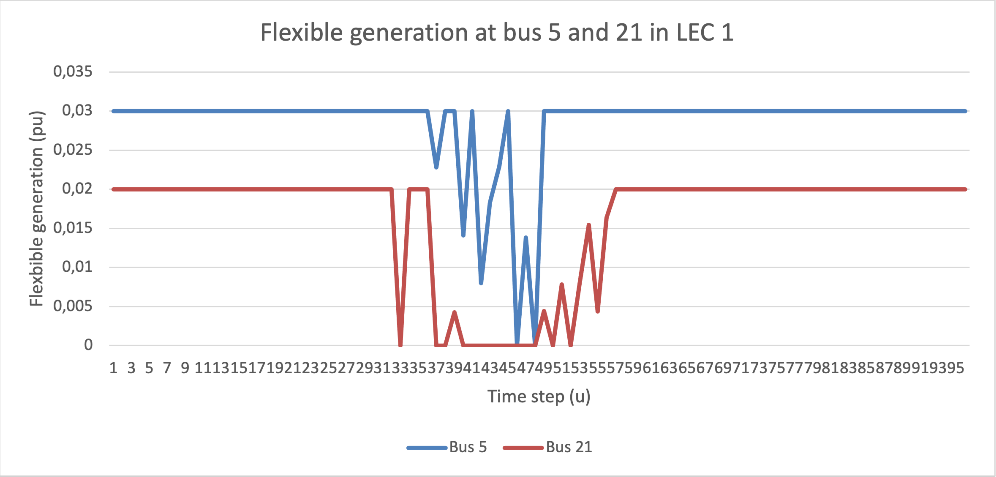

Figure 22: The flexible generation at bus 5 and 21 throughout the day after the implementation of the grid tariff, no voltage regulations.

The trend of the flexible generation remains the same after the voltage restrictions are enabled (figure 23), the major difference is that it does not fall below 0.15 pu, this is in order to maintain the voltages above the 0.9 pu-line.

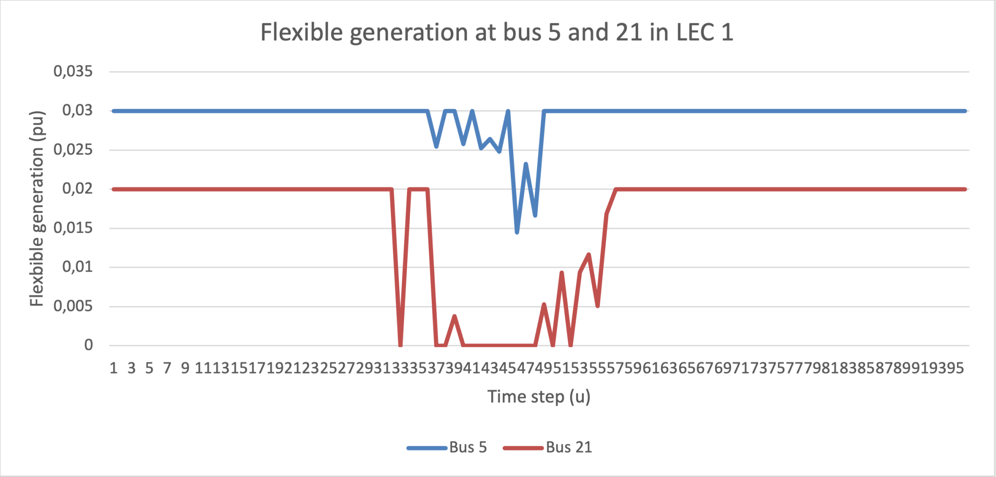

Figure 23: The flexible generation at bus 5 and 21 throughout the day after the implementation of the grid tariff, with voltage regulations.

The implementation of the tariff also impacted the usage of the batteries in the system, figures 24 and 25 shows how the state of charge of the batteries varied throughout the day without and with voltages regulations respectively.

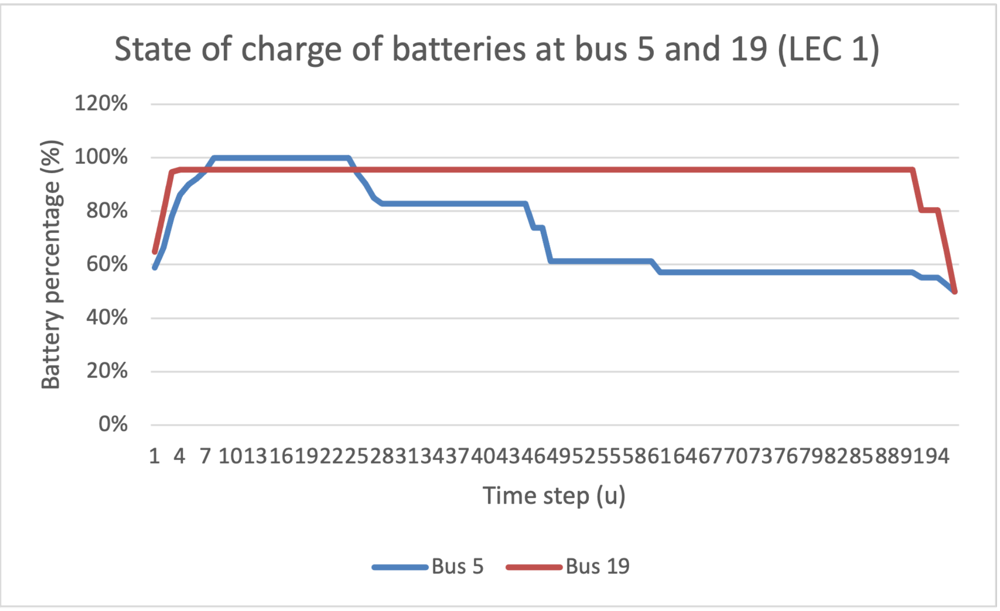

Figure 24: The state of charge of the batteries in the system throughout the day with the grid tariff in place, no voltage regulations.

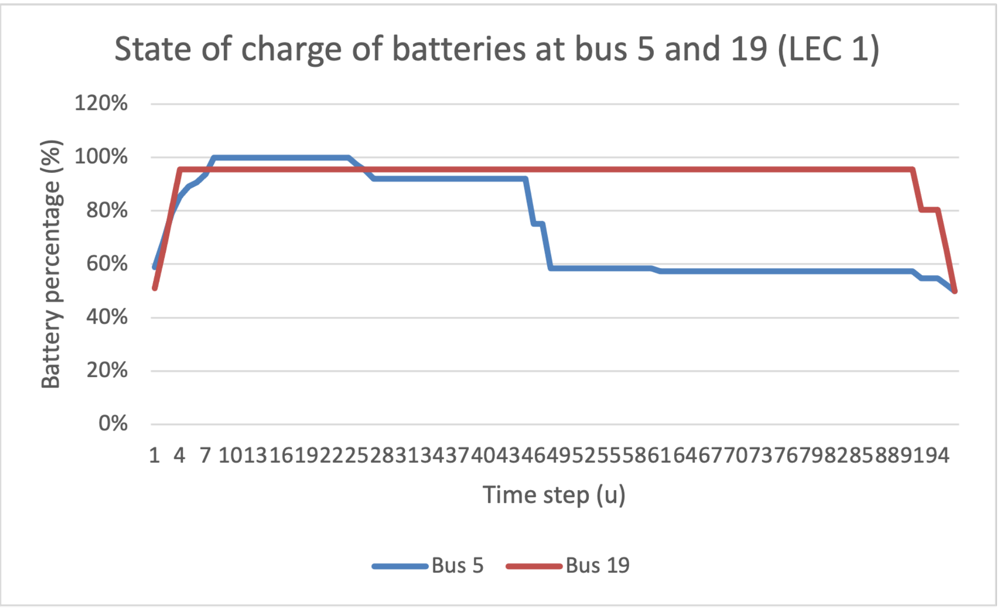

Figure 25: The state of charge of the batteries in the system throughout the day with the grid tariff in place, with voltage regulations.

6.5 Comparative results

Until now the results that have been presented are for each scenario alone, the results section aims to showcase the differences in the scenarios and the effects that the implementation of flexible generation, batteries and the grid tariff has had on the system.

The scenarios contain different levels of flexibility and therefore have different levels of self-sustainability. Figure 26 shows the amount of power imported to LEC 1 throughout the day for the different scenarios without voltage regulations in place. The base case scenario of course must import all the power needed to supply the loads from the distribution grid. When looking at this graph in comparison to the total load graph (figure 3) the losses in the system can also be detected. At peak for the base case the losses are about 0.015 pu (1.5 MW) which is almost 20% of the entire load demand in the LEC.

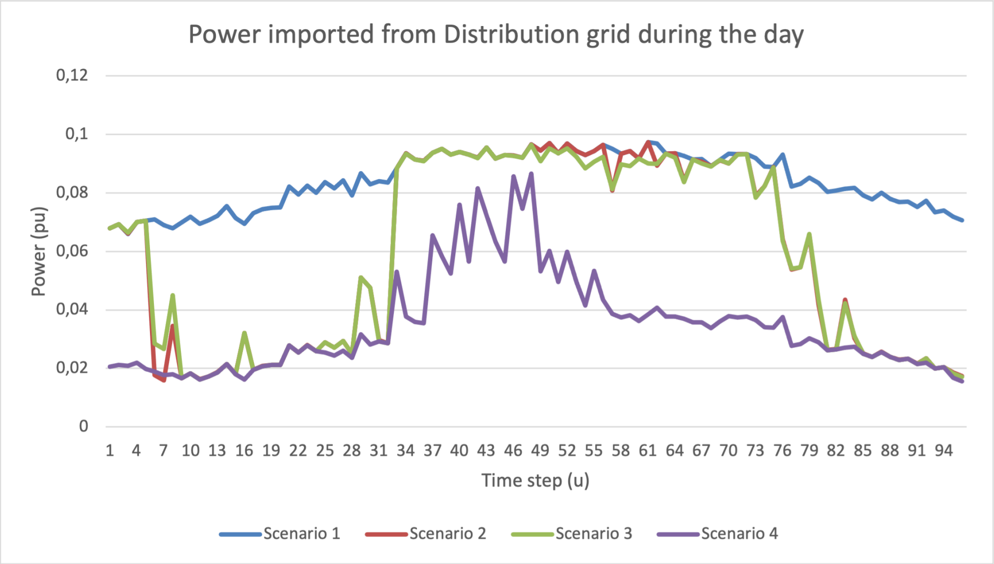

Figure 26: The amount of power imported to LEC 1 throughout the day in the different scenarios, without voltage restrictions.

When the voltage regulations are introduced, the amount of power imported to the LEC changes. The imported power to the LEC with the voltage regulations in place can be seen in figure 27. The base case now has to shed parts of the load at bus 7, and therefore the total import from the grid goes down. The other scenarios use flexible generation to supply the rest of the load demand.

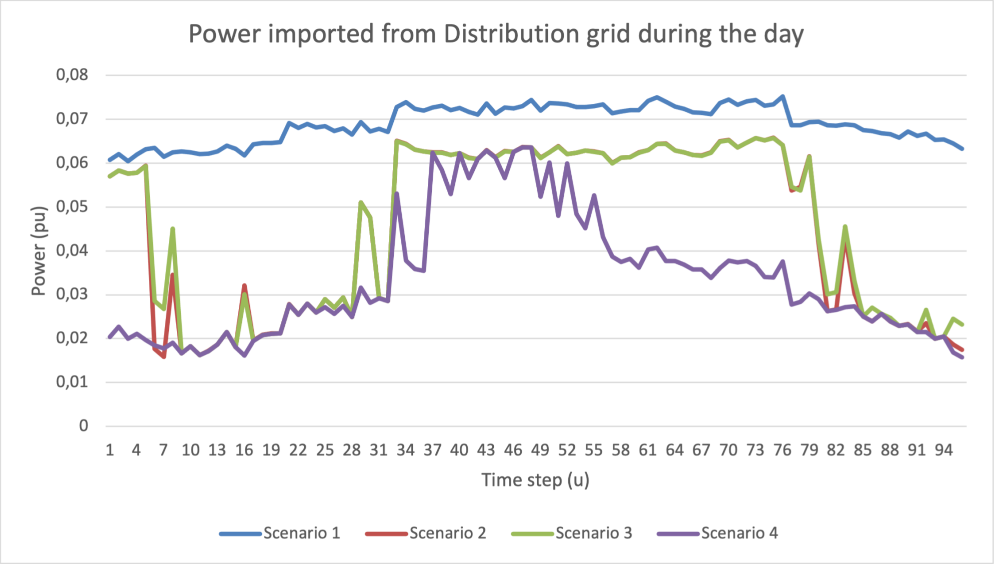

Figure 27: The amount of power imported to LEC 1 throughout the day in the different scenarios, with voltage restrictions.

To give a better overview of where each scenario has gotten its power from, table 5 shows the amount of load shedded, the flexible generation and the total amount of power generated throughout the day for each scenario.

LEC Number	Load shedding	Imported energy	Flexible generation	Total power required
Scenario 1	28.34 MWh	165.58 MWh	-	193.92 MWh
Scenario 2	-	108.76 MWh	82.130 MWh	190.89 MWh
Scenario 3	-	110.27 MWh	80.660 MWh	190.93 MWh
Scenario 4	-	80.881 MWh	109.58MWh	190.461 MWh

Table 5: The difference between imported energy and flexible generation for the different scenarios (With voltage regulations in place)

6.5.1 Economic dispatch

As the objective of the model is to minimize the costs in the system, the total cost of each scenario is an important factor. Table 6 shows the costs for each of the market entities, both in the day ahead market and in the flexibility market for each scenario. The cost difference between scenarios 1 and 2 (2 292 EUR) greatly exceeds the cost difference between 2 and 3 (23 EUR).

Scenario number	Market entity	Cost DA (EUR)	Cost FM (EUR)	Summed DA and FM (EUR)	**Total Cost (EUR)**
Scenario 1 (No VR)	DSO	78 454	81 348	159 802	**210 694**
	LEC 1	12 724	12 909	25 633	
	LEC 2	12 538	12 721	25 259	
Scenario 2 (No VR)	DSO	78 454	81 339	159 793	**208 402**
	LEC 1	12 724	11 735	24 459	
	LEC 2	12 538	11 612	24 150	
Scenario 3 (No VR)	DSO	78 454	81 353	159 807	**208 379**
	LEC 1	12 724	11 716	24 440	
	LEC 2	12 538	11 594	24 132	
Scenario 4 (No VR)	DSO	78 454	81 372	159 826	**219 142**
	LEC 1	12 724	17 057	29 781	
	LEC 2	12 538	16 997	29 535	

Table 6: The cost of the different markets, and total cost for all scenarios. Without voltage regulations.

As the voltage restriction restricts the possibility area for the optimization problem, this will increase the total costs of each scenario. Table 7 shows the costs of the different scenarios with the voltage restrictions active.

Scenario number	Market entity	Cost DA (EUR)	Cost FM (EUR)	Summed DA and FM (EUR)	**Total Cost (EUR)**
Scenario 1 (With VR)	DSO	78 454	81 146	159 600	**1 339 240**
	LEC 1	12 724	577 260	589 984	
	LEC 2	12 538	577 118	589 656	
Scenario 2 (With VR)	DSO	78 454	81 343	159 797	**209 923**
	LEC 1	12 724	12 475	25 199	
	LEC 2	12 538	12 389	24 927	
Scenario 3 (With VR)	DSO	78 454	81 324	159 778	**209 800**
	LEC 1	12 724	12 423	25 147	
	LEC 2	12 538	12 337	24 875	
Scenario 4 (With VR)	DSO	78 454	81 377	159 831	**219 179**
	LEC 1	12 724	17 072	29 796	
	LEC 2	12 538	17 014	29 552	

Table 7: The cost of each market entity, and total cost for all scenarios. With voltage regulations.

The base case scenario is clearly the most effected by the voltage regulations, this is of course because it has to shed a substantial part of the load at bus 7. From table 4 shows that this shedding alone costs 1 133 466 EUR. The cost difference between scenario 2 and 3 increases after the voltage regulations are enabled (from 23 to 123). The tariff scenario only become 37 EUR more expensive with voltage regulations which is a lot less than the 2 and 3, which increases by 1 521 and 1 421 EUR respectively.

7 Discussion of the results

In this section the results from the last section will be discussed. The problems that occur in the base case scenario will be highlighted, and the effects from the different flexibility resources in the scenarios will be discussed. The effects of the grid tariff will be looked at as well.

7.1 Base case

The base case scenario had zero flexibility resources in either of the LECs, and as seen from figure 7 the voltage at bus 4,5,6 and 7 all drop below the desired voltage limit of 0.9 pu. This is a severe problem as it can be damaging to the electrical components that are using the power delivered. Furthermore, when the voltage restrictions are applied (figure 8) the means it uses to maintain voltages at these buses is to shed a substantial part of the load at bus 7 which is the last bus on this branch. This is also very undesirable, and in the case of this case study, extremely expensive.

7.2 With flexible generation

In this section the effects of including flexible generation at bus 5 and 21 in the LECs will be examined. Figure 10 shows the voltage without voltage restrictions at bus 4,5,6 and 7 during the day. It is clear that the system now easier can supply all buses in the grid without problems, but the voltages still drop below 0.9 pu when the prices of flexible generation exceed the prices for power from the grid (Figure 2). When the voltage regulations are applied, the voltages can now be maintained without the need of shedding parts of the load at bus 7 (figure 11). Looking at figure 12 and 13 in comparison, it is clear that the flexible generation at bus 5 has to increase greatly during these time steps to maintain the voltages without shedding load when the voltage regulations are applied.

7.3 Including the batteries

The voltage situation (figures 10 and 11) with the batteries included remain similar to the previous scenario where there were only flexible generation, with some minor differences in the time steps when the batteries were charging/discharging. The same can be said for the flexible generation (figures 16 and 17), but some it is clear that the flexible generation required is a bit less during the time period when it is at its most expensive. It is clear that the voltage regulations has had effects on the way the system uses the installed batteries (figures 18 and 19). In the case without voltage regulation the battery gets charged to 100%, but its full capacity is never used. In the case with, the system uses the full capacity of the big battery at bus 5 in the period when the flexible generation is expensive.

It can be made a point towards the batteries being a bit excessive in this system, this is mainly because the system manages to avoid load shedding with the flexible generation alone. If there were some more volatile loads in the system, for example an electrical ferry dock, the batteries would have much more effect.

7.4 Effects of the grid tariff

There has now been included an extra tariff on all power purchased from the distribution grid to the LECs. From the voltage graphs (figure 20 and 21) it can be seen that the voltage levels still do not remain at acceptable limits without the voltage regulations in place. This is because the most cost efficient way to supply the LECs still are to stop most of the flexible generation in LEC in the middle of the day (figure 22). This is due to the price difference between the flexible power generated in the LEC exceeds the grid tariff added to the power imported to the LEC. It is nevertheless clear that the amount of flexible generation throughout the day is substantially bigger than in the previous scenarios. The usage of the batteries is similar to the previous scenario, with the exception that it does not benefit of its full capacity with the voltage regulations in place. As the use of the flexible generation increases, the need of batteries in the system decreases.

7.5 Comparative results

In this part the comparative results from last section will be discussed, and the differences between the scenarios will be highlighted. Figure 26 and 27 shows the power imported to the LEC during the day for the different scenarios with and without voltage regulations. Of course, the base case scenario will import the most energy both with and without regulations, whilst the scenario with the tariff included imports the least. Scenario 2 and 3 follows each other very closely with the exceptions when the batteries in scenario 3 is either charging or discharging.

The differences between the imported power and the flexible generation in the LEC becomes clear from table 5. The most noteworthy result here is the fact that the model decides to import more energy to the LEC after the batteries are introduced (from scenario 2 to 3), this is of course due to the LEC being able to buy more power from the distribution grid when the prices are low, and therefore require less flexible generation when the prices are high. The loads remain the same for all scenarios, so the differences in the total power required to supply the LEC are the same as the differences in active losses in the LEC. It is not surprising that the losses in the base case scenario is far greater than in the other scenarios, nor that scenario 4 has the least losses. The reason why scenario 3 has bigger losses than scenario 2 comes back to the fact that it imports more energy from the distribution grid, which have to travel further, and therefore also causes more losses.

The economic differences between the scenarios (tables 6 and 7) shows that the inclusion of the flexible introduction has a greater effect on the total cost than the introduction of batteries to a system which already has flexible generation. As discussed previously, the load and price profiles does is not designed for maximum utilization of the batteries in the grid, and therefore the economic effects are quite small as well. When adding the voltage regulations, the biggest cost increase happens in scenario 1, this is of course because it must shed a severe part of the load at bus 7, which is extremely expensive in this case. A more realistic way to implement load shedding in the model would have been to have different pricing at different buses, and to have an increasing price relative to the percentage of the load that is shedded. For this project however, load shedding was not considered as a flexibility asset, and the price was therefore set extremely expensive so that the model would do everything to avoid it.

The price difference between scenario 2 and 3 is relatively small both with and without voltage regulations, which alludes that the implementation of batteries of this size would not be economically beneficial. Numbers from (21) suggests a battery price of about 300 USD/kWh, giving the 6 MWh battery at bus 5 an investment price of 1.8 million USD (1.74 million EUR). With a price difference of only 123 EUR per day (45 0000 EUR/year), an assumed discount rate of 5% and a lifespan of 25 years the net present value of this investment would be around 670 000 EUR, making it a very bad investment.

Unsurprisingly, the voltage regulations have the smallest effect of scenario 4, this is due to the fact that the voltages almost stay above without the regulations in place (figure 20). Another important effect is that the extra flexible generation it needs to keep the voltages above 0.9 pu, costs less extra because the tariff removes much of the price differences between the imported and the flexible generation.

8 Conclusion and further work

This section will try to answer the objective part of the introduction, to showcase whether the thesis managed to fulfill the goals which were set at the beginning of the work. The review section of this thesis aimed to investigate the existing literature on the key elements in a flexibility market, both in terms of flexibility resources and market actors.

The main objective of this thesis was to develop a model capable of simulating the effects of different flexibility resources distributed across the low voltage grid. The model has shown to be capable both of clearing the market with different flexibility resources included, and to show the economic effects of their implementation. The case study could however have been more experimental for it to showcase the model's full capacity.

8.1 Further work

The model created in this thesis builds on a previous model for TSO/DSO coordination created by (18). With the addition of the model presented in this thesis the possibility to model a full-scale power grid, from top to bottom has been made possible. This could be very interesting work, but there would be some work needed for the models to work together.

As mentioned in the conclusion, the case study carried out in this thesis could have been more comprehensive. Additional elements that could have been added were load shifting and line congestion which were carried out at the TSO/DSO level in (19). Another thing the model would be able to handle is intermittent generation in the LEC. This would mean that the system could be simulated with renewable generation such as wind or solar at some of the buses. The generation of renewables could either be randomized or follow a weather schedule.

Lastly, all data used in this thesis is generated or fabricated in some way. It could be extremely interesting to showcase the models' capabilities on a real grid with real-life data for loads and generators.

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Appendix

A

Variable	**Explanation**
N/n	Set of nodes/index of nodes in distribution grid
M/n	Set of nodes/index of nodes in LEC
T/t	Set of hours/index of hours
U/u	Set of time unites/index of time units
j	Index of recieving node
u	Varaible representing the voltage divided by $\sqrt{2}$
R	Variable equal to $V^2\cos(\theta)$, θ is the voltage angle
I	Variable equal to $V^2\sin(\theta)$, θ is the voltage angle
$P^{G,Flex}$	Flexible power generation
$c^{G,Flex}$	Cost of flexible generation
P^{charge}	Charging of the battery
P^{disch}	Discharging of the battery
c^{batt}	Cost of battery use
P^{LS}	Load shedding
P^{LS}	Cost of load shedding
G	Conductance of line
B	Susceptance of line
P^{L}	Active Load
P^{G}	Active Generation
Q^{L}	Reactive load
Q^{G}	Reactive generation
$P^{G,Flex,min}$	Minimum amount of flexible generation
$P^{G,Flex,max}$	Maximum amount of flexible generation
$P^{SoC,min}$	Minimum state of charge of the battery
$P^{SoC,min}$	Maximum state of charge of the battery
P^{SoC}	State of charge of the battery
$P^{charge,min}$	Minimum charging of the battery
$P^{disch,min}$	Minimum discharging of the battery
$P^{charge,max}$	Maximum charging of the battery
$P^{disch,max}$	Maximum discharging of the battery
$P^{SoC,init}$	Initial state of charge of battery
δ	Binary variable of battery operation
η^{charge}	Charging efficiency of the battery
η^{disch}	Disharging efficiency of the battery

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