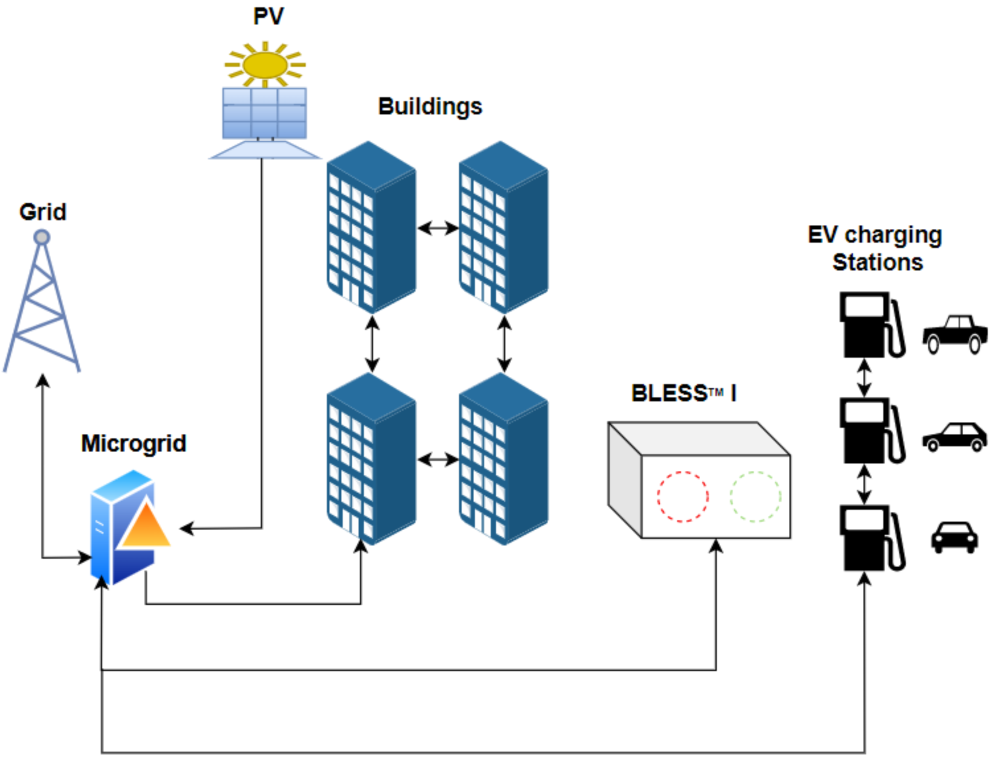

Techno-Economic assessment of battery energy storage system in microgrids with the potential for energy sharing

Impact of Battery Energy Storage System in microgrids

Master's thesis in Sustainable Energy Systems

GOPALAKRISHNAN SIVAKUMAR

DEPARTMENT OF SPACE, EARTH AND ENVIRONMENT
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2022
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GOPALAKRISHNAN SIVAKUMAR

Department of SPACE, EARTH AND ENVIRONMENT
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GOPALAKRISHNAN SIVAKUMAR

Supervisor: Anders Grahl, BatteryLoop
Supervisor & Examiner: David Steen, Department of Electrical Engineering

Master's Thesis 2022
Department of SPACE, EARTH AND ENVIRONMENT
Division of ENERGY TECHNOLOGY
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

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Abstract

The increased use of variable renewable energy sources emphasizes the significance of energy management for load and power generation balancing. One strategy is to promote microgrids with distributed generation sources. This thesis project investigates how a battery energy storage system can aid microgrids.This topic was chosen in response to the Swedish government's announcement of a new regulation allowing energy sharing between houses within a community. It investigates the commercial viability of a microgird-based battery energy storage system. This project also investigates energy management strategies and the potential revenue and emission reduction for system owners, as well as grid owners and power systems. A case study was performed for a residential real estate property with the possibility of including charging stations in the parking lot. Their electricity demand data was gathered from the facility owner. The product of BatteryLoop commonly known as BatteryLoop Energy Storage System-I (BLESS^{TM} I) was used to increase the grid's reliance and to encourages the use of EV charging and Vehcile to Grid technology (V2G).

The final results indicate that using a battery energy storage system without optimization techniques is inefficient. The battery energy storage system in microgrids provides significant revenue to system owners while also assisting in peak management and emission reduction. The combination of peak shaving, energy arbitrages, and ancillary services provides the greatest revenue and payback period for a BESS system in microgrids. If vehicle-to-grid technology becomes a well-established technology in the future, the combination of BESS and V2G yields the greatest benefit but at the same time it reduces the scope of BESS system. Overall, the microgird with only PV generation has a longer payback period than the PV system with BESS combination. About eight possibilities were analysed in this case study and the final conclusion obtained was PV with BESS maximizes the use of self-generation sources while also maximizing profit. More details about the cases analysed will be discussed further in the later sections.

Keywords: Microgrids, EV charging, Energy storage systems, Peak shaving, Ancillary services, BatteryLoop, Energy management.

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Gopalakrishnan Sivakumar, Gothenburg, June 2022

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

BESS	Battery Energy Storage Systems
BLESS^{TM} I	BatteryLoop Energy Storage Systems
EV	Electric Vehicles
V2G	Vehicle to Grid
CO_2	Carbon-di-Oxide
IC	Internal Combustion Engines
VRe's	Variable Renewable Energy sources
CHP	Combined Heat and Power Plant
ESS	Energy Storage Systems
DSM	Demand Side Management
ROCOF	Rate of Change of Frequency
TSO	Transmission System Operator
DSO	Distribution System Operator
FFR	Fast Frequency Response
FCR	Frequency Containment Reserve
FRR	Frequency Restoration Reserve
RR	Replacement Reserve
FCR-D	Frequency Containment Reserve-Deviation
FCR-N	Frequency Containment Reserve-Normal Operation
MIP	Mixed-Integer Programming
LP	Linear Programming
IP	Integer Programming
SOC	State of Charge
SOH	State of Health
EL	Electricity
NREL	National Renewable Energy Laboratory
Bat Ch	Battery Charge
Bat Dis	Battery Discharge
EV Ch	Electric Vehicle Charge
EV Dis	Electric Vehicle Discharge
PV	Photovoltaic
RES	Renewable-based Energy Sources

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1

Introduction

1.1 Project Background

All over the globe people are working to achieve carbon neutrality in order to combat climate change caused by global warming. CO_2 emissions are the major threat to this world as they are the primary contributors to global warming. The emissions from the electric power generation and transportation are the two biggest sources and efforts to be taken to minimize it in order to reduced global warming impact. Electric power generation accounts for around 25% of global greenhouse gas emissions, while transportation accounts for approximately 17% of global greenhouse gas emissions[1][2]. Several studies have been conducted in order to reduce CO_2 emissions, and as a result of these studies, a range of upgrades such as retrofits to the present technologies have been suggested and implemented to this day[2][3].

196 countries have signed the Paris agreement, a legally binding international pact on climate change, in order to work together to reduce emissions around the world. It was signed in 2015 with the goal of keeping global warming far below 2 degrees celsius, preferably 1.5 degrees celsius[4][5]. To achieve these objectives, countries have begun to make fossil power plants carbon neutral by implementing carbon capture and storage systems and transitioning to fossil-free energy sources[6]. Furthermore, by replacing the traditional internal combustion (IC) engines with the introduction of EV's into the transportation sector is a step towards a carbon-free world[7].

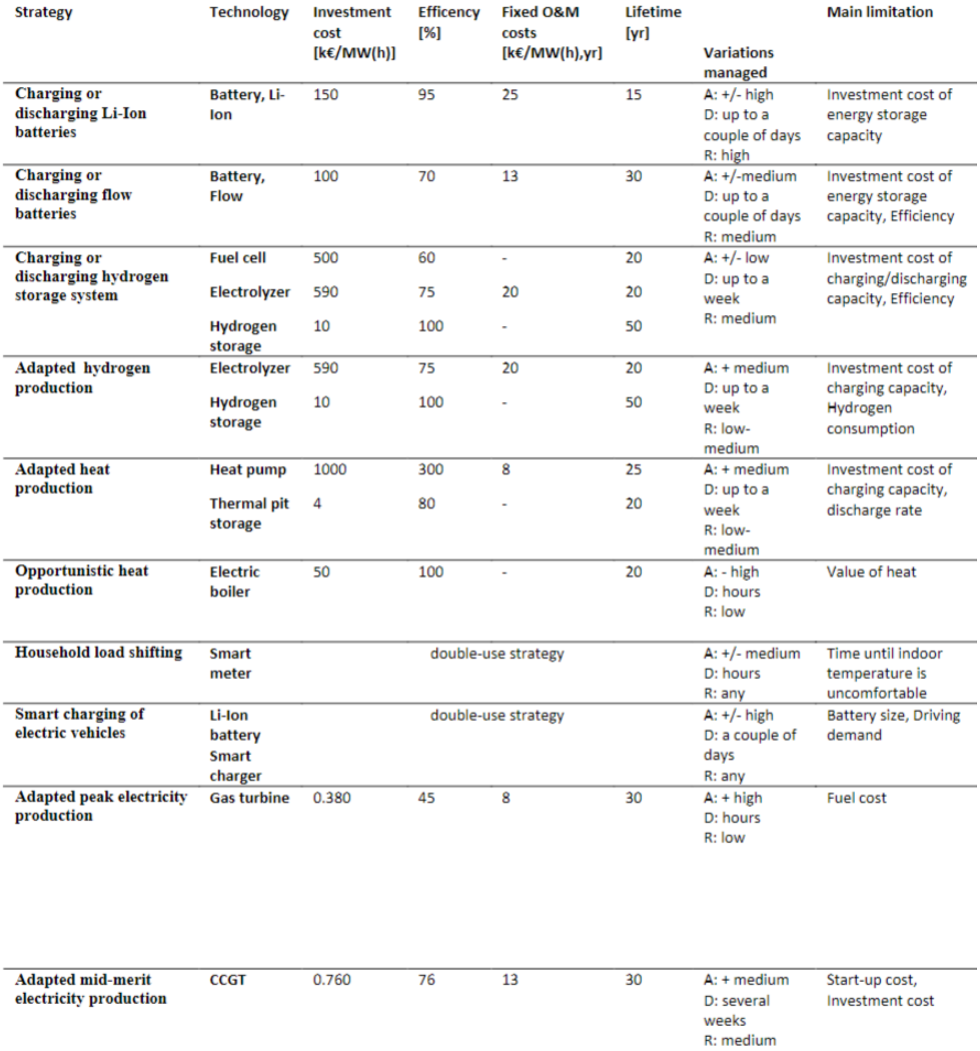
The main renewable energy sources include wind, solar, hydro, geothermal and biomass[8]. Although there are many renewable energy sources their application for electricity generation is based upon their distinct characters. In the recent years, solar and wind has seen a conspicuous growth which is challenging the traditional way of electricity production and consumption[9]. Solar and wind are known as variable renewable energy sources (VRe's) because of their weather dependent character[10],[11]. They are known as intermittent generations meaning that their production is not constant, and it can't be controlled based upon the need[12],[13].

Due to this problem of intermittency, there can be many issues in the grid system such as voltage fluctuation, frequency fluctuation, several unexpected peak hours and black outages[14][15][16]. Their intermittent behaviour and distributed locations, in addition with the increased energy demand, creates both challenges and opportunities to the operation of electric power system. Microgrid is a concept that is evolving in the power and energy industry[17]. It can be a part of the solution to the challenges that are faced by the electric power system due to high penetration of solar and wind[18].It could be the best possible solution to co-ordinately manage the local load, distributed generators and the energy storage systems in the electric power system[18][19][20]. The main solution to balancing the power demand with variable renewable power sources is to adopt the variation management strategies into the system like demand side management and energy storage systems[21][22].

There are different types of energy storage systems like batteries, pumped hydro, thermal energy storage, hydrogen storage and several others. Each energy storage system provides different strategies to the electricity systems. Those strategies are Complementing, Shifting, Absorbing and Peaking[23],[24]. These strategies are basically classified based on their amplitude (A), duration (D) and recurrence (R) shown in Figure 1.1. The most common type of energy storage systems in the household is the batteries. They provide shifting strategy which is the best technology to compensate the variations caused by solar. The energy storage systems which provide complementing strategies such as hydrogen storage system are used for wind power & hydro power.

These energy storage systems store the power from these technologies when they have high production and supply that power when there is a deficit in power generation[25][26]. These energy storage systems thereby reduce the peak and try to maintain a stable power output from the systems. These technologies also help in keeping the price stable and constant. Sweden is a country that produces 56% of its electricity demand from renewable sources[27]. Most of their renewable power generation sources like Hydro and Wind are located in the northern part of the Sweden whereas their major consumers are in the southern part[28]. Transmitting power for longer distances incurs a huge transmission losses and limitation in capacity these problems can be sorted with the help of microgrids due to the promotion of distributed generation systems.

Table 1.1: Variation management strategies classification [29]



Strategy	Technology	Investment cost [k€/MW(h)]	Efficency [%]	Fixed O&M costs [k€/MW(h),yr]	Lifetime [yr]	Variations managed	Main limitation
Charging or discharging Li-Ion batteries	Battery, Li-Ion	150	95	25	15	A: +/- high D: up to a couple of days R: high	Investment cost of energy storage capacity
Charging or discharging flow batteries	Battery, Flow	100	70	13	30	A: +/-medium D: up to a couple of days R: medium	Investment cost of energy storage capacity, Efficiency
Charging or discharging hydrogen storage system	Fuel cell	500	60	-	20	A: +/- low D: up to a week R: medium	Investment cost of charging/discharging capacity, Efficiency
	Electrolyzer	590	75	20	20		
	Hydrogen storage	10	100	-	50		
Adapted hydrogen production	Electrolyzer	590	75	20	20	A: + medium D: up to a week R: low-medium	Investment cost of charging capacity, Hydrogen consumption
	Hydrogen storage	10	100	-	50		
Adapted heat production	Heat pump	1000	300	8	25	A: + medium D: up to a week R: low-medium	Investment cost of charging capacity, discharge rate
	Thermal pit storage	4	80	-	20		
Opportunistic heat production	Electric boiler	50	100	-	20	A: - high D: hours R: low	Value of heat
Household load shifting	Smart meter	double-use strategy				A: +/- medium D: hours R: any	Time until indoor temperature is uncomfortable
Smart charging of electric vehicles	Li-Ion battery Smart charger	double-use strategy				A: +/- high D: a couple of days R: any	Battery size, Driving demand
Adapted peak electricity production	Gas turbine	0.380	45	8	30	A: + high D: hours R: low	Fuel cost
Adapted mid-merit electricity production	CCGT	0.760	76	13	30	A: + medium D: several weeks R: medium	Start-up cost, Investment cost

1.2 Company Background

BatteryLoop is a fast-growing start-up that is a part of the stena sphere. In November 1939, Sten Allan Olsson, then 23, established the Sten A. Olsson Metal products trading company. Later, Stena has evolved into a major international corporation active in a variety of industries, including shipping, real estate, and recycling. Sten Allan Olsson's spirit is to develop economically and environmentally sustainable solutions for resource management[30].

Stena has been a leading vehicle recycler for decades. Stena Recycling has worked with the automotive industry and certified car dismantlers since the ELV directive was implemented in 2007 to ensure the highest possible recycling rate of end–of–life vehicles. This now includes the batteries of electric vehicles.

BatteryLoop was founded in 2017 as part of Stena Recycling to investigate new possibilities for reusing electric vehicles batteries for energy storage. In December 2019, the first energy storage system was delivered. Today's market includes both used and new batteries. BatteryLoop is its own company and a subsidiary of Stena Metall as of September 2021. This thesis will investigate about how these battery energy storage systems can benefit microgrids.

1.3 Scope

It is now legal in Sweden to share electricity between houses, according to a new regulation that went into effect on January 1, 2022[31]. That is, if a solar panel is installed on one house and a nearby house on the same or different property, the energy can be shared between them. If the two houses are on the same property, a grid connection in the second house to which the energy is shared is not required; however, if the houses are on different properties, a grid connection in both houses is required, and it is legal to share energy between them.This thesis project will investigate how battery energy storage systems are going to play a vital role and how it is going to benefit the microgrids as a result of this new regulation.

1.4 Aim and Goals

The main goal of this project is to evaluate the benefits of using the battery energy storage system in microgrids and also to identify the best possible way to operate it. This project includes the following steps to achieve the goal:

1. Analyzing the current challenges that microgrids face due to the lack of energy storage systems.
2. Examine the benefits of battery energy storage systems in microgrids.
3. Evaluate how optimized battery usage and optimal charging methods benefits the system.
4. Evaluate how vehicles to grid would impact the operations of microgrids.
5. Economic assessment of battery energy storage systems in microgrids for both short term and long term perspective.

1.5 Procedure

This section provides a brief overview of the procedure that will be followed:

1. The first step is to conduct a literature review of existing mcirogrids and the problems they are facing today.
2. After determining what data must be collected, the decision has to be made on which modeling tool has to be used for the optimization function.
3. Determining how to obtain the forecasting data and which software to be used for forecasting it.
4. Gathering product data about the BLESS^{TM} I system, a BatteryLoop product which is going to be used in this project.
5. Develop an optimization model using all of the data gathered.

6. Analyze the data obtained from the optimization models and draw conclusions about the findings.

1.6 Limitations

Since thesis projects have time constraints, this project was trimmed and framed accordingly. The company's limits are also included in the limitations. The household demand of four apartments was only considered in this project. The number of EVs ranged from 30 to 200. Only solar generation was considered as a power generation source in the area. wind, CHP, and other technologies were not considered within the microgrid structure. Because of the fixed product available in the company, the battery capacity of BLESS^{TM} I was considered the scope of sizing battery energy storage was neglected. This model is based on historical data and does not replicate the exact real-world scenario, nor is it a decision-making model at the precise location. It is also assumed that the BLESS^{TM} I participates in FCR-D 24 hours a day, 365 days a year. The number of charging ports in this model is assumed to be the number of cars in the scenario, but in reality, with a higher number of cars using at different time steps, there will be very few charging ports.

2

Theory

This chapter describes the microgrid structure as well as the components that make it up. It also provides an overview of how the Swedish electricity market operates and describes the various simulations that were evaluated for this project.

2.1 Microgrids

A microgrid is a local energy grid with control capabilities, which allows it to disconnect from the traditional grid and operate independently. The US Department of energy microgrid exchange group defines the microgrid in this manner[32]. Microgrids are becoming more popular due to their resilience and reliability of power supply. People in cities and urban areas are enticed to use microgrids because of their reliability for electric power, which allows them to attract more companies and industries to their location. These microgrids could also be useful for hospitals, schools, universities, and military bases because they avoid power outages by operating in island mode[17][33].

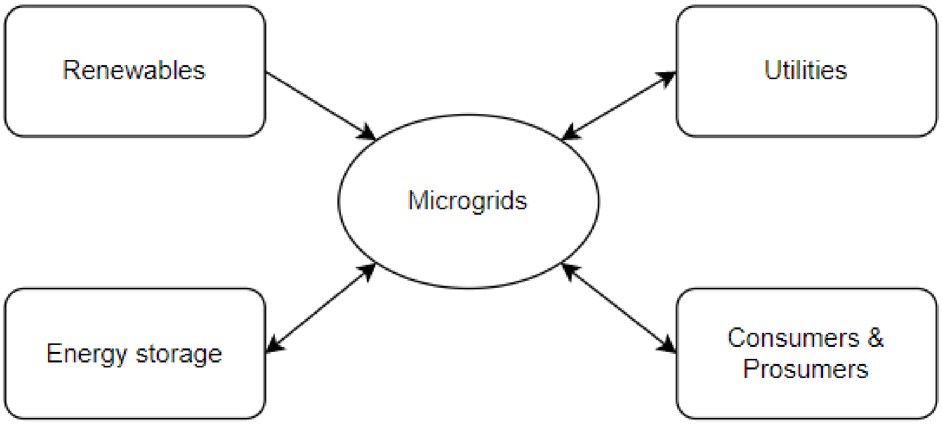


Figure 2.1: Schematic structure of microgrids

Microgrids also have several benefits listed as follows:

1. Maximum utilization of self generation such as solar PV & wind
2. Helps the efficient use of EV charging ports & vehicle to grid technology.
3. Reduces the grid congestions and peak loads.
4. Offers system stability and reliability.

5. With energy storage system in microgrids it can provide ancillary services.
6. Due to its reliability for the power supply it can add some eco points to the buildings.
7. Improves power quality by reducing harmonics.
8. Microgrids also reduce energy losses due to less transmission distance.
9. Helps in energy arbitrages.

2.1.1 Components of microgrids

The physical interconnection between the microgrid and the main grid is the breaker that connects and disconnects from the main grid. It enables energy trading when there is an energy surplus or deficit within the microgrid. Furthermore, the interconnection allows to import energy for storage when energy prices are low in order to consume when energy prices are high. In this way, the total cost can be reduced. In an island mode, the microgrid disconnects from the main grid and, with the help of these generation sources and the storage system, can meet the needs of the consumers. The structure of microgrids differs depending on location and the size of the area.

Microgrids essential components are:
1. Power generation sources
2. Frequency and voltage control system
3. Breaker to connect and disconnect from grid
4. Energy storage systems
5. Consumers & prosumers

2.1.1.1 Power Generation Sources

On a grid scale, power generation systems are classified as base load generation, mid-load or intermediate load generation, and peak load generation. These systems are classified according to their investment cost, start-up time, start-up cost, and running cost. Generally in microgrids the power generation sources would be solar, wind and in some cases Combined Heat and power plants. The microgrid should confirm that it has sufficient capacity for generation systems and energy storage systems to meet demand and manage the system when it is off grid.Several studies are being conducted in this field, one of which is using EV batteries as an energy storage system and using that energy for peak shaving with the option of vehicle to grid[34]. This technology was also considered in this model, and its impact on battery energy storage systems was investigated.

2.1.1.2 Renewable Energy Sources

The most common renewable energy sources in the microgrids are the solar power and wind power.

Solar Power: Solar cells convert the solar irradiance to electrical energy through photovoltaic effect. The cost of solar panels was very high in the beginning when it was introduced but in the later period the cost started to fall, and it has seen a drastic decrement in price in the recent years due to which its usage has been increased. Solar power doesn't incur any running cost, but it has a huge investment cost. It can produce energy very close to the consumers there by decreasing the transmission losses. Through this solar energy even the consumers become prosumers as they can produce power at their own site. Since solar power is weather dependent, and sun doesn't shine all the time its generation is intermittent. Also, the sun shines in the morning and doesn't occur in the night so the generation profile will have diurnal variations [35]. Solar has its highest generation during summer and lowest in winter. It also has production only in the daytime and zero production during night times, so in order to be self sufficient using solar energy battery storage systems are obligatory[36].

Wind Power: Wind turbines convert the kinetic energy of wind to electrical energy. It is also an intermittent generation technology as wind doesn't blow all the time it is also a weather dependent technology. Initially there were only onshore wind technology, but later research paved way for the offshore wind technologies. Wind energy has higher production during winters and lower during summer it is exact opposite to the solar power and higher production during night hours and lower during day hours. Wind turbine also has high investment cost and no running cost but low maintenance cost[37]. Wind power plants provides complementing strategy so hydrogen storage would be the best storage option as it is suitable for complementing strategies. Future researches are about how to use wind power for frequency regulation market[38].

2.1.1.3 Energy Storage Systems

The energy storage system in a microgrid is extremely crucial, as evidenced by the challenges that the microgrid faces, which are listed below. The most common type of energy storage system used in microgrids is the battery energy storage system[39][40]. There are also other storage systems such as hydrogen storage system, thermal energy storage systems and so on. Each system provides different variation management strategies so it is advisable to choose the storage system based on the strategy required for the generation system[41][42]. The best example would be the solar power generation which requires shifting strategy storage solution so batteries are the optimal storage system to merge with solar production other technologies such as hydrogen storage would not be a perfect match as hydrogen storage provides complementing strategy. It makes a perfect pair with wind power generation[43].

Challenges faced by microgrids without energy storage systems: [11]

1. Since distributed generation systems lack inertia, both frequency and voltage control are required in an island mode. This frequency and voltage control will be a challenge to be managed without an energy storage system
2. Since microgrids involves more intermittent generation sources, energy management is more difficult. Furthermore, EV charging adds to its difficulties.
3. Without an ESS, the microgrids lacks system stability and reliability and also provides poor power quality because of harmonics
4. Energy losses will be higher in microgrids without ESS due to higher uneven peaks.

2.1.1.4 Consumer & Prosumers

The distinction between consumers and prosumers is that consumers only use electricity from microgrids, whereas prosumers use electricity and also supply electricity to microgrids when needed. The prosumers have onsite generation sources, such as rooftop PV, that they use to generate electricity and supply to the grid. End users of microgrids include households, industries, agriculture, trade, and services[44][45].

2.2 Energy Management Strategies

As the use of intermittent generation sources grows in power systems, so does the need for energy management. If energy is not managed properly, it can cause several uneven peaks, high frequency fluctuations, and lengthy blackouts[46][47]. To flatten the uneven peaks and to support the grid during peak hours and frequency fluctuations several energy management strategies are followed.

Here, three types of energy management strategies are discussed below:

1. Peak shaving & load levelling
2. Energy arbitrage
3. Frequency regulation/ Ancillary services

2.2.1 Peak shaving & load levelling

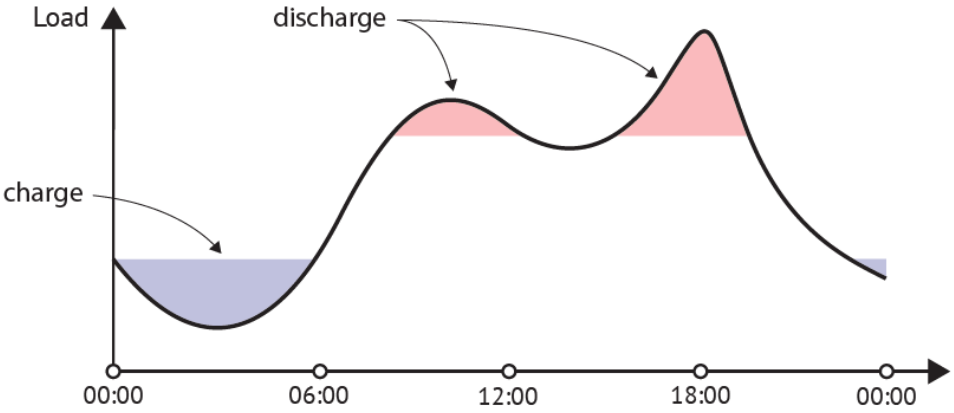


Figure 2.2: Load shifting and Peak shaving

With rising EV charging demand and an intermittent energy generation system, there is a risk of energy losses, high production costs, extremely high electricity prices, and an increase in global emissions. To solve these issues, the peaks must be shaved and the loads must be flattened. Peak shaving can be accomplished through load shifting and utilizing energy storage systems. Load shifting refers to shifting demand from peak hours to off-peak hours. This load shifting strategy is also referred to as Demand Side Management (DSM). The other way to do peak shaving is through energy storage systems, that is charging the energy storage during off peak hours and discharging it during peak hours. This could help in a way to reduce the peak demand from the grid. Through this peak shaving methods the burden on the grid is reduced and also maximizes the utilization of intermittent generation sources thereby reducing the curtailment. This peak shaving process also benefits the customer financially[48][49][50]. In Sweden, houses pay 50SEK per kilowatt of peak power each month, so lowering the peak power each month could save the customer 50SEK/kWp[51]. The more peak shaving they can do, the more the reduced cost they get.

2.2.2 Energy arbitrage

Energy arbitrage requires trading with the grid, which is not possible in island mode. Trading energy entails purchasing electricity at a low price and selling it at a high price, which entails charging the BLESS^{TM} I during low price hours and discharging to the grid during high price hours. Since the high price commonly corresponds to the peak in the grid, this energy arbitrage process generates additional revenue for the BLESS^{TM} I system while also supporting the grid during peak hours. Since microgrids typically purchase electricity during low-cost hours, this process lowers their operating costs. This energy arbitrage process benefits both the BLESS^{TM} I owners and the grid owners[52][53].

2.2.3 Frequency regulation

As Sweden is phasing out nuclear and promoting wind and solar there will be a risk of loosing inertia in the system. In the thermal generation and hydro plants, there are rotating bodies which provides inertia to the system. This inertia helps in maintaining frequency for a shorter period when there is a frequency fluctuation. The change in frequency occurs when there is a sudden rise in supply or demand. This change of frequency if not maintained within a limit it can damage the electrical components and create a blackout at the same time there is also a risk of occurring accidents. In maintaining frequency this inertia in the system plays a vital role, if there is more inertia in the system the rate of change of frequency which is also known as ROCOF will be less[54][55]. If there is less inertia in the system, then the ROCOF will be higher which means the rate at which the frequency falls will be higher. If the ROCOF is high, then the need of fast responding technologies like batteries and demand side response increases. The storage cost of batteries per kWh of energy is very high and the accessibility of controlling demand side response is not well established yet.

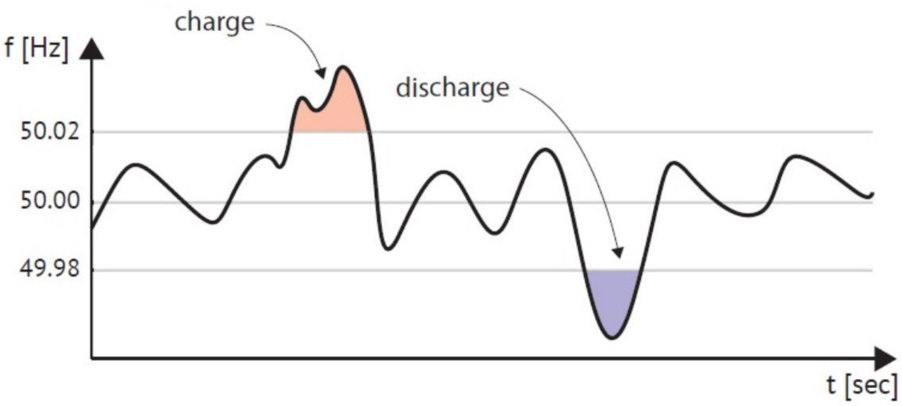


Figure 2.3: Frequency regulation

2.3 Electricity Market in Sweden

The Swedish electricity market works on two types one is known as the physical market and the other is financial market. The physical market is basically the Nord Pool market where the auction takes place for the demand and supply and based on those curves the price is set for that hour whereas the financial market works on the financial contracts or agreements made for the future perspective[56][57][58]. The physical market are for the short term basis and the financial market are for the long term perspective[59][60]. Generally, the retailers are the one who handles consumer like Residential buildings bids and they participate on the physical market on behalf of customers whereas larger companies and industries work on the financial market in order to avoid price edging and speculation[61].

The physical market works on two types one is the day ahead and intra day market and the other is the spot market. In the day ahead market the auction takes place the previous day before the actual power trading day and the market closes exactly at the noon. Whereas the intra day market takes places on the day of trading to compensate for the surplus or deficit. The major players in the Nord Pool market are the suppliers, retailers, consumers and brokers & traders.

In the case of financial markets, the contracts are made between the suppliers and the consumers for the amount of demand for each hour and price for that specific hour. The actual power trading will take place as it is in the spot market if the spot price is higher than the contract set price then the supplier will settle the difference to the consumer if the spot price is lower than the contract price then the consumer must settle to the supplier.

As mentioned earlier, in Sweden the major generation technologies are in the north and the consumers are in the middle and southern part of Sweden. This creates the need for transmitting energy for a longer distance. In order to minimize the transmission losses, the power is transmitted at a higher voltage level. The grid that handles this higher voltage levels (220-400KV) and longer distances is known as the transmission grid. From the transmission grid the power flows to the distribution grid (regional and local grids) where the voltage is stepped down to (Below 130KV). From the distribution grid the power is stepped down in a transformer and fed into the consumers (400V). This transmission grid is owned and operated by Svenska Kraftnät in Sweden, and it is known as the Transmission System Operator (TSO). The TSO's are responsible for the balance and as well as reliability of the system. The distribution grid is operated by the DSO's and they are responsible for the supply and reliability for the distribution lines and consumers [62].

2.3.1 Frequency Regulation Market

In Sweden, the frequency should be kept between 49.9 Hz to 50.1 Hz; if it falls below 49.9 Hz or rises above 50.1 Hz, the frequency containment reserves kick in. FCR-N is activated for any deviations from 50 Hz, FCR-D starts at 49.9Hz. The frequency containment reserves are activated in the order determined by their bid price and frequency deviation. The TSO can pay the suppliers an up regulating or down regulating price depending on the need. When the frequency falls below 49.9Hz, the up regulating price kicks in, indicating that more power is required. When the frequency exceeds 50.1 Hz, the down regulating price kicks in, indicating that consumption should increase and the price for consuming power is paid[63].

The frequency regulation process functions on four process as shown above:

1. Fast Frequency Reserve (FFR)
2. Frequency Containment Reserve (FCR)
3. Frequency Restoration Reserve (FRR)
4. Replacement Reserve (RR).

2.3.1.1 Fast Frequency Reserve

Fast frequency reserve is an automatically activated service that deals with the power system's initial rapid and deep frequency deviations. When there were thermal generation systems, these kinds of frequency fluctuations could be handled easily because the ROCOF in those systems was higher, allowing the system inertia to support the frequency deviations and delay the frequency drop, whereas in the near future solar and wind dominate the power systems, resulting in a lack of inertia in the system and thus less ROCOF[64]. To compensate for these deviations, generation technologies with the ability to supply power when needed and consume when needed are required. Batteries are the best technology for participating in the FFR market because they can consume and supply power when needed, and their ramp up time is very short. This is the main advantage of batteries for the FFR market, but it also has a disadvantage that the cost of energy storage is very high, which means SEK/kWh is very high[65].

2.3.1.2 Frequency Containment Reserve

Frequency Containment Reserve is also an automatically activated service when there is a frequency deviation.

It works on basis of two types as follows:

1. Frequency Containment Reserve for Disturbances (FCR-D)
2. Frequency Containment Reserve for Normal Operations (FCR-N)

FCR-D is a service that is automatically activated to stabilize the frequency in the event of a disturbance. Unlike the FCR-N market, one can bid to participate in either the up regulating or down regulating market separately in FCR-D. If 100KW is bid in the FCR-N market, it can be up regulated or down regulated depending on the situation[66][67]. FCR-N is also a service that is automatically activated and stabilizes the frequency in the event of minor changes in consumption or production. Participants in the FCR market are compensated based on the bid price. They are compensated if they participate in a specific hour, regardless of whether the frequency deviation occurs or not[68][69].

2.3.1.3 Frequency Restoration Reserve

This works based on two types:

1. Automatic Frequency Restoration Reserve (aFFR)
2. Manual Frequency Restoration Reserve (mFFR)

As the name states one type is automatic so it kicks in to restore the frequency back to 50Hz and the other type is manual so it should be manually turned on to restore the frequency back to 50Hz. The automatic restoration kicks in and restores to 50Hz within minutes whereas the manual operation restores the frequency within 12-15minutes[70][71].

2.3.1.4 Replacement Reserve

At present there are no replacement reserves in the Nordic power markets but it is a possible solution in future.

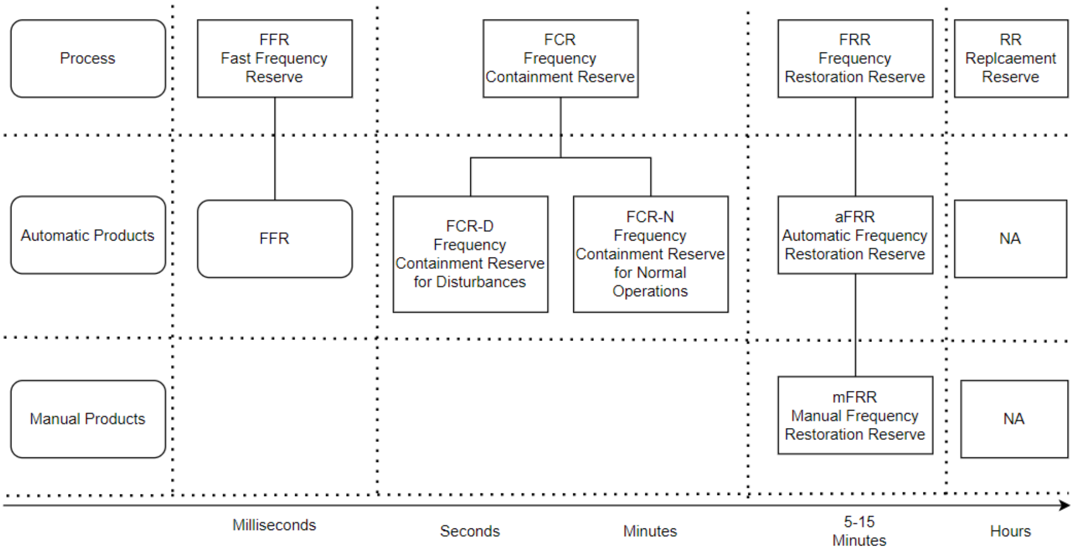


Figure 2.4: Frequency regulation market structure

2.4 Mathematical Optimization

Since these models convert a real-life situation into a mathematical form, the importance of mathematical optimization in the energy industry has grown in recent years. It is a must-have tool for creating an optimization model for manufacturing and scheduling operations research. Moreover, when making decisions, production managers now take optimization into account. The objective function in these models can be set either to minimize production costs or maximize profit. The primary distinction between production planning and scheduling is that production is tactical in nature, whereas scheduling is based on operations research. While statistics and predictive analysis have astounded the world with their incredible ability to influence decision-making, mathematics has also entered the race to provide decision-making guidance. Because mathematical models are capable of applying logic to mathematics while prioritizing the objective function and constraints. Using previous statistics and predictive analysis, optimal way of battery usage or EV charging can be obtained. These tasks are difficult for humans to complete without these optimization models because humans cannot identify everything.

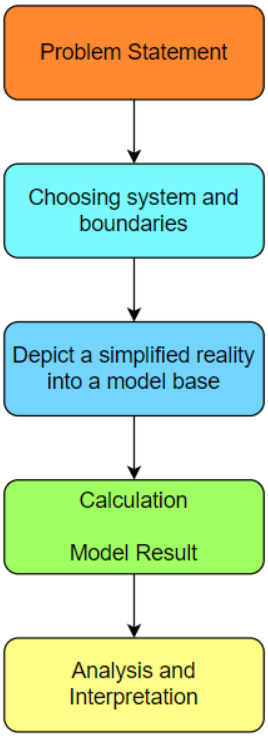


Figure 2.5: Mathematical modelling process flow

Model formulation is crucial in decision-making situations because it communicates the heart of the business decision issue. The process of converting verbal descriptions and numerical data into mathematical formulations that demonstrate the relevant relationship between decision factors, objectives, and resource constraints is known as formulation. The Mixed Integer Programming (MIP) and Linear Programming (LP) method, which has been widely used in various fields such as the production or manufacturing industries, is the most common approach to solving optimization or scheduling problems. Mixed integer programming is the common type which is widely used since it has the ability to find an optimal solution even for high complex models. MIP is a combination of LP and Integer Programming (IP). These models are used in the energy sector for dispatch and investment planning. These models aid in the efficient use of resources and the preparation of plans[72].

The following are the most important elements used in mathematical modeling to convert a real-world scenario to a mathematical formation:

1. Decision Variables
2. Objective function
3. Constraints

Decision variables are those that can be chosen by the model based on the objective function and constraints. The model's limitations are fed in as constraints, while the user defines the objective function, parameters and the decision variables. There are varieties of softwares available for solving the optimization problems e.g. python, GAMS, Julia, OPL, etc. For this thesis project, the optimization model was created using the Opl platform. Similarly, there are varieties of solvers such as Pymo, PulP, GAMS, CPLEX, Gurobi, etc. out of which CPLEX was used as a solver here in this project. More details on variables, constraints, and objective functions will be covered later in the section 3.4.

2.5 Schematic representation of the project site

The general microgrid structure and operation were discussed in the section 2.1. This section is going to elaborate about the microgrid structure of the project site chosen for this thesis. The current project site includes residential buildings as well as a vacant field nearby that is used for parking. This thesis investigates how installing PV panels and energy storage systems, as well as adding charging stations in parking lots with the possibility of V2G, would impact energy use from the grid. As shown in Figure 2.1 the microgrid is connected with the main grid with the possibility of energy trading. In Figure 2.6 the solar PV generation is shown as seperate generation sources but in reality those are commonly roof top PV's. So the buildings are not the consumers whereas they are prosumers. The product of BatteryLoop which is BLESS^{TM} I is the energy storage system used in this site. The EV charging stations are to be placed in the parking lot which is few meters away from the apartment. The project site is a residential building located in Gothenburg.

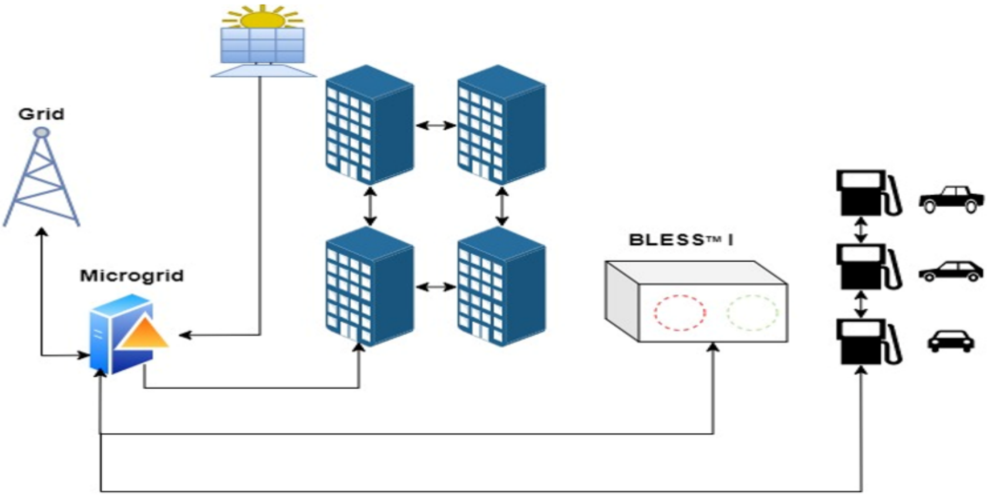


Figure 2.6: Schematic representation of the site

2.5.1 Buildings

Four buildings are considered in this project site. Each building has 106 apartments distributed across 9 stairwells. The roof top area of all buildings combined is approximately 2000m^2, which is suitable for PV installation. The household is already equipped with electricity and a common subscription; no individual subscriptions exist.The household electricity data is obtained from the facility owner. These buildings has different fuse limits as shown below and the energy transfer between them is limited by the fuse constrain.

Table 2.1: Fuse limits for Buildings

Building no.	Fuse limit
1	3x63 A
2	3x50 A
3	3x50 A
4	3x100 A

2.5.2 EV charging stations

There are currently no EV charging stations on the project site, but there is a parking lot close to the buildings. This area is also considered within the project boundary to allow for energy sharing. The site currently has 200 parking spaces available. As a result, the charging demand predicted here is based on assumptions. MATLAB was used to generate this forecasted demand data. The method for obtaining it is discussed in the later section.

2.5.3 BatteryLoop Energy Storage System (BLESS^{TM} I)

In this thesis, the battery energy storage system which is considered for investigation is the BLESS^{TM} I which is a product of BatteryLoop. BatteryLoop is a company which provides second life for the EV batteries, that is the batteries which has a minimum SOH of 80% that no longer will be suitable for to be used in EV but it still has the capability to work as an energy storage system[38], [39]. The old EV batteries are obtained and then refurbished before being used in a second life application. This BLESS^{TM} I has the capability to provide a power output of 155KW and can store energy of 240KWh. This thesis will investigate different scenarios how this BLESS^{TM} I can be used efficiently and benefit the system by maximizing the profit.

Figure 2.7: Image of the BLESS

3

Methods

3.1 CPLEX Optimization Model

The MIP and LP problems are solved using the CPLEX solver. This solver can be used in the Opl platform and is also Python compatible. The first step in this modeling process is to feed the parameters. The parameters in this case are the PV generation profile, household demand data, Electricity spot price data, and EV driving demand data. In the NREL database the location is selected as Gothenburg and the data obtained is for the location of Gothenburg Landvetter which is 30Kms away from the project site. The EV driving distance is obtained in MATLAB by assuming the departure profile and arrival profile as a normal distribution curve and the driving distance to be a weibull function. All the data obtained here are approximate and not 100% accurate. Those datas are fed into this model as hourly data, and because this model is simulated for a year, it accounts for 8760 hours of data.

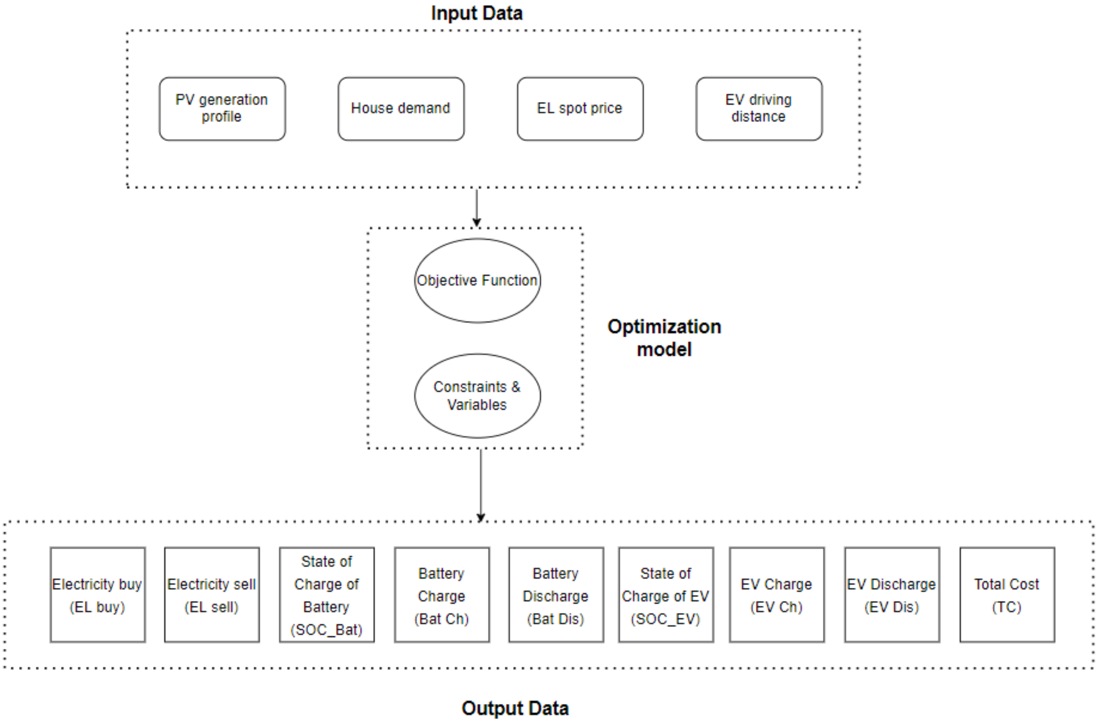


Figure 3.1: Model flow chart

Table 3.1: Parameters data source

Data	Data source
PV generation profile	NREL Database
Household demand	Electricity company
EL spot price	Nordpool Database
EV driving demand	MATLAB

Following the parameters, the decision variables and constraints should be defined and fed into the CPLEX solver. The decision variables are the ones that give the model the flexibility to determine the best way to operate. In this model the examples of decision variables are the EL buy, EL sell, BatCh, BatDis, EVCh and EVDis. The constraints are the model's limitations that define the system's boundaries. The final step is to feed the objective function, which should either maximize profit or minimize operation costs. Based on these conditions, the model shows how the process can be optimized. So here the model decides on when to charge and discharge EV's and batteries and also when to buy electricity from the grid and When to sell electricity to the grid. This is an example of functioning of the optimization model.

3.2 Scenarios

Several case scenarios has been simulated to evaluate the benefits of the BLESS^{TM} I in the microgrids. The simulation scenarios includes the case with and without batteries. It is also helpful in finding out how the different market functioning and participation would impact on the revenue as the cases have been analysed for individual market participation and also in combinations. The different case scenarios which are evaluated are described in detail as follows.

3.2.1 Scenario 1: PV without BLESS^{TM} I

This scenario simulates the reference case where there is no BLESS^{TM} I at the site. Several cases have also been evaluated in this scenario. The cases are discussed further below.

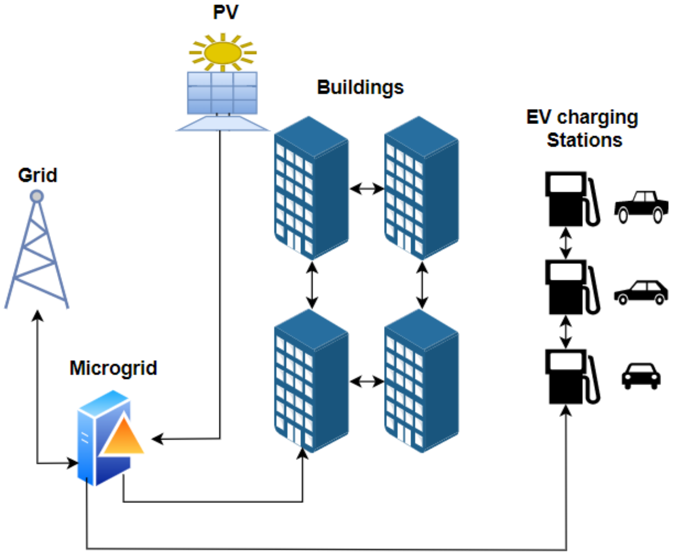


Figure 3.2: Reference case

3.2.1.1 Case 1: Excess energy curtailed

In this case, the microgird does not have the option of selling excess energy to the grid. The link between the microgrid and the main grid is unidirectional, so it will only be able to purchase electricity from the grid. The excess energy generated in this case through PV is curtailed to the ground. This scenario is depicted in Figure 3.3

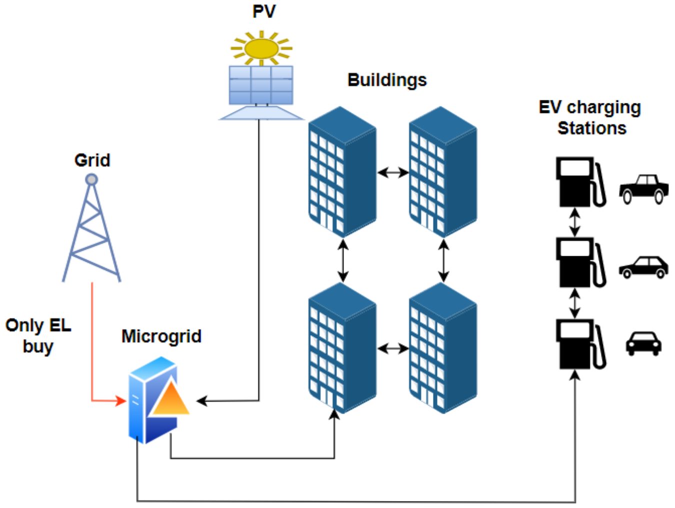


Figure 3.3: Case 1

3.2.1.2 Case 2: Excess energy sold back to the grid

Here, the microgrid have the possibility of selling excess energy to the grid. The link between the microgrid and the main grid is bidirectional, so it can purchase electricity from the grid and also sell electricity to the grid during excess production hours. The owners get paid on the basis of spot price of that hour for selling energy to the grid. This scenario is depicted in the Figure 3.4

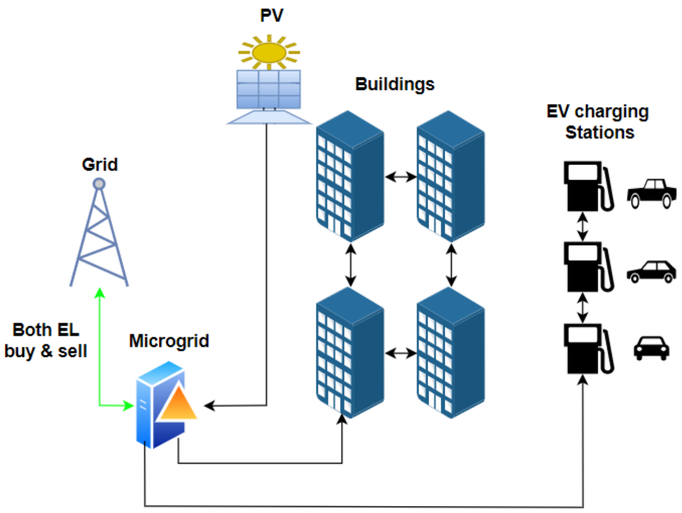


Figure 3.4: Case 2

3.2.1.3 Case 3: Including V2G

While the configuration remains the same as in Case 2, the vehicle to grid (V2G) option is a new feature in this case. The use of EV batteries as an energy storage system is referred to as "vehicle to grid" (V2G). When needed, energy can be drawn from EVs using this V2G feature. The only difference in setup is that the undirectional charging infrastructure has been replaced with bidirectional charging infrastructure. This V2G allows for peak shaving and energy arbitrage.

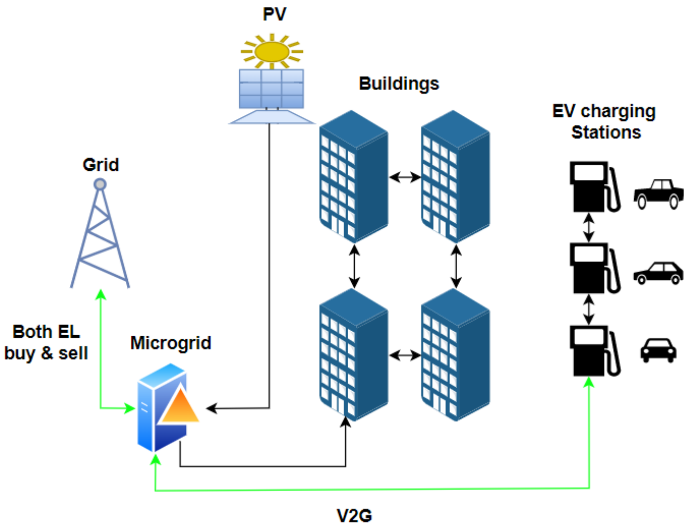


Figure 3.5: Case 3

3.2.2 Scenario 2: PV with BLESS^{TM} I

This scenario simulates the case where there is a BLESS^{TM} I at the site. Several cases have also been evaluated in this scenario. The cases are discussed further below.

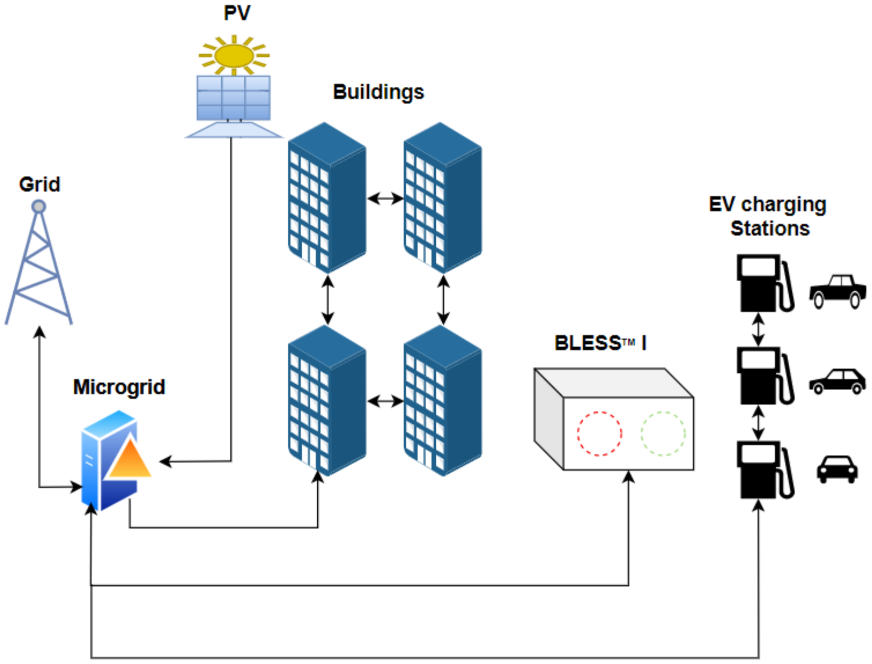


Figure 3.6: Case with BLESS^{TM} I

3.2.2.1 Case 4: Non-Optimal Discharge

The BLESS^{TM} I here charges when there is an excess of energy produced by the solar PV panels and discharges when there is a deficit of energy. In this case, the BLESS^{TM} I does not participate in energy arbitrage or peak shaving. This is a highly inefficient way of using the BLESS^{TM} I system. This case was created to demonstrate how optimization benefits the energy system.

3.2.2.2 Case 5: Peak shaving

As stated in section 2.2.1, peak shaving generates a revenue of 50SEK per kW per month of reduced peak. Despite participating in energy arbitrage, peak shaving adds value to the BLESS^{TM} I system. In this case, the microgrid buys electricity from the main grid during low-cost hours and uses it to satisfy household & EV demand or to charge the BLESS^{TM} I. During high prices, the BLESS^{TM} I system provides energy, so the microgrid either reduces energy consumption from the grid or supplies energy to the grid, depending on demand for that hour. This case study was created to investigate how BLESS^{TM} I system could benefit the microgrids by peak shaving resulting in reduced total cost.

3.2.2.3 Case 6: Including V2G combination with BLESS^{TM} I

In this case even the vehicle batteries are used as an energy storage system. This case was done to analyse the behaviour of V2G in combination with BLESS^{TM} I and also to evaluate whether the V2G adds additional benefits.

3.2.2.4 Case 7: Ancillary services without V2G

The BLESS^{TM} I participates in the frequency regulation market (Basically FCR-D in this model) and this case was analysed to see the benefits that BLESS^{TM} I system gains by participating in it. BLESS^{TM} I system provides ancillary services despite doing peak shaving and participating in energy arbitrage.

3.2.2.5 Case 8: Ancillary services with V2G

It is same as the above case with the possibility of V2G.

3.3 Assumptions made for modelling

Several assumptions have been made for this model to replicate the real case operation scenario. They are as follows:

1. All EV's are connected to the charging port when they are parked.
2. EV's battery capacity is standard and assumed to be 30kWh.
3. EV's battery operation limit is assumed to be between 3KWh to 24kWh.
4. Grid fees + Energy tax = 0.36SEK/kWh
5. PV investment cost is assumed to be 10 000SEK/kWp
6. BLESS^{TM} I capacity is 240kWh with peak power output of 155kW and normally operated between 24kWh to 192kWh
7. The ESS investment cost (including installation) is assumed to 3 000 000 SEK.
8. Investment cost of the charging infrastructure with bidirectional support is not considered.
9. Charging infrastructure capacity is 3.7kW per charging point.
10. Participating in FCR-D all hours of the year.
11. All the bids are within the marginal limit and get paid for all hours of the year.

3.4 Modelling

IBM ILOG CPLEX Optimization Studio was used to run this simulation. This section depicts the process of creating constraints equations, decision variables, and other variables. Since peak shaving revenue is calculated monthly, this modelling is performed for each month. The modelling was completed for a number of case scenarios, which are described in section 3.2. Only the key models are described here, one with only peak shaving, another with peak shaving and V2G, and the last with ancillary services in addition to the previously mentioned services. Over the course of a year, the final results are combined and analysed.

3.4.1 Peak shaving Model

3.4.1.1 Indexes

Time (i) = $\{1 \ldots .744\}$ (Data split for every month)
Buildings (j) = $\{1 \ldots 4\}$
EV No. (k) = $\{1 \ldots 30\}$ (30 for 30vehicles case, 200 for 200 vehicles case)

3.4.1.2 Parameters

The parameters are the one which are being fed into the model as an input data. The values which are known already used in the equations are defined as parameters.

Table 3.2: Parameters

Parameters	Unit	Description
Price (P (i))	SEK/kWh	hourly price of the electricity
House Demand (D (i,j))	kWh/h	Household demand data for four buildings
Total Demand (tot_D (i))	kWh/h	Sum of electrical demand for all four buildings
PV generation profile for 1kWp (PV (i))	kWh/h	PV generation profile for 1kW peak capacity
Charge rate (C)	-	C-rate of the battery. Its value is 1.4
Grid Fees (GF)	SEK/kWh	Grid fees for buying electricity. Its value is 0.36
PV capacity (X)	kW	Installed capacity of PV. It changes for different cases for analysis.
BLESS^{TM} I capacity (Y)	kWh	It is fixed capacity and its value is 240kWh.
Driving Demand (Drive (i,k))	kWh/h	Driving demand for 30cars
Peak demand (maxD(j))	kW	Peak demand in building 1,2,3,4

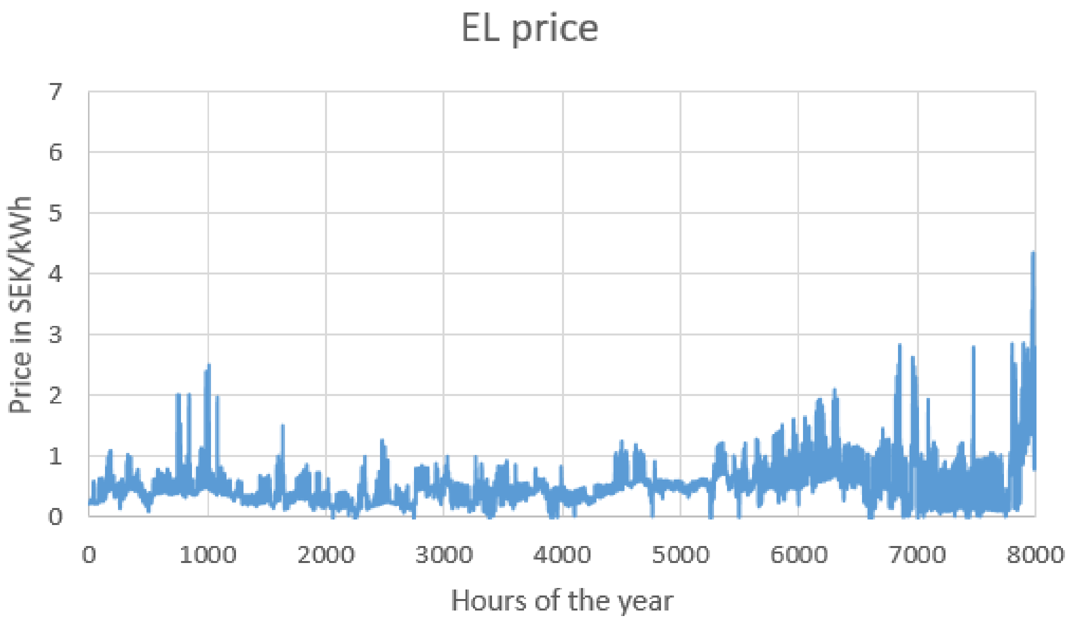


Figure 3.7: Electricity spot price for the year 2021

The above Figure 3.7 represents the electricity spot price data used in this model. Since this model was done for the year 2022 the latest available data for the last year 2021 was used.

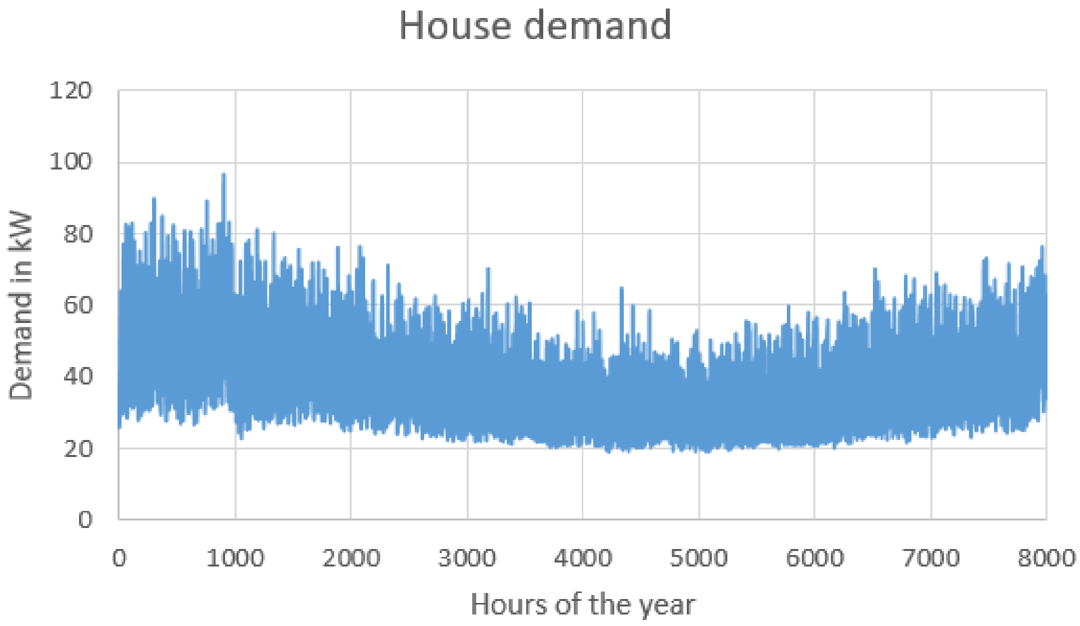


Figure 3.8: House Demand

The above Figure 3.8 represents the combined household demand of the four buildings. This is the demand data which was obtained from the facility owner before the installation of BESS and EV charging ports.

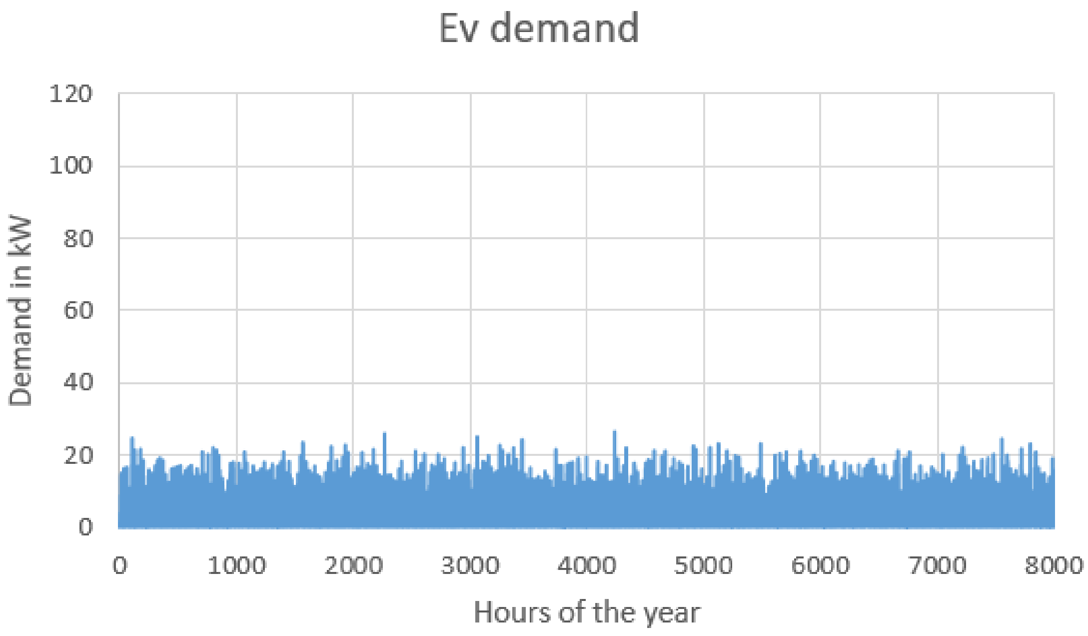


Figure 3.9: EV Demand

The above Figure 3.9 represents the EV charging demand for 30cars used in this model. First, the driving demand data was made by using an assumption that the cars arrival and departure profile follows a normal distribution curve and their driving distance follows a weibull function. After obtaining a driving demand data the EV charging demand data is calculated based on assumption that EV consumption is 0.2kWh/km. As stated earlier currently there are no EV charging ports in the project site, this demand profile was assumed to be the direct charging of EV demand. In all the below case comparison the base demand is assumed to be the house demand + direct charging EV demand.

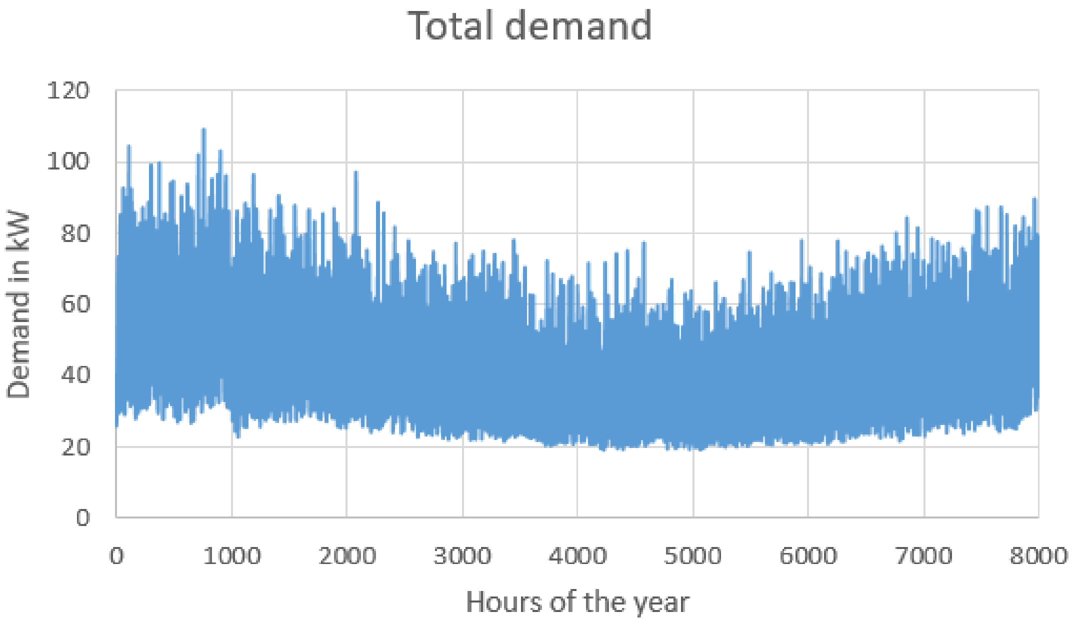


Figure 3.10: Total Demand (House demand+EV demand)

The Figure 3.10 represents the total demand which was used in the model which is the summation of the house demand (figure 3.8) and EV demand (figure 3.9).

3.4.1.3 Decision Variables

Table 3.3: Decision Variables

Decision variable	Unit
Total operation cost (TC)	SEK
Electricity purchase from the grid for building (EL buy(i,j))	kWh/h
Peak Electricity purchase from the grid for building 1 (maxEL buy(j))	kW
Electricity selling to the grid (EL sell(i,j))	kWh/h
Total Electricity purchase from the grid (Tot_ELbuy(i))	kWh/h
Total Electricity selling to the grid (Tot_ELsell(i))	kWh/h
BLESS^{TM} I charging (Bat Ch(i,j))	kWh/h
BLESS^{TM} I discharging (Bat Dis(i,j))	kWh/h
Total BLESS^{TM} I charging (Tot_BatCh(i))	kWh/h
Total BLESS^{TM} I discharging (Tot_BatDis(i))	kWh/h
EV charging (EV Ch(i,k))	kWh/h
Total EV charging (Tot_EVCh(i))	kWh/h
State of Charge of BLESS^{TM} I (SOC_Bat(i))	kWh
State of Charge of EV (SOC_EV(i,k))	kWh

3.4.1.4 Objective function

This section explains how to formulate the objective function. The objective function is set to minimise the total cost of the operation, resulting in an optimal method of operation.

$$\begin{aligned}
\text{Min Total Cost } &= \sum_{i=1}^{8760}\sum_{j=1}^{4}((\text{ Tot\_Elbuy } (i) * (P(i) + GF) - \text{Tot\_Elsell}(i) * P(i)) \\
&- ((\text{maxD(j = 1)} - \text{maxELbuy(j = 1)}) * PP) - \\
&((\text{maxD(j = 2)} - \text{maxELbuy(j = 2)}) * PP) - ((\text{maxD(j = 3)} - \text{maxELbuy(j = 3)}) * PP) \\
&- ((\text{maxD(j = 4)} - \text{maxELbuy(j = 4)}) * PP)
\end{aligned} \tag{3.1}$$

In the equation (3.1) the term Tot_Elbuy(i) refers to the electricity bought from the grid and Tot_Elsell(i) refers to the electricity sold to the grid. The term P(i) is the spot price and the GF is the grid fees which is assumed as a constant value of 0.36SEK/kWh. The cost of grid-purchased electricity is calculated by multiplying the amount of electricity purchased by the price that is the sum of spot price and grid fees. In contrast, the revenue obtained by selling to the grid is calculated by multiplying the amount of electricity sold to the grid by the spot price.
maxD1 is the maximum electricity demand for the building 1 that is before installing the PV's and the BESS. maxELbuy1 is the peak demand of the building 1 after installing the PV's and BESS. Similarly it is done for other buildings. Finally the term PP refers to the Peak price which is the subscriber has to pay to the grid owner. To calculate the total operating cost, the cost for purchasing electricity is

subtracted from the revenue obtained by selling the electricity and also the cost saved by reducing the peak.

3.4.1.5 Constraint equations

Supply demand constraint:
This constraint is framed to balance the supply and demand. The demand should not be greater than the generation that is the demand is satisfied only from the generation mentioned in this equation. In (3.2) D(i,j) refers to the demand of the houses, X refers to the PV capacity and PV(i) refers to the generation profile for the PV.

$$\begin{aligned}&\mathrm{D(i)(j)} \leq X * PV(i) + \mathrm{Elbuy}(i,j) + \mathrm{BatDis}(i,j) - \mathrm{Elsell}(i,j) - \mathrm{BatCh}(i,j)\\ &- \mathrm{EVCh}(i,k) \forall i,j,k\end{aligned} \tag{3.2}$$

$$\begin{aligned}&\mathrm{Tot\_D(i)} \leq 4 * X * PV(i) + \mathrm{Tot\_Elbuy}(i) + \mathrm{Tot\_BatDis}(i) - \mathrm{Tot\_Elsell}(i)\\ &- \mathrm{Tot\_BatCh}(i) - \mathrm{Tot\_EVCh}(i) \forall i\end{aligned} \tag{3.3}$$

Elbuy (i) and ELsell(i) refers to the electricity that is being bought from the grid and sold to the grid respectively. BatCh(i,j) and BatDis(i,j) refers to the battery charge and discharge respectively and similarly does the EVCh(i,k). The generation from the PV, the electricity purchased from the grid and the battery discharge are considered as a generation whereas the battery charge and EV charge are considered as consumption.

Battery constraints:

$$\mathrm{SOC\_Bat(i)} = \mathrm{SOC\_Bat}(i-1) + \mathrm{Tot\_BatCh}(i) - \mathrm{Tot\_BatDis}(i) \forall i \geq 2 \tag{3.4}$$

$$\begin{aligned}&\mathrm{SOC\_Bat(i)} = \mathrm{SOC\_Bat}(xx) + \mathrm{Tot\_BatCh}(i) - \mathrm{Tot\_BatDis}(i) \forall i = 1;\\ &xx = lasttimestep\end{aligned} \tag{3.5}$$

In (3.4) SOC_Bat(i) refers to the state of charge of battery at ith time step and SOC_Bat(i-1) refers to the state of charge of battery at previous time step. The state of charge of battery is calculated by adding the battery charge and subtracting the battery discharge from the state of charge of battery at previous time step. This applied only from the second time step. For the first time step the equation (3.5) is used as it doesn't have a previous time step so the SOC of the last time step is considered to make it as a loop. SOC_Bat(1-xx) refers to the state of charge of battery at the last time step.

Summing up: These summations were done to use it in equation 3.3.

$$\sum_{j=1}^{4} \text{BatCh}(i,j) = \text{Tot\_BatCh}(i) \forall i \tag{3.6}$$

$$\sum_{j=1}^{4} \text{BatDis}(i,j) = \text{Tot\_BatDis}(i) \forall i \tag{3.7}$$

$$\sum_{j=1}^{4} \text{ELbuy}(i,j) = \text{Tot\_ELbuy}(i) \forall i \tag{3.8}$$

$$\sum_{j=1}^{4} \text{ELsell}(i,j) = \text{Tot\_ELsell}(i) \forall i \tag{3.9}$$

$$\sum_{k=1}^{30} \text{EVCh}(i,k) = \text{Tot\_EVCh}(i) \forall i \tag{3.10}$$

EV Battery constraints:

$$\text{SOC\_EV(i,k)} = \text{SOC\_EV}(i-1,k) + \text{EVCh}(i,k) - \text{Drive}(i,k) \forall i \geq 2, k \tag{3.11}$$

$$\begin{aligned} &\text{SOC\_EV(i,k)} = \text{SOC\_EV}(xx,k) + \text{EVCh}(i,k) - \text{Drive}(i,k) \forall i = 1, k; \\ &xx = lasttimestep \end{aligned} \tag{3.12}$$

These constraints are similar to the case used for the batteries to calculate their state of charge. SOC_EV(i,k) refers to the state of charge of the kth car in ith time step and it follows the same for SOC_EV(i-1,k) and EVCh(i,k). The Drive(i.k) refers to the cars driving demand that is kth car ith time step driving demand.

EV battery operation limit:
This condition states that the state of charge of EV battery should be within the limit 3kWh to 24 kWh which is their opertional limit should be 10% to 80% of its battery capacity.

$$3 \leq \text{SOC\_EV}(i,k) \leq 24 \forall i, k \tag{3.13}$$

EV charging constraint:

$$\text{EVCh}(i,k) = 0 \forall Drive(i,k) > 0 \tag{3.14}$$

$$\text{EVCh}(i,k) \leq 3.7 \forall i, k \tag{3.15}$$

Equation 3.4 states that the EV charging should be zero when the vehicle is in driving. EVCh(i,k) refers to the EV charging of the kth car at ith time step should be zero forall Drive(i,k) is greater than zero. Equation 3.5 states that the EV charging should always be less than 3.7 for all i times and k cars. This constraint is used to state that the maximum power output of the charging stations.

BLESS^{TM} I operation limit:
This operation limit constraint is similar to the one for the EV batteries. Their operation range should be between 10% to 80% of its battery capacity.

$$24 \leq \text{SOC\_Bat}(i) \leq 192 \forall i \tag{3.16}$$

BLESS^{TM} I charging constraint:
This constraint equation was framed to include the c-rate limitation for the batteries. In 3.17 and 3.18 C refers to the C-rate and Y refers to the battery capacity.

$$\text{BatCh}(i,j) \leq \text{C*Y} \, \forall i,j \tag{3.17}$$

$$\text{BatDis}(i,j) \leq \text{C*Y} \, \forall i,j \tag{3.18}$$

Fuse constraint: All the below constraints depicts the limitation of the transmission in terms of fuse constraints. The fuse constraint for the first, second, third and fourth buildings are 43.47kW, 34.5kW, 34.5kW and 69kW respectively. The maximum output of the battery is 155kW which is stated in equation 3.27 and 3.28.

$$\text{ELbuy}(i,j) \leq 43.47 \, \forall i, j = 1 \tag{3.19}$$

$$\text{ELbuy}(i,j) \leq 34.5 \, \forall i, j = 2 \tag{3.20}$$

$$\text{ELbuy}(i,j) \leq 34.5 \, \forall i, j = 3 \tag{3.21}$$

$$\text{ELbuy}(i,j) \leq 69 \, \forall i, j = 4 \tag{3.22}$$

$$\text{ELsell}(i,j) \leq 43.47 \, \forall i, j = 1 \tag{3.23}$$

$$\text{ELsell}(i,j) \leq 34.5 \, \forall i, j = 2 \tag{3.24}$$

$$\text{ELsell}(i,j) \leq 34.5 \, \forall i, j = 3 \tag{3.25}$$

$$\text{ELsell}(i,j) \leq 69 \, \forall i, j = 4 \tag{3.26}$$

$$\text{Tot\_BatCh}(i) \leq 155 \, \forall i \tag{3.27}$$

$$\text{Tot\_BatDis}(i) \leq 155 \, \forall i \tag{3.28}$$

3.4.2 Vehicle to Grid Model

3.4.2.1 Parameters

The variable below apply in addition to the one indicated in Table 3.2.
V2G cost = 1 SEK/kWh (paid to EV owners)

3.4.2.2 Decision Variables

The variables below apply in addition to the one indicated in Table 3.3.

Table 3.4: Decision variables in addition to the previous table 3.3

Decision variable	Unit
EV discharging (EVDis)	kWh/h
Total EV discharging (Tot_EVDis)	kWh/h

3.4.2.3 Objective function

The same terms and explanation applies as stated in 3.4.1.4. The only new term which is included in equation is the EV Discharge which is denoted by EV_Dis as this case is done for the vehicle to grid simulation.

$$\text{Total Cost } = \sum_{i=1}^{8760}\sum_{j=1}^{4}((\text{ Tot\_Elbuy } (i) * (P(i) + GF) + \text{Tot\_EVDis}(i) * V2Gcost) \\ - \text{Tot\_Elsell}(i) * P(i)) - ((\text{maxD(j = 1)} - \text{maxELbuy(j = 1)}) * PP) - \\ ((\text{maxD(j = 2)} - \text{maxELbuy(j = 2)}) * PP) - \\ ((\text{maxD(j = 3)} - \text{maxELbuy(j = 3)}) * PP) - ((\text{maxD(j = 4)} - \text{maxELbuy(j = 4)}) * PP) \tag{3.29}$$

3.4.2.4 Constraint equations

$$\text{D(i,j)} \leq X * PV(i) + \text{Elbuy}(i,j) + \text{BatDis}(i,j) - \text{Elsell}(i,j) - \text{BatCh}(i,j) \\ - \text{EVCh}(i,k) + \text{EVDis}(i,k) \forall i,j,k \tag{3.30}$$

$$\text{Tot\_D(i)} \leq 4 * X * PV(i) + \text{Tot\_Elbuy}(i) + \text{Tot\_BatDis}(i) - \text{Tot\_Elsell}(i) \\ - \text{Tot\_BatCh}(i) - \text{Tot\_EVCh}(i) + \text{Tot\_EVDis}(i) \forall i \tag{3.31}$$

$$\sum_{k=1}^{30} \text{EVDis}(i,k) = \text{Tot\_EVDis}(i) \forall i \tag{3.32}$$

$$\text{SOC\_EV(i,k)} = \text{SOC\_EV}(i-1,k) + \text{EVCh}(i,k) - \text{Drive}(i,k) - \text{EVDis}(i,k) \forall i \geq 2, k \tag{3.33}$$

$$\text{SOC\_EV(i,k)} = \text{SOC\_EV}(xx,k) + \text{EVCh}(i,k) - \text{Drive}(i,k) - \text{EVDis}(i,k) \forall i = 1, k; \\ xx = lasttimestep \tag{3.34}$$

$$\text{EVDis}(i,k) = 0 \forall Drive(i,k) > 0 \tag{3.35}$$

$$\text{EVDis}(i,k) \leq 3.7 \forall i,k \tag{3.36}$$

Add equations 3.4 to 3.10 and equations 3.13 to 3.28 to the equations listed above.

3.4.3 Ancillary services

For Ancillary services the BLESS^{TM} I was assumed to only participate in FCR-D market. The bid is considered to be 150kW capacity and the deviation appears with rare recurrence with the maximum time of 20mins so the capacity of 50kWh was reserved for that case and with the remaining capacity the BLESS^{TM} I was used to do peak shaving and energy arbitrages. This bid was not included in the model because if it were, the model would tend to trade energy in the FCR market because the price would be higher than the spot price. In reality, energy exchange occurs only two to three times per year, whereas in other cases, it simply participates in the market as a reserved capacity and is paid, so it is not activated for the majority of the year. To solve this problem and keep things simple, 50kWh of battery were reserved for FCR-D, so only equation 3.37 was included in the model, and the price for FCR-D was used in the final calculation, assuming that the bid is always within the margin and get paid.
Hence, the model formulation was the same but equation 3.16 was replaced by 3.37.

$$74 \leq \text{SOC\_Bat}(i) \leq 192 \forall i \tag{3.37}$$

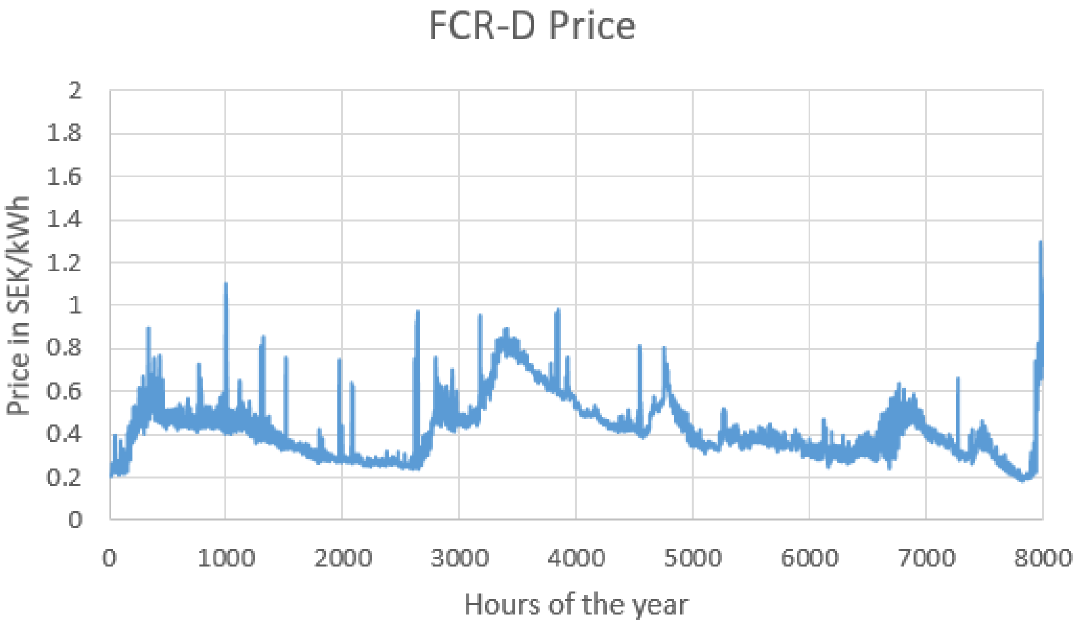


Figure 3.11: FCR-D price

4

Results

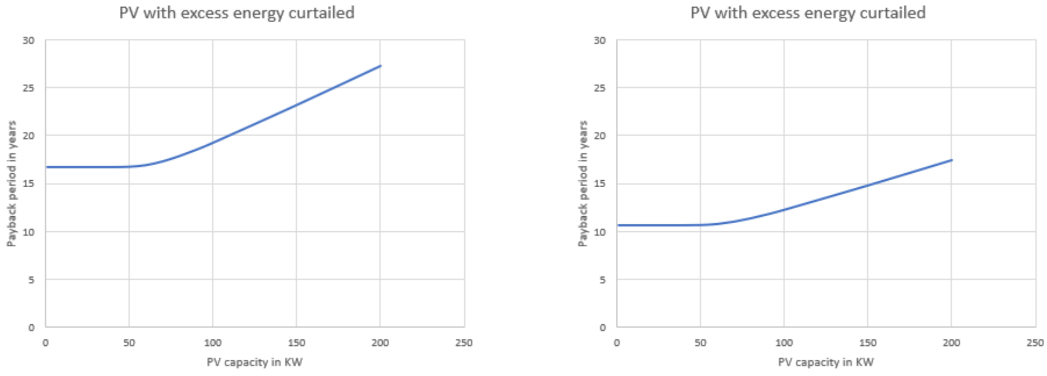
This section presents and discusses all of the findings from the various case studies.

4.1 Results for Scenario 1

As stated earlier about how different scenarios were considered and their results are discussed below. Scenario 1 depicts the case that didn't have BLESS^{TM} I in the system

4.1.1 Case 1: Excess energy curtailed

Case 1 depicts the situation, if there is no way to sell excess energy to the grid. Two scenarios have been evaluated for this, one depicting the case with grid fees and energy tax and the other without grid fees and energy tax. Figure 4.1 depicts the outcome of this scenario. As a result, the higher the energy tax and grid fees, the shorter the payback period. Another point is that the payback period remains constant up to 60kW, after which it increases. Figure 4.2 shows that the PV excess production increases from 60kW, which explains the reason for increase in payback period. As the capacity increases above 60kW, the capacity becomes useless because it generates low revenue and simply wastes energy by curtailing it to the ground, so investment rises while revenue falls. This is the reason for the longer payback period.



Excluding grid fees and energy tax

Including grid fees and energy tax

Figure 4.1: Payback period comparison for case 1 with and without grid fees

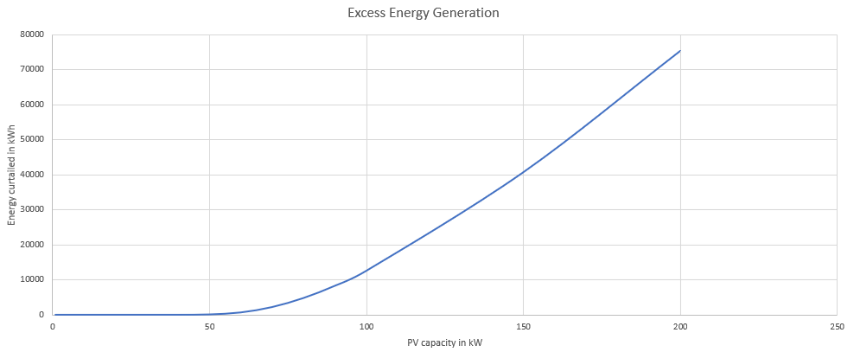
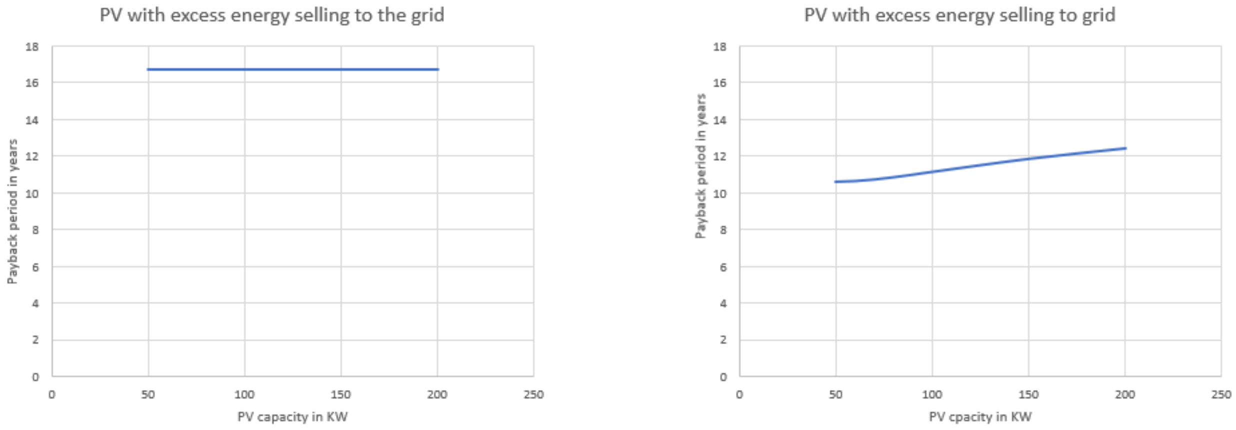


Figure 4.2: Excess energy generation vs PV capacity

4.1.2 Case 2: Excess energy sold back to the grid

Case 2 depicts the situation, if there is a way to sell excess energy to the grid. Same two scenarios have been evaluated for this, one depicting the case with grid fees and energy tax and the other without grid fees and energy tax. Figure 4.3 depicts the outcome of this scenario. When PV capacity increases, so does excess energy generation, which must be sold to the grid for which it only receives revenue based on the spot price. However, if the PV is sized appropriately, it can reduce energy consumption from the grid, which provides more benefit because it saves the money that must be paid to purchase that energy, which is spot price plus energy tax. It can be concluded that self-generation for personal use is more advantageous than selling to the grid. This demonstrates how BESS can benefit the system by storing excess energy and using it for later demand.



Excluding grid fees and energy tax

Including grid fees and energy tax

Figure 4.3: Payback period for case 2 with and without grid fees

4.1.3 Case 3: Including V2G

Case 3 depicts what would happen if the V2G facility was added to Case Scenario 2. This case was created to test how V2G would function as a replacement for BESS.

Figure 4.4 shows that the V2G facilitate addition benefits the system by assisting in peak shaving, which generates revenue and reduces the payback period. In figure 4.4 the peak shaved per year graph depicts the summation of peak shaved per month for the whole year. The greater the number of vehicles, the larger the benefit of V2G. In this case it is assumed that the EV owners get paid 1 SEK/kWh for providing V2G.

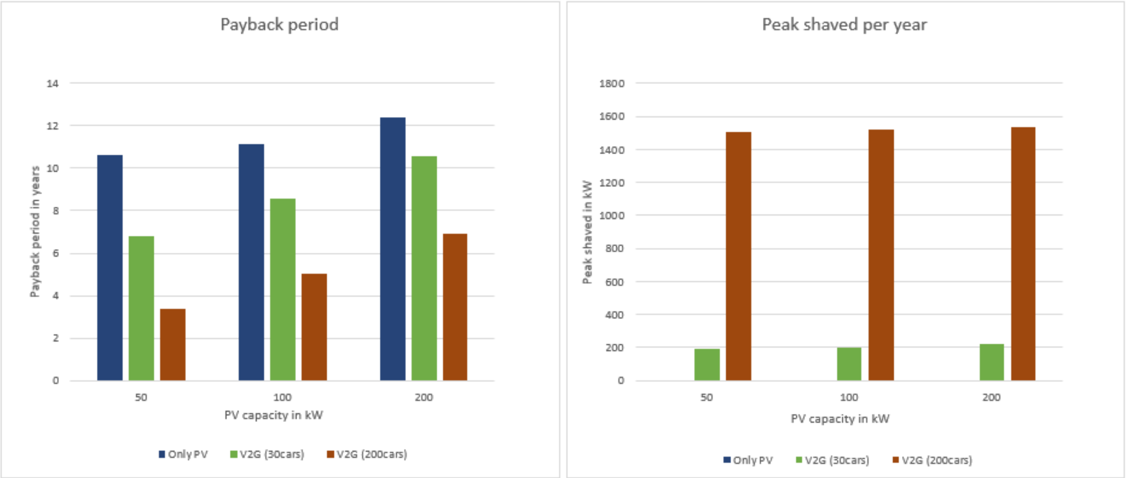


Figure 4.4: Payback period and peak reduction per year comparison for case only with PV and PV+V2G with 30 cars and 200 cars

4.2 Results for Scenario 2

Scenario 2 depicts the case that have BLESS^{TM} I in the system

4.2.1 Case 4: Non-Optimal Discharge

The payback period in this case includes both the BLESS^{TM} I system and the PV system. This scenario depicts a non-optimal discharge method for the BLESS^{TM} I system. This BLESS^{TM} I system generates more revenue than the previous cases because it participates in energy arbitrages and also increases the self consumption of PV generation. Despite the fact that it adds more benefits, the payback is very high because it is calculated for the BLESS^{TM} I system and PV system. More opportunities must be identified in order to generate more revenue to shorten the payback period.

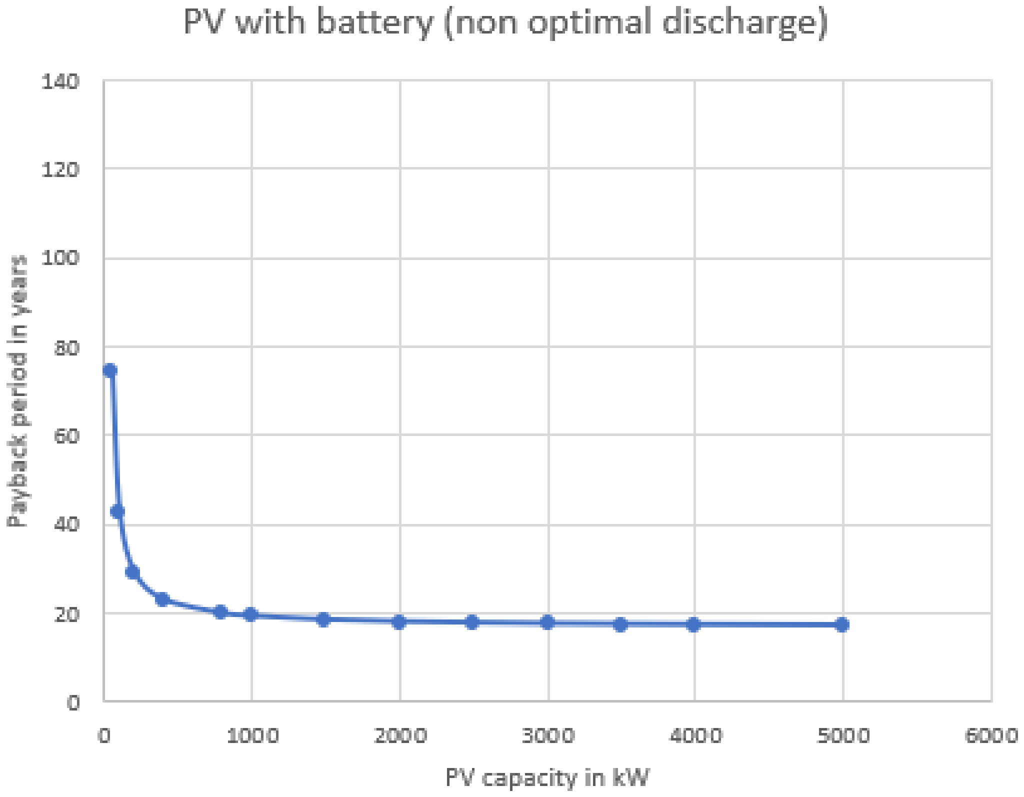


Figure 4.5: Payback period for case PV with batteries and dispatched in non-optimal way

4.2.2 Case 5: Peak shaving without V2G

Peak shaving is a method that generates revenue for the BLESS^{TM} I system while also benefiting the grid system. Figure 4.6 shows that the payback period has decreased when compared to Figure 4.5 . Figure 4.7 shows the kW of peak shaved using the BLESS^{TM} I system. The more EV's there are, the more peak shaving can be done; this is why the 200 cars scenario has a lower payback period than the 30 cars scenario.

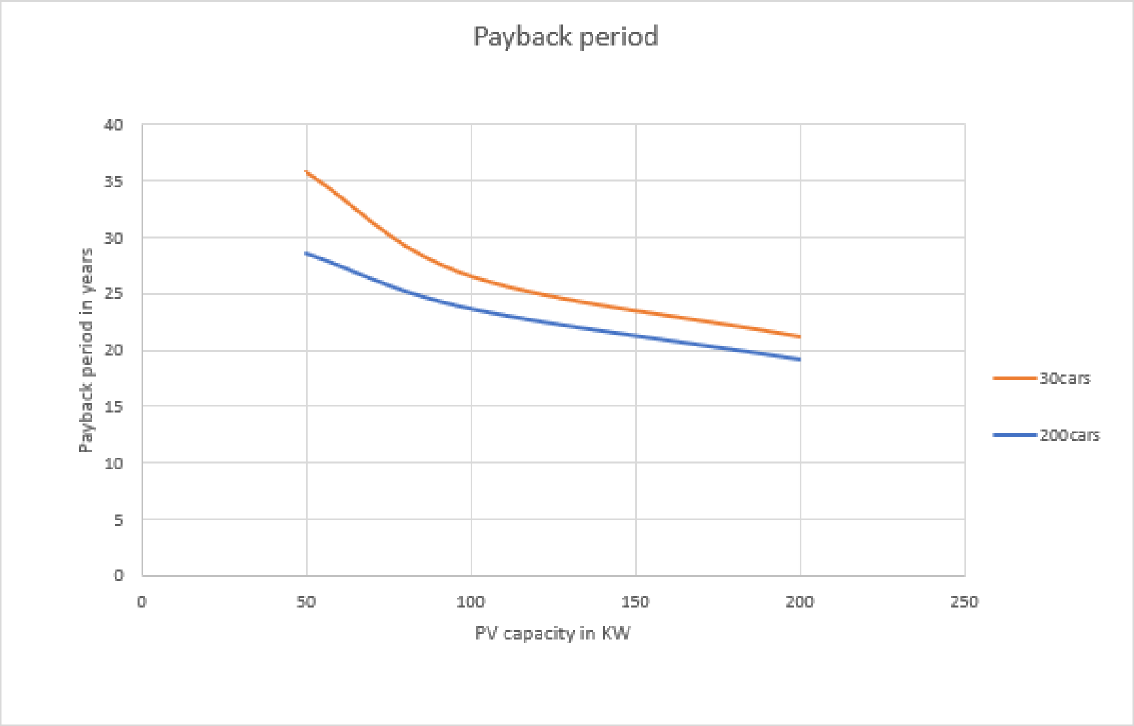


Figure 4.6: Payback period comparison with 30 cars and 200 cars for case 5 without V2G and with BLESS^{TM} I for different PV sizes

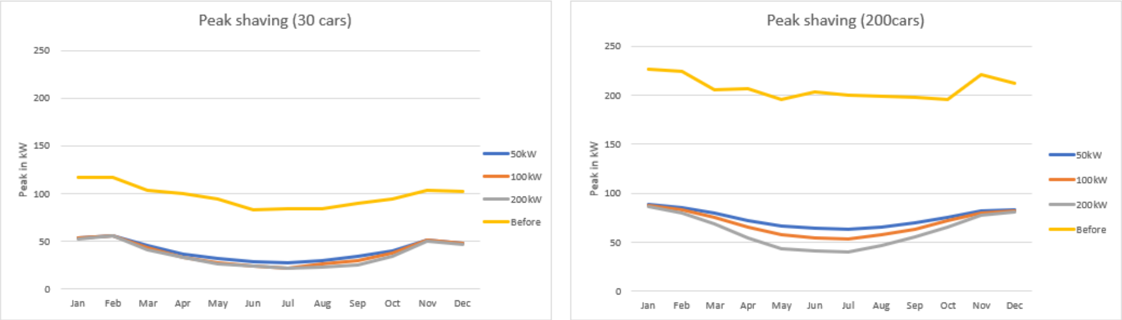


Figure 4.7: Peak shaving comparison for 30 and 200 cars

4.2.3 Case 6: Including V2G in combination with BLESS^{TM} I

This case examines whether connecting a vehicle to the grid would benefit the system. Figure 4.8 shows that the payback period for this case is shorter than for the previous case that does peak shaving. It is also clear that the V2G could contribute to peak shaving. This implies that the V2G provides additional benefits in terms of reduction in its payback period and generates additional revenue to the BLESS^{TM} I system. Still, the payback period is very high, so more opportunities to reduce the payback period are being investigated.

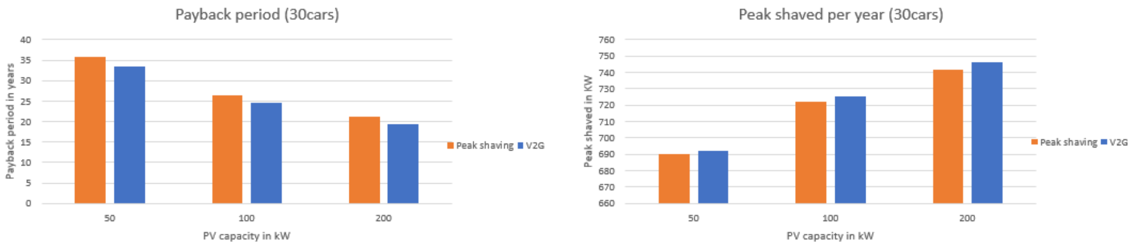


Figure 4.8: Comparison of payback period and peak shaved per year for the case only peak shaving and for the case peak shaving+V2G with 30 cars

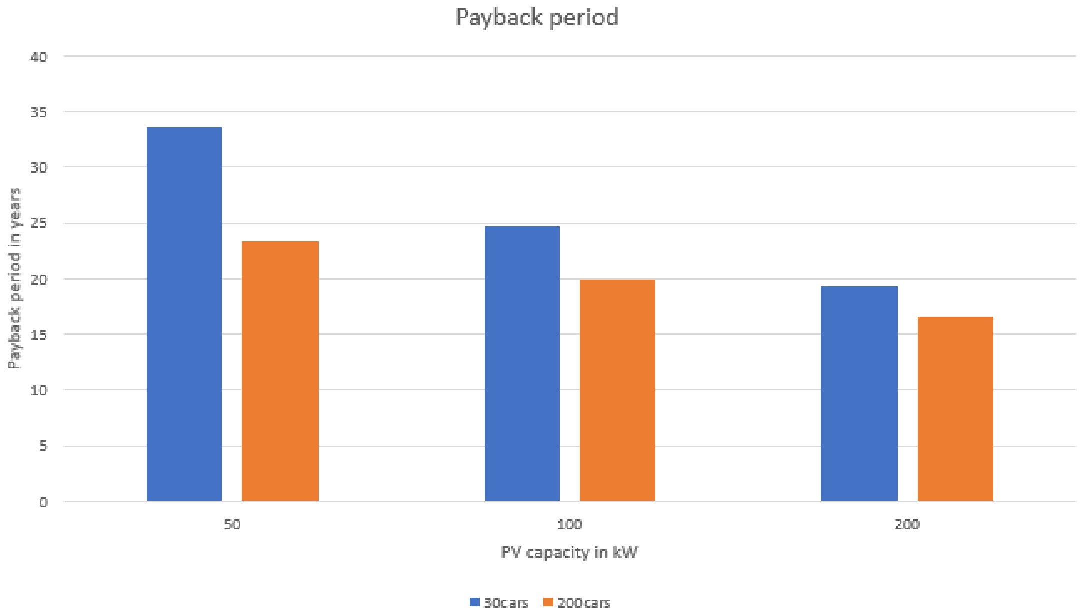


Figure 4.9: Payback period comparison for the case Peak shaving+V2G with 30cars and 200cars

4.2.3.1 Case 7 & 8: Ancillary services without & with V2G

This scenario looks into how the BLESS^{TM} I can offer ancillary services and how the payback period changes. Figure 4.10 shows that the BLESS^{TM} I participating in the FCR-D market has the shortest payback period, bringing the BLESS^{TM} I system into the real business case scenario. Peak shaving comparisons with other cases show that, despite participating in the FCR market, it can do good peak shaving. Figure 4.11 depicts a comparison of the BLESS^{TM} I providing ancillary services with and without V2G, as well as the case where only PV without a BLESS^{TM} I performs peak shaving with V2G. It can be concluded that the V2G in conjunction with the BLESS^{TM} I system is more advantageous.

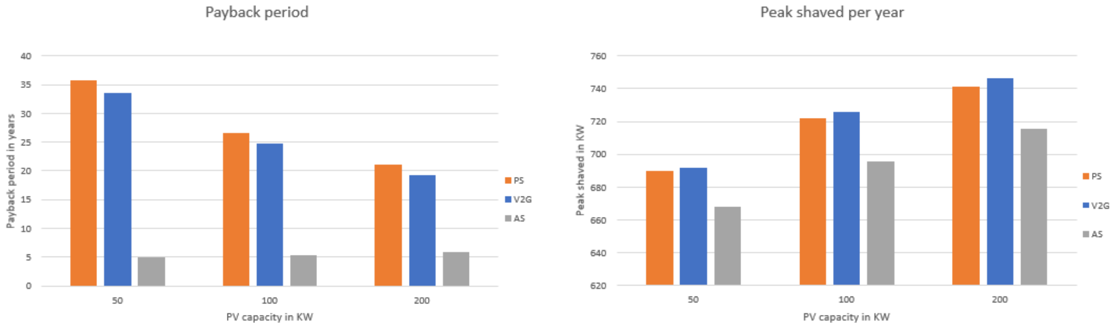


Figure 4.10: Comparison of the pay back period and peak shaved per year for the cases only peak shaving, peak shaving+V2G and peak shaving+V2G+Ancillary services

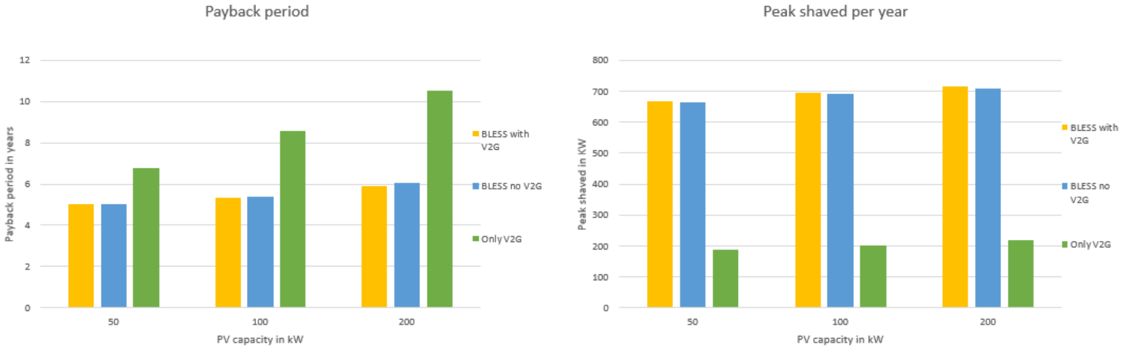


Figure 4.11: Comparison of the pay back period and peak shaved per year for the cases only V2G no BLESS, BLESS but no V2G and BLESS+V2G

4.3 Illustration how BLESS^{TM} I supports microgrids

Figure 4.12 compares the demand curves for peak shaving only with V2G without a BLESS^{TM} I system and for the case with a BLESS^{TM} I system. For the 30 car scenarios, it can be seen that the demand curve only with V2G has several uneven peaks, whereas the case with BLESS^{TM} I has flattened the peaks. Without BLESS^{TM} I, energy management will be more difficult because of the uneven peaks, and it will also force gas turbines to run for longer periods of time, resulting in environmental impacts.

In the case of 200 cars, the peaks are flattened by V2G, but their demands are uneven, making it difficult for the base load to operate and satisfy the demand. In the case of the BLESS^{TM} I system, the demand is more even, making it more suitable for the operation of base load systems.

This result is based on the given constraints, but in practice, if wind power generation and several other generation systems with various types of energy storage systems operate within the microgrid, this illustration may change.

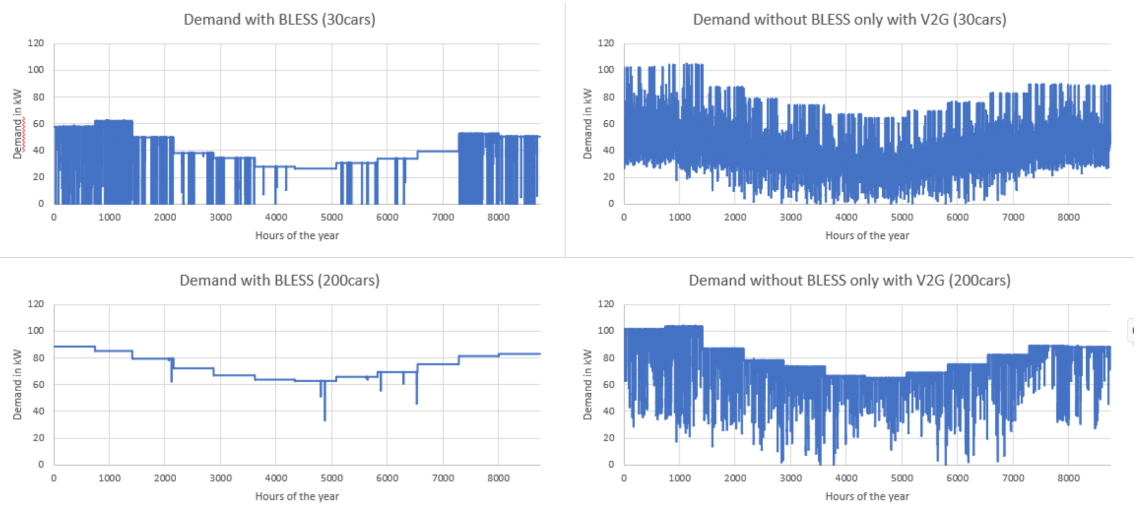
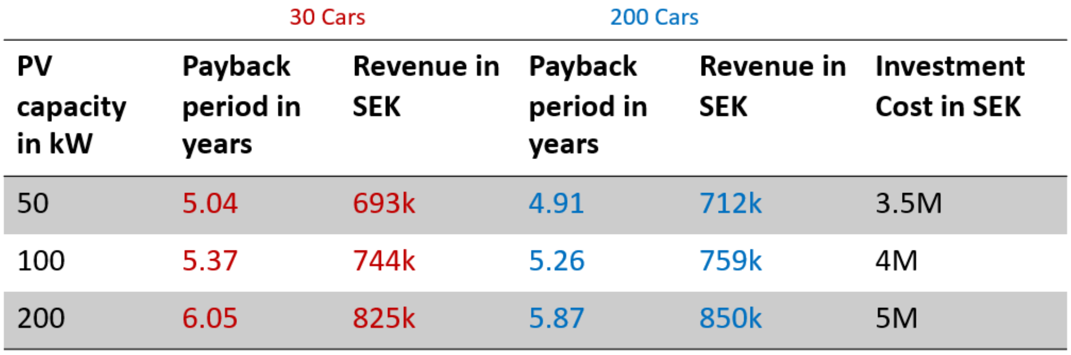


Figure 4.12: After demand curve comparison for the case with BLESS and for the case without BLESS and only with V2G for 30cars and 200 cars

4.4 Cost Comparison

Table 4.1 compares the cost of the investment to the revenue generated. As a result, it is up to the customer to determine the investment cost based on the projected revenue and payback period.

Table 4.1: Cost comparison



	30 Cars		200 Cars		
PV capacity in kW	Payback period in years	Revenue in SEK	Payback period in years	Revenue in SEK	Investment Cost in SEK
50	5.04	693k	4.91	712k	3.5M
100	5.37	744k	5.26	759k	4M
200	6.05	825k	5.87	850k	5M

5

Conclusion

The techno economic evaluation of battery energy storage systems in microgrids demonstrates that the BESS benefits microgrids in a variety of ways. This study has helped to understand the benefits of the new regulation that is establishing energy sharing between houses. For the investigated buildings it was found that the payback period increased significantly for PV systems larger than 50kW, the main reason for this was that a larger share of the production was curtailed or exported at low price. Similarly, they were not able to support in energy arbitrages as well. They can just be able to export electricity when there is an excess production for the spot price but they can't purchase electricity from the grid during low price hours and store it and sell it back to the grid at high price. Changes in energy tax and grid fees affect the payback period; the higher the energy tax and grid fees, the higher the self-consumption of PV generation should be in order to obtain a higher benefit. Participating in energy arbitrage is more advantageous than curtailing excess energy as depicted by the results of the study, this reason boosts the scope for batteries. BESS could help with peak shaving and energy arbitrage, as well as provide ancillary services to the grid system. Optimizing EV charging and BESS usage results in greater benefits by supporting the grid during peak hours and also benefiting the customers by lowering their payback period. The demand side management and demand side response would be extremely beneficial in combination with the optimized charging strategies but here those cases were not analysed. Despite peak shaving and energy arbitrage, the BESS system generated the most revenue when ancillary services were provided. This is shown in the Figure 4.10. Here in this case, the BESS participates only in FCR-D market if the battery capacity can be increased then the BESS has the possibility to participate in FCR-N and also in FFR markets. Batteries are more suitable to participate in fast frequency response market due to their low start up time and fast ramp up time and cost. Batteries are more suitable for these kind of purposes. The battery degradation rate for participating in these kind of services have not been considered in this study. Based on this summary, it is possible to conclude that the BESS maximizes the use of self-generation systems like Solar and wind. This as well supports the efficient use of EV charging systems, reducing peak demand and grid congestion. This depicts that the V2G benefits the BESS in terms of reducing their payback period when they work in combination but also V2G reduces the room for battery energy storage system as it does the part of the work of the batteries. The model will be useful in scheduling the operations of generation systems and charging of EV's. This model will help to plan the operation and functioning based on the day ahead spot price and it can also be used to analyse for a new project site and predict the maximum revenue that can generate.

Finally this project proves the need of battery energy storage system in microgrids and proves the flexibility it could provide for the operations and also the benefits the BESS provides to the microgirds.

5.1 Future Work

To further investigate the potential for microgrids in Sweden, the following would be worth looking into:

Microgrid with other storage solutions and other generation technologies: Since only one type of energy storage was studied, the outcome may differ significantly with other types of energy storage. It would thus be interesting to investigate whether pumped hydro, hydrogen, and other types of batteries such as redox batteries could produce a different result. Since here in this mcirogrid structure only solar PV's were considered to be generation sources it would interesting to assess the case with wind and CHP sources with the electricity demand coupled with heat demand.

For the case change in FCR market bid system: Now the FCR market fucntions based on the bid system and the generation technologies are paid based on their bid price. In future, it is predicted that the FCR market system can change to pay as you clear system which is similar to how the generation system gets paid in the spot market.

How future V2G can impact the microgrids: At present, the V2G concept is in its initial stage of growth which can grow into a future dominant technology. Analyses with the future improvement such as high power batteries and charging ports is needed to study this case. It can also include a case where the EV's in the parking lot can be coordinated to provide ancillary service and if that develops how it would have an impact in investment of BESS systems.

How future charging technologies can impact the microgrids: In this project, the charging infrastructure maximum power capacity was assumed to be 3.7 kW but now the technologies have improved and is developing to 300kW maximum power. These sudden power drawing will have impact on the grid and opportunities to be seen how the BESS can support and also the V2G can play a vital role with these large capacities.

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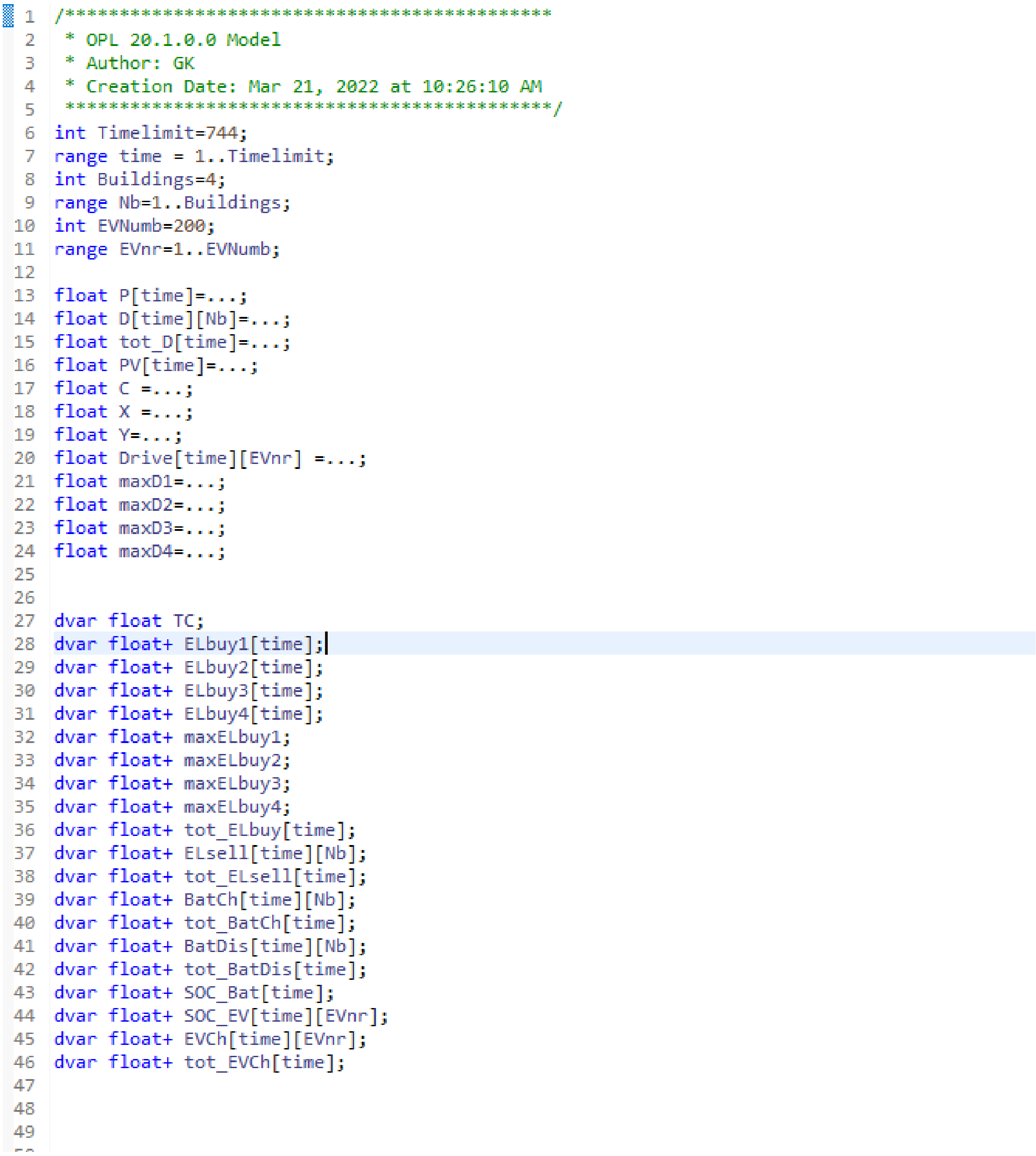
A

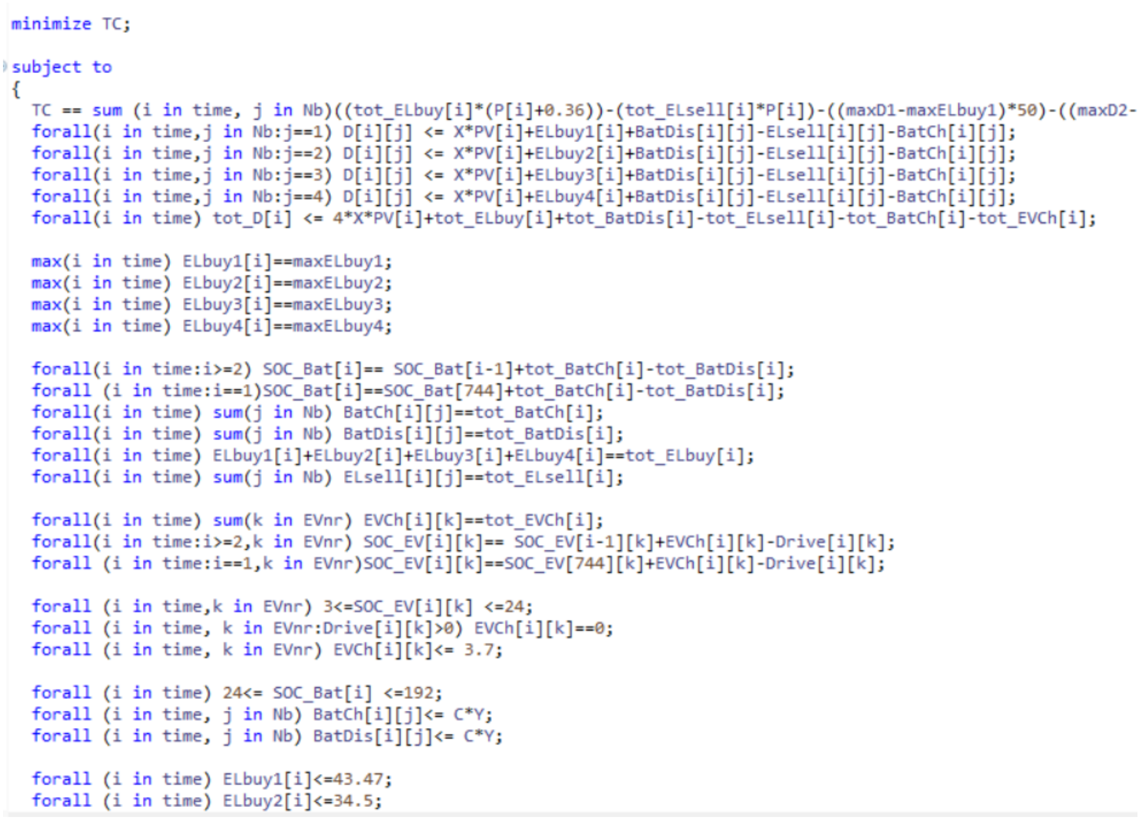
Appendix 1

CPLEX Code for Peak shaving model



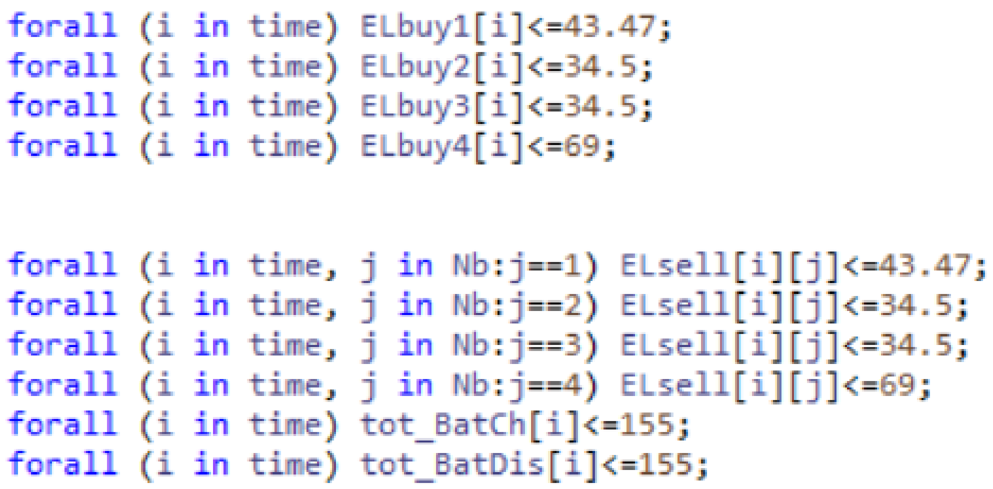
```
/*********************************************
 * OPL 20.1.0.0 Model
 * Author: GK
 * Creation Date: Mar 21, 2022 at 10:26:10 AM
 *********************************************/
int Timelimit=744;
range time = 1..Timelimit;
int Buildings=4;
range Nb=1..Buildings;
int EVNumb=200;
range EVnr=1..EVNumb;

float P[time]=...;
float D[time][Nb]=...;
float tot_D[time]=...;
float PV[time]=...;
float C =...;
float X =...;
float Y=...;
float Drive[time][EVnr] =...;
float maxD1=...;
float maxD2=...;
float maxD3=...;
float maxD4=...;


dvar float TC;
dvar float+ ELbuy1[time];
dvar float+ ELbuy2[time];
dvar float+ ELbuy3[time];
dvar float+ ELbuy4[time];
dvar float+ maxELbuy1;
dvar float+ maxELbuy2;
dvar float+ maxELbuy3;
dvar float+ maxELbuy4;
dvar float+ tot_ELbuy[time];
dvar float+ ELsell[time][Nb];
dvar float+ tot_ELsell[time];
dvar float+ BatCh[time][Nb];
dvar float+ tot_BatCh[time];
dvar float+ BatDis[time][Nb];
dvar float+ tot_BatDis[time];
dvar float+ SOC_Bat[time];
dvar float+ SOC_EV[time][EVnr];
dvar float+ EVCh[time][EVnr];
dvar float+ tot_EVCh[time];



```

Figure A.1: Peak shaving model



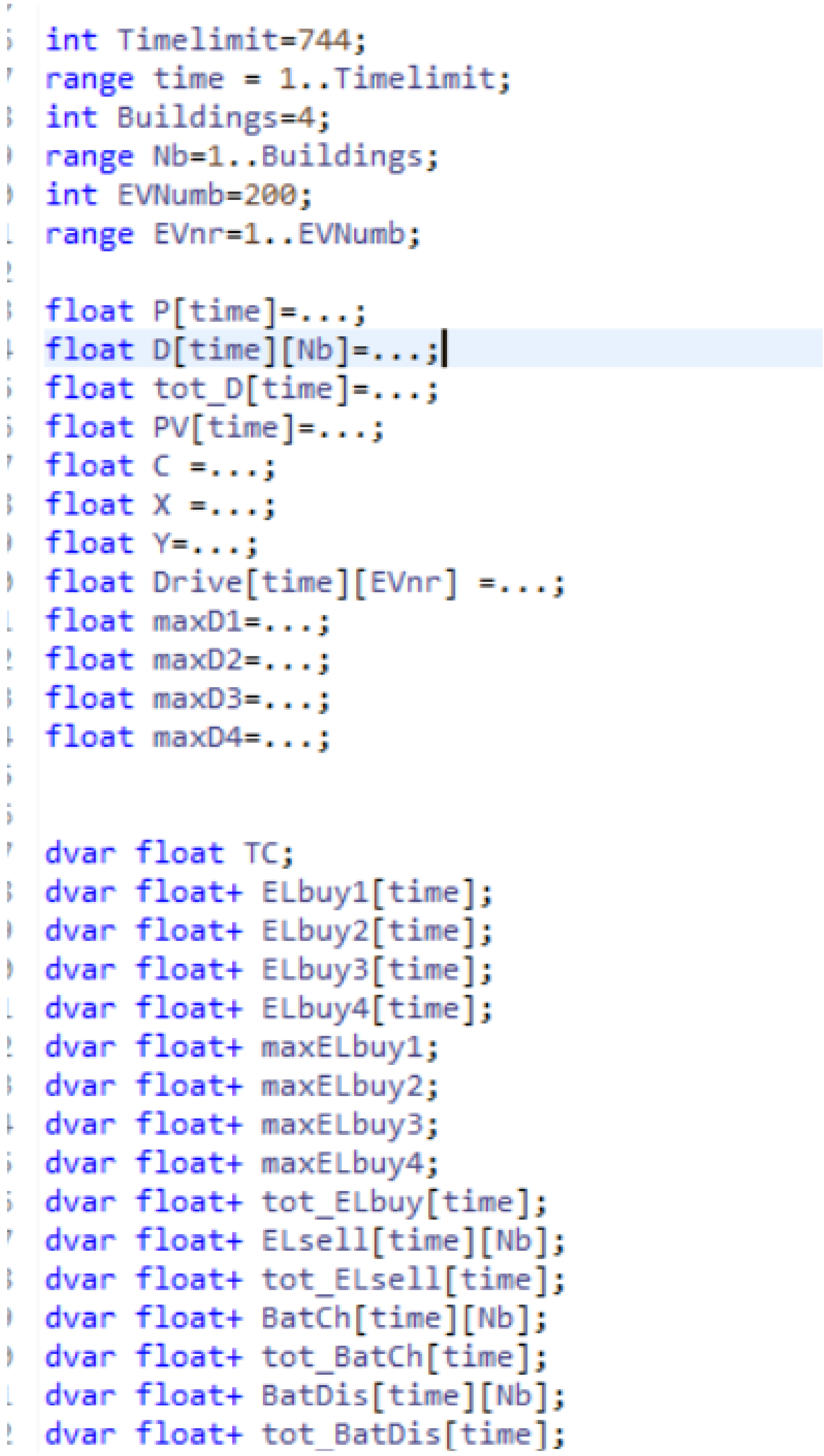
```
minimize TC;

subject to
{
  TC == sum (i in time, j in Nb)((tot_ELbuy[i]*(P[i]+0.36))-(tot_ELsell[i]*P[i])-((maxD1-maxELbuy1)*50)-((maxD2-
  forall(i in time,j in Nb:j==1) D[i][j] <= X*PV[i]+ELbuy1[i]+BatDis[i][j]-ELsell[i][j]-BatCh[i][j];
  forall(i in time,j in Nb:j==2) D[i][j] <= X*PV[i]+ELbuy2[i]+BatDis[i][j]-ELsell[i][j]-BatCh[i][j];
  forall(i in time,j in Nb:j==3) D[i][j] <= X*PV[i]+ELbuy3[i]+BatDis[i][j]-ELsell[i][j]-BatCh[i][j];
  forall(i in time,j in Nb:j==4) D[i][j] <= X*PV[i]+ELbuy4[i]+BatDis[i][j]-ELsell[i][j]-BatCh[i][j];
  forall(i in time) tot_D[i] <= 4*X*PV[i]+tot_ELbuy[i]+tot_BatDis[i]-tot_ELsell[i]-tot_BatCh[i]-tot_EVCh[i];

  max(i in time) ELbuy1[i]==maxELbuy1;
  max(i in time) ELbuy2[i]==maxELbuy2;
  max(i in time) ELbuy3[i]==maxELbuy3;
  max(i in time) ELbuy4[i]==maxELbuy4;

  forall(i in time:i>=2) SOC_Bat[i]== SOC_Bat[i-1]+tot_BatCh[i]-tot_BatDis[i];
  forall (i in time:i==1)SOC_Bat[i]==SOC_Bat[744]+tot_BatCh[i]-tot_BatDis[i];
  forall(i in time) sum(j in Nb) BatCh[i][j]==tot_BatCh[i];
  forall(i in time) sum(j in Nb) BatDis[i][j]==tot_BatDis[i];
  forall(i in time) ELbuy1[i]+ELbuy2[i]+ELbuy3[i]+ELbuy4[i]==tot_ELbuy[i];
  forall(i in time) sum(j in Nb) ELsell[i][j]==tot_ELsell[i];

  forall(i in time) sum(k in EVnr) EVCh[i][k]==tot_EVCh[i];
  forall(i in time:i>=2,k in EVnr) SOC_EV[i][k]== SOC_EV[i-1][k]+EVCh[i][k]-Drive[i][k];
  forall (i in time:i==1,k in EVnr)SOC_EV[i][k]==SOC_EV[744][k]+EVCh[i][k]-Drive[i][k];

  forall (i in time,k in EVnr) 3<=SOC_EV[i][k] <=24;
  forall (i in time, k in EVnr:Drive[i][k]>0) EVCh[i][k]==0;
  forall (i in time, k in EVnr) EVCh[i][k]<= 3.7;

  forall (i in time) 24<= SOC_Bat[i] <=192;
  forall (i in time, j in Nb) BatCh[i][j]<= C*Y;
  forall (i in time, j in Nb) BatDis[i][j]<= C*Y;

  forall (i in time) ELbuy1[i]<=43.47;
  forall (i in time) ELbuy2[i]<=34.5;
```

Figure A.2: Peak shaving model



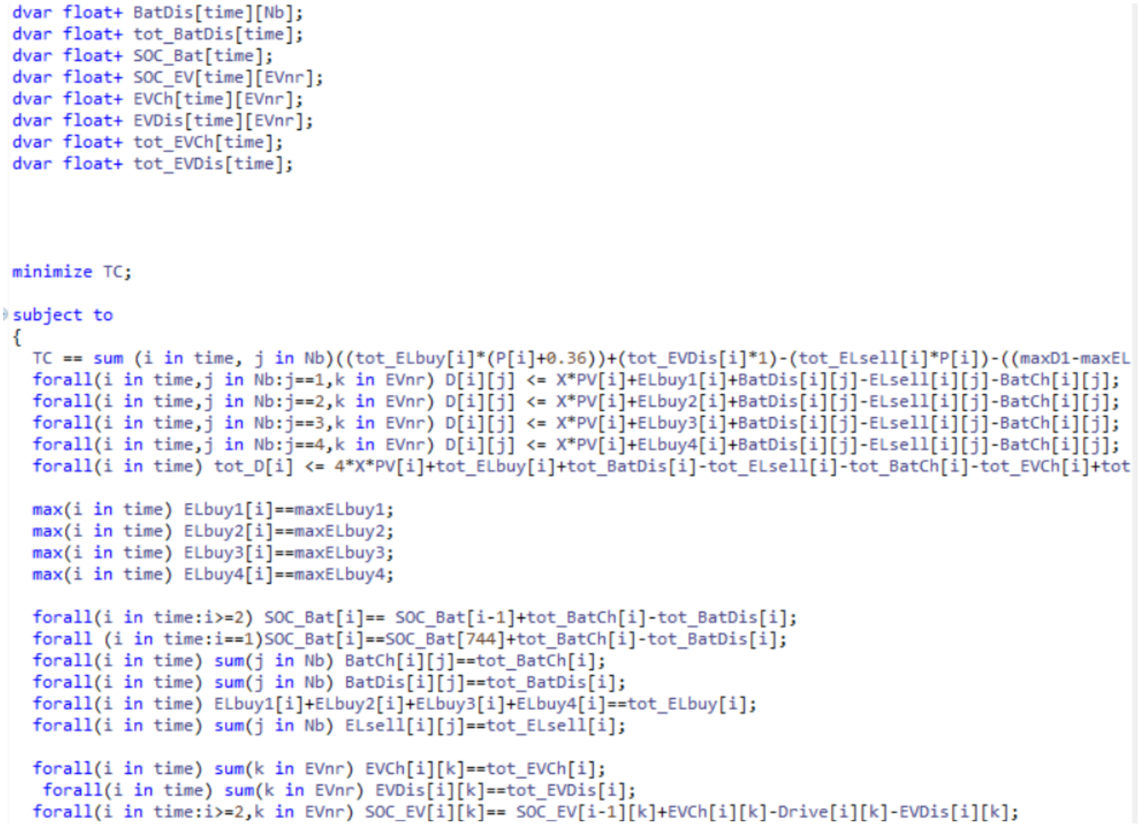
```
forall (i in time) ELbuy1[i]<=43.47;
forall (i in time) ELbuy2[i]<=34.5;
forall (i in time) ELbuy3[i]<=34.5;
forall (i in time) ELbuy4[i]<=69;


forall (i in time, j in Nb:j==1) ELsell[i][j]<=43.47;
forall (i in time, j in Nb:j==2) ELsell[i][j]<=34.5;
forall (i in time, j in Nb:j==3) ELsell[i][j]<=34.5;
forall (i in time, j in Nb:j==4) ELsell[i][j]<=69;
forall (i in time) tot_BatCh[i]<=155;
forall (i in time) tot_BatDis[i]<=155;
```

Figure A.3: Peak shaving model



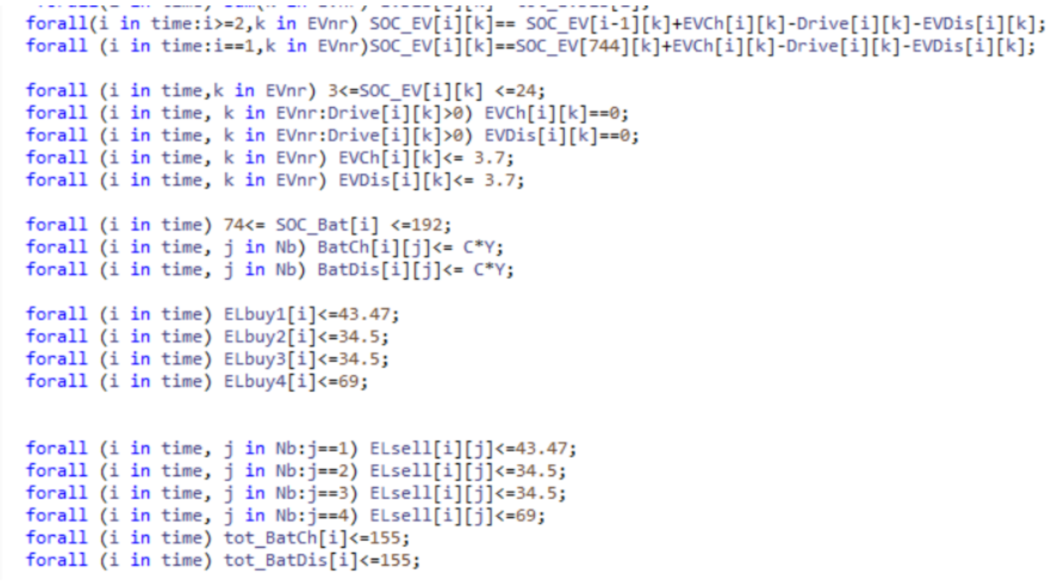
```
int Timelimit=744;
range time = 1..Timelimit;
int Buildings=4;
range Nb=1..Buildings;
int EVNumb=200;
range EVnr=1..EVNumb;

float P[time]=...;
float D[time][Nb]=...;
float tot_D[time]=...;
float PV[time]=...;
float C =...;
float X =...;
float Y=...;
float Drive[time][EVnr] =...;
float maxD1=...;
float maxD2=...;
float maxD3=...;
float maxD4=...;


dvar float TC;
dvar float+ ELbuy1[time];
dvar float+ ELbuy2[time];
dvar float+ ELbuy3[time];
dvar float+ ELbuy4[time];
dvar float+ maxELbuy1;
dvar float+ maxELbuy2;
dvar float+ maxELbuy3;
dvar float+ maxELbuy4;
dvar float+ tot_ELbuy[time];
dvar float+ ELsell[time][Nb];
dvar float+ tot_ELsell[time];
dvar float+ BatCh[time][Nb];
dvar float+ tot_BatCh[time];
dvar float+ BatDis[time][Nb];
dvar float+ tot_BatDis[time];
```

Figure A.4: V2G model



```
dvar float+ BatDis[time][Nb];
dvar float+ tot_BatDis[time];
dvar float+ SOC_Bat[time];
dvar float+ SOC_EV[time][EVnr];
dvar float+ EVCh[time][EVnr];
dvar float+ EVDis[time][EVnr];
dvar float+ tot_EVCh[time];
dvar float+ tot_EVDis[time];



minimize TC;

subject to
{
  TC == sum (i in time, j in Nb)((tot_ELbuy[i]*(P[i]+0.36))+(tot_EVDis[i]*1)-(tot_ELsell[i]*P[i])-((maxD1-maxEL
  forall(i in time,j in Nb:j==1,k in EVnr) D[i][j] <= X*PV[i]+ELbuy1[i]+BatDis[i][j]-ELsell[i][j]-BatCh[i][j];
  forall(i in time,j in Nb:j==2,k in EVnr) D[i][j] <= X*PV[i]+ELbuy2[i]+BatDis[i][j]-ELsell[i][j]-BatCh[i][j];
  forall(i in time,j in Nb:j==3,k in EVnr) D[i][j] <= X*PV[i]+ELbuy3[i]+BatDis[i][j]-ELsell[i][j]-BatCh[i][j];
  forall(i in time,j in Nb:j==4,k in EVnr) D[i][j] <= X*PV[i]+ELbuy4[i]+BatDis[i][j]-ELsell[i][j]-BatCh[i][j];
  forall(i in time) tot_D[i] <= 4*X*PV[i]+tot_ELbuy[i]+tot_BatDis[i]-tot_ELsell[i]-tot_BatCh[i]-tot_EVCh[i]+tot

  max(i in time) ELbuy1[i]==maxELbuy1;
  max(i in time) ELbuy2[i]==maxELbuy2;
  max(i in time) ELbuy3[i]==maxELbuy3;
  max(i in time) ELbuy4[i]==maxELbuy4;

  forall(i in time:i>=2) SOC_Bat[i]== SOC_Bat[i-1]+tot_BatCh[i]-tot_BatDis[i];
  forall (i in time:i==1)SOC_Bat[i]==SOC_Bat[744]+tot_BatCh[i]-tot_BatDis[i];
  forall(i in time) sum(j in Nb) BatCh[i][j]==tot_BatCh[i];
  forall(i in time) sum(j in Nb) BatDis[i][j]==tot_BatDis[i];
  forall(i in time) ELbuy1[i]+ELbuy2[i]+ELbuy3[i]+ELbuy4[i]==tot_ELbuy[i];
  forall(i in time) sum(j in Nb) ELsell[i][j]==tot_ELsell[i];

  forall(i in time) sum(k in EVnr) EVCh[i][k]==tot_EVCh[i];
   forall(i in time) sum(k in EVnr) EVDis[i][k]==tot_EVDis[i];
  forall(i in time:i>=2,k in EVnr) SOC_EV[i][k]== SOC_EV[i-1][k]+EVCh[i][k]-Drive[i][k]-EVDis[i][k];
```

Figure A.5: V2G model



```
  forall(i in time:i>=2,k in EVnr) SOC_EV[i][k]== SOC_EV[i-1][k]+EVCh[i][k]-Drive[i][k]-EVDis[i][k];
  forall (i in time:i==1,k in EVnr)SOC_EV[i][k]==SOC_EV[744][k]+EVCh[i][k]-Drive[i][k]-EVDis[i][k];

  forall (i in time,k in EVnr) 3<=SOC_EV[i][k] <=24;
  forall (i in time, k in EVnr:Drive[i][k]>0) EVCh[i][k]==0;
  forall (i in time, k in EVnr:Drive[i][k]>0) EVDis[i][k]==0;
  forall (i in time, k in EVnr) EVCh[i][k]<= 3.7;
  forall (i in time, k in EVnr) EVDis[i][k]<= 3.7;

  forall (i in time) 74<= SOC_Bat[i] <=192;
  forall (i in time, j in Nb) BatCh[i][j]<= C*Y;
  forall (i in time, j in Nb) BatDis[i][j]<= C*Y;

  forall (i in time) ELbuy1[i]<=43.47;
  forall (i in time) ELbuy2[i]<=34.5;
  forall (i in time) ELbuy3[i]<=34.5;
  forall (i in time) ELbuy4[i]<=69;


  forall (i in time, j in Nb:j==1) ELsell[i][j]<=43.47;
  forall (i in time, j in Nb:j==2) ELsell[i][j]<=34.5;
  forall (i in time, j in Nb:j==3) ELsell[i][j]<=34.5;
  forall (i in time, j in Nb:j==4) ELsell[i][j]<=69;
  forall (i in time) tot_BatCh[i]<=155;
  forall (i in time) tot_BatDis[i]<=155;
```

Figure A.6: FCR-D model

DEPARTMENT OF SOME SUBJECT OR TECHNOLOGY
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se

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