Norwegian University
of Life Sciences

**Master's Thesis 2023 30 ECTS**
Faculty of Science and Technology

# Networked Microgrids with Electric Vehicle Batteries for Improved Resiliency and Maximum Utilization of Distributed Renewable Energy Resources

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Environmental Physics and Renewable Energy

# Preface

This master's thesis concludes the finalization of my M.Sc. degree in Environmental Physics and Renewable Energy. The thesis is conducted at the Faculty of Science and Technology at the Norwegian University of Life Sciences.

This thesis focuses on how networked microgrids can increase resilience and better utilize distributed energy resources. It also explores the implementation of electric vehicles as energy storage within microgrids. Networked microgrids represent a new and expanding area of research that aligns perfectly with my field of interest. Even if the work has been challenging and frustrating at times, I have acquired extensive knowledge that I hope will be valuable for my work in Statnett SF.

I want to express my gratitude toward my supervisor, Jagath Sri Lal Senanayaka, for his invaluable guidance and knowledge throughout the development of my thesis. I also want to extend my thanks to my professors, lecturers, and fellow students over the past five years. Without all of you, my time studying would not have been as fulfilling and enjoyable as it has.

Lastly, I wish to express my heartfelt thanks to my parents, Elling and Ann-Kari, for their continued support and encouragement throughout my time at NMBU.

Atle Hanssen
Ås, July 2023

# Abstract

In today's distribution grid, issues have emerged due to the increasing energy production from distributed energy resources such as photovoltaic systems. As the distribution grid is not designed for large-scale production that can lead to bidirectional power flow, problems with voltage regulation, power quality, grid instability, and electrical problems in transformers may arise [1]. Today's power grid is also vulnerable to power outages due to faults in the grid or targeted attacks against the power grid. With the implementation of networked microgrids, one can reach a higher energy supply provision to critical loads during disconnection from the utility grid.

This master's thesis models and studies a networked microgrid with the aim of highlighting how such grids can increase the resilience of the power grid and how to maximize the use of distributed energy resources. The thesis also focuses on how the battery capacity of electric vehicles can be utilized in the power grid. A case study is designed and modeled to examine these questions in Simulink. The case study examines the resiliency of networked microgrids in comparison to non-networked microgrids and consists of three interconnected microgrids. The first microgrid houses a hospital, the second accommodates an office building, and the third includes a residential area. All microgrids contain photovoltaic systems for energy production, electric vehicles for energy storage, and varying loads. 40 % of the load demand in the hospital is defined as critical loads and should be prioritized in case of power outages. Three different scenarios have been simulated and compared. In the first scenario representing a normal operation, the microgrids are interconnected to each other as well as the utility grid. In the second scenario, there is a power outage in the utility grid, and all microgrids are disconnected from each other. This results in all the microgrids operating in islanded mode. In the third and final scenario, a power outage in the utility power grid results in networked microgrid operation where the microgrids exchange power among themselves. The main objective is to supply the critical loads in the hospital with continuous power flow.

The results indicated that networked microgrid operation enhances resilience, achieves a higher utilization of distributed energy resources, and validates the feasibility of using electric vehicles as energy storage systems compared to islanded mode operation. The duration of limited power supply to the critical loads decreased by 69.2 %. The total time with load shedding was reduced by 12.3 %, and the maximum load shed value was reduced from 88.7 % to 66.6 %. Further, photovoltaic production increased by 143.7 % in networked microgrid operation compared to operation in islanded mode. Utilizing electric vehicles as energy storage can increase flexibility and can yield a high storage capacity during periods of high demand. However, during periods of low demand, such as nighttime, it may provide a small and sometimes insufficient storage capacity.

This work can be enhanced by implementing electricity prices and the use of Mixed-Integer Linear Programming to optimize power flow between each microgrid and between the microgrids and the utility grid. However, due to the time limitations of this master's thesis, these measurements had to be excluded.

# Sammendrag

I dagens distribusjonsnett har det oppstått problemer knyttet til økende energiproduksjon fra distribuerte energiressurser som for eksempel solcellesystemer. Ettersom distribusjonsnettet ikke er designet for kraftproduksjon som kan føre kraftflyt mot konvensjonell retning kan dette skape problemer med spenningskvaliteten, nettverkstabilitet, effektkvalitet og elektriske problemer i transformatorer [1]. Dagens kraftnett er også sårbar for strømbrudd som følge av feil i nettet eller målrettede angrep mot strømnettet. Ved å implementere sammenkoblede mikronett vil en kunne oppnå forbedret strømforsyning til kritiske laster mens en er frakoblet hovedkraftnettet.

Denne masteroppgaven modellerer og studerer et sammenkoblet mikronett og har som målsetning å belyse hvordan sammenkoblede mikronett kan øke resiliteten i kraftnettet. Oppgaven har også fokus på utnyttelse av distribuerte energiressurser og hvordan batterikapasiteten i elbiler kan utnyttes i kraftnettet. For å svare på disse spørsmålene er en casestudie designet og modellert i Simulink. Casestudien undersøker resiliteten til sammenkoblede mikronett sammenlignet med ikke-sammenkoblede mikronett og består av tre interkoblede mikronett. Mikronettene inneholder hhv. et sykehus, et kontorbygg og et boligområde med 60 husholdninger. Alle mikronettene inneholder solcelleanlegg for energiproduksjon, elbiler for energilagring og variable laster. 40 % av lastbehovet til sykehuset er definert som kritiske laster og skal prioriteres ved strømbrudd. Det er simulert tre ulike scenarioer som sammenlignes. I det første scenarioet simuleres normal drift der mikronettene er sammenkoblet til hverandre og hovedkraftnettet. I scenario to er det strømbrudd i hovedkraftnettet, og alle mikronettene frakobles hverandre. Dette resulterer i at hvert mikronett opererer selvstendig i øymodus. I det tredje og siste scenarioet er det strømbrudd i hovedkraftnettet, men mikronettene opererer som et sammenkoblet mikronett og har kraftflyt mellom hverandre. Hovedformålet er å sikre kontinuerlig strømforsyning til sykehusets kritiske laster.

Resultatene viste at sammenliknet med øydrift vil sammenkoblede mikronett øke resiliteten, oppnå høyere utnyttelse av distribuerte energiressurser og bekrefter gjennomførbarheten av å bruke elbiler som energilagring. Tiden med begrenset strømforsyning til de kritiske lastene i sykehuset ble redusert med 69.2 %, den totale tiden med lastutkopling ble redusert med 12.3 % og den maksimale lastutkoplingsverdien ble redusert fra 88.7 % til 66.6 %. Videre økte energiproduksjonen fra solcellesystemet med 143.7 % under operasjon som et sammenkoblet mikronett sammenlignet med øydrift. Bruk av elektriske kjøretøy som energilagringssystem økte fleksibiliteten og kunne gi høy lagringskapasitet i perioder med høy lastetterspørsel. Imidlertid kunne det også resulterer i liten og noen gang utilstrekkelig lagringskapasitet i perioder med lav etterspørsel, hovedsakelig om natten.

Arbeidet kan videre forbedres ved å implementere strømpriser og optimaliseringsmetoden Mixed-Integer Linear Programming for å optimalisere effektflyten mellom mikronettene og mellom mikronettene og hovedkraftnettet. På grunn av tidsbegrensninger i oppgaven måtte dette utelukkes.

# Table of Contents

**Preface** ii

**Abstract** iii

**Sammendrag** iv

**List of Figures** vii

**List of Tables** viii

**List of Abbreviations** ix

**1 Introduction** **1**
1.1 Background and Motivation . . . . . 1
1.2 Research Questions . . . . . 2
1.3 Case Study . . . . . 3
1.4 Thesis Outline . . . . . 4

**2 Theory** **5**
2.1 Electric Power Systems and the Power Grid . . . . . 5
2.2 Challenges in Today's Power Grid . . . . . 7
2.2.1 Power Loss . . . . . 7
2.2.2 Congestion . . . . . 7
2.2.3 Voltage Regulation . . . . . 7
2.2.4 Cyber Attacks . . . . . 7
2.2.5 Integration of Distributed Energy Resources and Distributed Generation 8
2.2.6 Enhancing Resilience in Power Supply for Critical Infrastructure . . . . . 9
2.3 Emerging Solutions to Address Challenges in the Power Grid . . . . . 9
2.3.1 Smartgrid . . . . . 9
2.3.2 Energy Storage Systems and Electric Vehicle Batteries . . . . . 10
2.3.3 Microgrids . . . . . 13
2.3.4 Networked Microgrids . . . . . 14

**3 Method** **16**
3.1 Introduction to Methodology . . . . . 16
3.2 Description of Model . . . . . 16
3.2.1 Working Principles . . . . . 18
3.3 System Parameters and Data . . . . . 20
3.3.1 Load Data . . . . . 20
3.3.2 PV System . . . . . 20
3.3.3 Storage Capacity . . . . . 21
3.4 Microgrid 1 - Hospital . . . . . 22
3.4.1 MG1 Load Curve . . . . . 22
3.4.2 MG1 PV System . . . . . 23
3.4.3 MG1 Energy Storage System . . . . . 23
3.5 Microgrid 2 - Office Building . . . . . 25

3.5.1 MG2 Load Profile . . . 25
3.5.2 MG2 PV System . . . 26
3.5.3 MG2 Energy Storage System . . . 26
3.6 Microgrid 3 - Residential Area . . . 29
3.6.1 MG3 Load Profile . . . 29
3.6.2 MG3 PV System . . . 29
3.6.3 MG3 Energy Storage System . . . 30
3.7 Summary and Comparison of the Data in the three MGs . . . 31
3.8 Simulation Scenarios . . . 34
3.8.1 Scenario 1 - Grid-Connected . . . 34
3.8.2 Scenario 2 - Grid Failure - Islanded Mode . . . 34
3.8.3 Scenario 3 - Grid Failure - NMG Mode . . . 34
3.9 Choice of Modeling Software . . . 34

**4 Results 35**
4.1 Scenario 1 - NMG is Grid-Connected . . . 35
4.1.1 Power Flow . . . 35
4.1.2 Battery Performance . . . 36
4.1.3 Grid Power and Energy . . . 38
4.2 Scenario 2 - Grid Failure - Islanded operation . . . 39
4.2.1 Power Flow . . . 39
4.2.2 Battery Performance . . . 40
4.2.3 Generation Shedding and Load Shedding . . . 41
4.3 Scenario 3 - Grid Failure - NMG Operation . . . 43
4.3.1 Power Flow . . . 43
4.3.2 Battery Performance . . . 44
4.3.3 Load Shedding . . . 45
4.4 Summary and Comparison Between the Scenarios . . . 46

**5 Discussion 48**
5.1 Resiliency . . . 48
5.2 EVs used as ESS . . . 48
5.2.1 EV Availability . . . 49
5.3 General Discussion . . . 50

**6 Conclusion 51**

**7 Implications and Future Research 52**

**8 References 53**

**Appendix A: Simulink Model 56**

# List of Figures


1 Illustration of grid segmentations in Norway. . . . . . . . . . . . . . . . . . . . . . 6
2 Bidirectional EV charging. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 12
3 Generic illustration of an MG . . . . . . . . . . . . . . . . . . . . . . . . . . . . 13
4 Generic illustration of an NMG. . . . . . . . . . . . . . . . . . . . . . . . . . . . 14
5 Block diagram of NMG model . . . . . . . . . . . . . . . . . . . . . . . . . . . . 17
6 Block diagram of MG model. . . . . . . . . . . . . . . . . . . . . . . . . . . . . 17
7 Plot of the solar irradiation in Ås from June 4th to June 6th. . . . . . . . . . . . . 21
8 Hourly load curve for the hospital in MG1. . . . . . . . . . . . . . . . . . . . . . 23
9 Storage capacity, accessible capacity, and maximum power delivery in ESS1. . . 25
10 Load profile OB in MG2. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 26
11 Storage capacity, accessible capacity, and maximum power rates for the ESS in MG2. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 28
12 Load curve 60 households in MG3. . . . . . . . . . . . . . . . . . . . . . . . . . 29
13 Total storage capacity, available capacity, and maximum power rates in ESS3. . 31
14 Load curves in MG1, MG2 and MG3. . . . . . . . . . . . . . . . . . . . . . . . 32
15 Total capacity, accessible capacity, and maximum power rates in MG1, MG2, and MG3. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 33
16 Power flow in the MGs in Scenario 1. . . . . . . . . . . . . . . . . . . . . . . . 35
17 Battery performance of Scenario 1. . . . . . . . . . . . . . . . . . . . . . . . . . 37
18 Power flow between the MGs and the utility grid. . . . . . . . . . . . . . . . . . 38
19 Power flow in the MGs in Scenario 2 . . . . . . . . . . . . . . . . . . . . . . . . 40
20 Battery performance of Scenario 2. . . . . . . . . . . . . . . . . . . . . . . . . . 41
21 Generation shedding for MG3 and load shedding for MG1 in Scenario 2. . . . . 42
22 Power flow in the MGs in Scenario 3. . . . . . . . . . . . . . . . . . . . . . . . 43
23 Battery performance of Scenario 3. . . . . . . . . . . . . . . . . . . . . . . . . . 44
24 Load shedding in Scenario 3. . . . . . . . . . . . . . . . . . . . . . . . . . . . . 45
25 Simulink: Top-level of the NMG connected to the utility grid. . . . . . . . . . . 56
26 Simulink: Extract of the inside of MG1. . . . . . . . . . . . . . . . . . . . . . . 57
27 Simulink: Power flow controller MG1. . . . . . . . . . . . . . . . . . . . . . . . 58
28 Simulink: First layer inside night battery in MG1. . . . . . . . . . . . . . . . . . 60
29 Simulink: Power integration and SoC calculation in MG1 night battery. . . . . . 60
30 Simulink: Enabled subsystem to reset the battery's energy. . . . . . . . . . . . . 61
31 Simulink: Net Energy variable and linear energy transitions in MG1. . . . . . . 61
32 Simulink: MG3 power control including power exchange to MG1. . . . . . . . . 64
33 Simulink: Scenario 3 control system. . . . . . . . . . . . . . . . . . . . . . . . . 65

# List of Tables


1 DER definitions. . . . . . . . . . 8
2 Technical characteristics of Lithium-Ion batteries. . . . . . . . . . 11
3 SoC limits for load shedding, generation shedding, and power sharing. . . . . . . 19
4 Collective parameters for all MGs. . . . . . . . . . 22
5 Summary of data and calculation used in the ESS in MG1. . . . . . . . . . 24
6 Summary of data and calculation used in the ESS in MG2. . . . . . . . . . 27
7 Summary of data and calculation used in the ESS in MG3. . . . . . . . . . 30
8 Grid reliance during the three days of simulation. . . . . . . . . . 39
9 Overview of shedding values for simulation Scenario 2 in islanded mode. . . . . . 42
10 Overview over shedding values for simulation Scenario 3. . . . . . . . . . 46
11 Duration and maximum load shedding values for all scenarios. . . . . . . . . . 46
12 Changes between Scenario 2 and Scenario 3 in load shedding. . . . . . . . . . 46
13 Energy load consumption for all scenarios in every MG. . . . . . . . . . 47
14 Generation shedding in MG3 summarized. . . . . . . . . . 47

# List of Abbreviations

**AC** alternating current.

**AMS** advanced metering system.

**DC** direct current.

**DER** distributed energy resource.

**DG** distributed generation.

**DSO** distribution system operator.

**ESS** energy storage system.

**EV** electric vehicle.

**HAN** home area network.

**IEA** International Energy Agency.

**Li-Ion** Lithium-Ion.

**MC** microgrid controller.

**MG** microgrid.

**NMG** networked microgrid.

**NVE** Norwegian Water Resources and Energy Directorate.

**OB** office building.

**PCC** points of common coupling.

**PV** photovoltaic.

**RMS** root mean square.

**SoC** state of charge.

**SSB** Statistics Norway.

**TSO** Transmission System Operator.

**UPS** uninterrupted power supply.

**V2G** vehicle to grid.

# 1 Introduction

Chapter 1 begins by providing the background and motivation behind the research. This is followed by the presentation of the research questions and a presentation of the case study. Lastly, the layout of the thesis is outlined.

## 1.1 Background and Motivation

As the world's demand for green renewable energy increases, the energy production from distributed energy resources (DERs) is also growing. Production from renewable energy sources such as Photovoltaic (PV) systems is more decentralized than traditional energy production. This increases the complexity of the power system due to the emergence of bidirectional power flow, as opposed to the previously established unidirectional flow pattern. This shift results in a more intricate system design.

Further, in light of the 2022 Russian invasion of Ukraine and gas shortages in Europe, the significance of having a secure and durable energy supply is undeniable. Russia has performed several attacks on the Ukrainian power grid, resulting in frequent power outages and blackouts. Ukrainian officials have stated that up to 40 % of the power grid is damaged, and almost a third of the power stations have been destroyed. By decentralizing power generation, one would reduce the exposure to military attacks from hostile forces [2]. Not only man-made occurrences may cause damage and power failure in the grid. The most common cause of power failures is caused by extreme weather events such as hurricanes, floods, heavy snowfall, and storms [3].

One way to increase resiliency is to implement distributed generation (DG) through the operational concept of microgrids (MGs). An MG is commonly defined as a group of interconnected loads and DGs within a clearly defined electrical boundary that acts as a single controllable entity [4]. The DG may include renewable photovoltaic (PV) systems and wind turbines, or non-renewable DGs such as fuel cells, combined heat and power plants, and diesel engines [5]. MGs can operate autonomously and can deliver reliable power even during power outages. To further increase the penetration of DERs, enhance reliability and resilience, and reduce the cost of energy, several MGs can operate interconnected in a networked microgrid (NMG) [5].

NMGs represent an innovative approach to energy distribution, enhancing the resilience and efficiency of power systems. By interconnecting multiple MGs, NMGs allow for greater flexibility and reliability in power supply, particularly in the face of grid disturbances or power failures. Each MG within the network can operate independently, supplying local loads, or collaboratively, sharing resources with other MGs. This dynamic operation facilitates optimal utilization of distributed energy resources, such as solar PV and energy storage systems [6]. Furthermore, the integration of electric vehicles into NMGs as mobile energy storage units adds another layer of versatility, enabling demand response and peak load management. As such, NMGs are poised to play a pivotal role in the transition toward more sustainable and resilient energy systems [7].

The relevance of MGs and NMGs extends beyond the potential threat of military attacks. Modern society is increasingly dependent on electrical energy. With the deployment of new smart grid technologies, more DG, and a higher proportion of energy production from intermittent renewable energy, the infrastructure and characteristics of the power grid are changing. This is in contrast to the traditional power grid consisting of large, adjustable power generation and a unidirectional power flow from the producer to the consumer. According to the International Energy Agency (IEA), the energy from solar power increased by 22 % or 179 TWh in 2021. From this increase, utility-scale plants were responsible for 52 %, residential segments 28 %, and industrial segments 19 %. This was the second-largest generation growth in the renewable energy segment after wind power [8].

Energy storage systems (ESSs) are essential in an MG because of the intermittent nature of renewable DERs. By implementing ESSs one can ensure a more stable and uninterrupted power flow to the loads when the power from the DERs is insufficient to supply the loads [9]. While there are several types of ESSs, electrochemical batteries are the most commonly used ESSs [9]. Traditionally, acquiring batteries has been very expensive, but the increasing number of electric vehicles (EVs) on the road carries considerable electrical storage capacity in their batteries. Norway is the country with the highest proportion of EVs in the world. As of November 2022, EVs accounted for 77 % of new passenger car sales, and nearly 20 % of all passenger cars currently on the road are EVs [10]. According to the forecast of Norwegian Water Resources and Energy Directorate (NVE), there could be 1.5 million EVs on the roads in Norway by the year 2030 [11]. Assuming these EVs will have an average capacity of 80 kWh in 2030 [12], they would have a total energy storage capacity of 120 GWh. This feature should be exploited, as it provides a significant storage capacity and a considerable amount of the investment has already been made. Furthermore, batteries can be used to balance discrepancies between the consumption and production of electrical energy in the power grid [13].

In this thesis, a case study is designed and a simulation is created by using MATLAB and Simulink to simulate how an NMG can increase grid resiliency and better utilize distributed renewable energy production by implementing EV batteries. The thesis will focus on technical aspects and regulatory, legislative, or economic matters will not be emphasized.

## 1.2 Research Questions

The main research questions for this thesis can be summarized as follows:

1. How can NMGs improve resiliency in the Norwegian power grid?

A secondary and third research question will also be examined:

2. How can one better utilize distributed energy resources by implementing NMGs in the power grid?

3. How can electric vehicles be used as ESSs in MGs?

## 1.3 Case Study

To examine the research questions, a simulation study comprising three MGs interconnected as an NMG is considered. A short introduction to the case study is given below.

In the case study, an NMG consisting of three MGs are simulated. The first MG houses a hospital with a high load demand and where the employees are working shifts throughout the day. The second MG includes an office building where there are only employees present during working hours from 07:00 to 18:00. The third MG contains 60 households. In this MG, most residents are not at home during regular working hours from 07:00 to 17:00. However, it is assumed that everyone is at home after these hours. Every MG contains PV systems for energy production and EVs for energy storage. The number of EVs present, and hence storage capacity available, depends on the number of people present in the given MG. Changes in the number of EVs occur linearly during a one-hour period.

The case study examines three scenarios. The first scenario examines how the NMG performs under normal working conditions connected to the utility grid. The power flow between every component is measured and inspected. The second scenario tests how each MG performs in islanded mode and serves as a comparison scenario. There is no power exchange between the MGs or the utility grid during this scenario. The third and final scenario examines how the NMG performs during a power failure in the utility grid. The MGs exchange power between themselves and the main focus is to provide the hospital with sufficient power to operate its critical loads.

The NMG's characteristics, variables, and data are chosen to represent a placement in southern Norway, and the sun irradiance is obtained from the Søråsjordet measurement station in Ås.

## 1.4 Thesis Outline

The arrangement of the next chapters in this thesis is designed to systematically present the objectives, models, results, discussion, and appendix related to this study.

- **Chapter 2** is a theory chapter that aims to summarize some of the existing knowledge about NMGs and present theoretical concepts related to NMGs and EVs.
- **Chapter 3** describes the case study and the simulation model, including simulation scenarios, assumptions, parameters, and system configurations.
- **Chapter 4** presents the results and findings from the simulation.
- **Chapter 5** discusses the results presented in Chapter 4.
- **Chapter 6** concludes the thesis and its most important findings.
- **Chapter 7** looks at implications and future research
- **Appendix A** provides excerpts from the Simulink model and MATLAB code used in the simulation and calculations.

# 2 Theory

In this chapter, the theory relevant to this thesis is presented. Firstly, an introduction to electric power systems and the power grid is given. Secondly, a presentation of challenges in today's power grid is provided. Lastly, solutions to address the challenges in the power grid are provided, including a presentation of MGs, NMGs, and ESSs.

## 2.1 Electric Power Systems and the Power Grid

In many ways, the idea of an electric power system began with Thomas A. Edison in the 1880s. He formulated the thought of a centrally located power station with distribution to the surrounding lights. On September 4, 1882, the Pearl Street Station opened. This was one of the world's first power stations and was operated by direct current (DC) generators driven by steam engines. The power station supplied 30 kW for 110 V incandescent lighting to 59 customers [14]. The power systems then rapidly developed. Edison's DC systems were soon expanded to three-wire 220 V systems allowing the load to increase somewhat, but voltage problems were encountered as transmission distance and load demands continued to increase. In 1885 the first commercial transformer was developed, making alternating current (AC) more attractive than DC, and Nikola Tesla's paper on two-phase induction and synchronous motors showed the advantages of polyphase vs single-phase systems. Germany's first three-phase AC line became operational in 1891, transmitting 12 kV over 179 km [14]. This is the same system used by most of the world today.

Even if the three-phase AC electrical power system remains the dominant method of power distribution to this day, great progress has been made. An electric power system comprises three integral elements, namely producers, distributors, and consumers, that are interdependent to transmit or receive electricity for various purposes like industry, work, communication, transport, and daily life [15]. Traditionally, the primary source of electricity generation has been large power plants fueled by fossil fuels such as coal, gas, or oil [16]. However, in the 1950s, nuclear energy also emerged as a significant source of power generation [17]. In the realm of renewable energy, hydropower remains the most established, widely used, and long-lasting source of electricity generation, ranging back to the late 1800s. In recent years, wind power and solar power have also experienced massive growth [18].

The conversion of mechanical or thermal energy from water, wind, or fuels into electrical energy is a central process in power plants. This energy is generated through the use of a turbine, which drives a generator and produces electrical energy that is transmitted to the power grid. As energy cannot be stored in the power grid, it must be consumed at the time of generation. However, significant research is being conducted to develop ESS, which will play a crucial role in achieving the goal of Net Zero Emissions by 2050 set by the IEA [19]. This may involve the use of various storage technologies, including hydrogen, compressed air, gravity storage, pumped hydropower, and batteries. Among these technologies, batteries are considered to be the most scalable and have seen the most significant growth in recent years [19].

The inclusion of batteries in the power grid allows for energy to be stored during times of surplus and converted back when needed, thereby improving stability, flexibility, short-time balancing, restoring grid operations following a blackout, and deferment of investment in new transmission and distribution lines [19].

The reliability of a well-functioning power system and the constant supply of electricity are crucial components of modern society and play a vital role in supporting nearly all significant public services and functions. As such, the power system constitutes critical infrastructure [20].

The power grid is typically segmented into multiple sections based on their respective voltage levels. Taking Norway as an example, the highest voltage level from 420 to 300 kV is the transmission grid. This is the highway of electrical power and the part that the Transmission System Operator (TSO) is responsible for. The transmission network includes foreign interconnections as well. Following the transmission grid in the regional grid with a voltage level from 33 to 132 kV. Some highly power-consuming industries may be connected directly to the regional grid. Finally, linked to the regional grid is the distribution grid. This is the lowest voltage part of the power grid and has a voltage that ranges from 230 V to 22 kV. A distinction is made between the high-voltage and low-voltage distribution grid with the division at 1 kV. The distribution system operator (DSO) has the main responsibility in this part of the power grid. The distribution grid connects end users such as households, service providers, and small-scale industries [20]. An illustration of the grid segmentation in Norway can be seen in Figure 1.

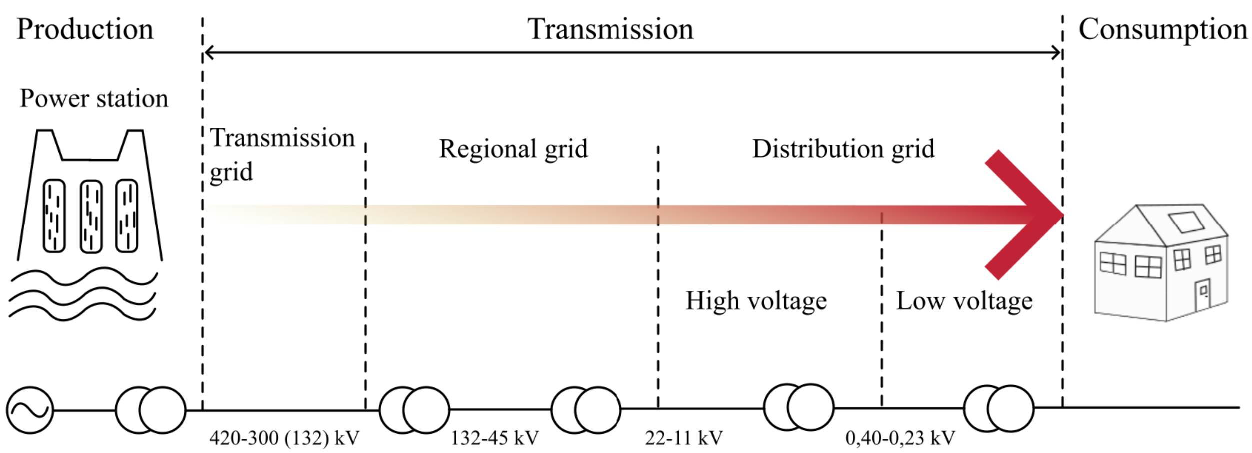


**Figure 1:** *Illustration of grid segmentations in Norway.*

The Norwegian power grid consists of more than 330000 km of power lines, whereas 300000 km of these are located in the distribution grid [1]. Power can be transmitted over great distances and runs in cables over the sea, in the ground, or as overhead cables [21]. In each country, one or more TSOs have been given central responsibility by the public authorities for monitoring and balancing the power supply in and from the transmission grid [21]. In many countries, the TSOs are often in charge of the development of the grid infrastructure, as well as operating the interconnecting cables to partner countries [[22], [20]].

## 2.2 Challenges in Today's Power Grid

Various challenges often result in decreased delivery quality, avoidable power failures, and a higher outage risk than desired. This section will present some of the most significant challenges in today's power grid.

### 2.2.1 Power Loss

Because of long distances from production to consumption, line losses are substantial. According to Energy Norway [1], there is a loss of 8.8 TWh in the power grid, where more than 50 % of the losses occur in the distribution grid. By implementing NMGs, these losses would substantially decrease because of the shorter distance from producer to consumer.

### 2.2.2 Congestion

Congestion is a significant problem in today's grid. Congestion is caused by the limited transmission capacity of power lines, which obstructs the delivery of the needed power supply. One could propose building more power lines, but this approach is costly, detrimental to nature, and associated with higher greenhouse gas emissions. Hence, it's essential to fully utilize the existing capacity. Implementing NMGs reduce the need to transport power over long distances thus alleviation congestion in the utility grid. NMGs also optimize the use of local energy resources and can work as a controllable load in the event of congestion in the utility grid, thus reducing the strain on the utility grid.

### 2.2.3 Voltage Regulation

Voltage is, in contrast to frequency, a local quality. Both active and reactive power have an effect on the voltage, and it is usually during rapid increases in active power that issues arise [1]. Distributed generation as well as highly varying production from small-scale power plants is often a triggering factor for voltage fluctuations beyond what is desirable. Problems with voltage quality also often arise in long radial lines. As more local production is connected to the grid in the future, it is assumed that significant changes in power flow will greatly increase the requirements for voltage regulation.

### 2.2.4 Cyber Attacks

The power grid, being a critical part of our infrastructure, is increasingly becoming a more appealing target for cyber threats. These threats can disrupt the power supply, inflict economic harm, and potentially pose a national security issue. The complexity of the power grid, together with its incorporation of information and communication technology, presents many vulnerability points that attackers can exploit.

Various forms of cyber threats exist against the power grid, including malware, ransomware, and targeted attacks on infrastructure control systems. The consequences of these attacks can be severe, leading to physical damage to equipment, interruption of power supply, and even extensive blackouts. A case in point is the 2015 cyber attack on Ukraine's power grid, resulting in 30 substations going offline and approximately 22500 persons losing power, underscoring the potential severity of such attacks [23].

### 2.2.5 Integration of Distributed Energy Resources and Distributed Generation

The concept of microgrids holds significant relevance primarily due to the widespread implementation of DG, and DER can be considered the cornerstone of MGs.

DER are small-scale energy resources usually located near the consumer. This can be distributed PV systems, energy storage systems, or flexible loads, among others [24]. There is no single definition of DERs, so the classification may vary depending on who is using the term, what context, and what purpose. Definitions from the European Commission (EC), US Federal Energy Regulatory Commission (FERC), and the Australian Energy Market Commission (AEMC) are seen in Table 1. These regulatory bodies oversee energy policies and regulations in their respective regions.

**Table 1:** *DER definitions by the European Commission, US Federal Energy Regulatory Commission, and the Australian Energy Market Commission [24].*

| **Organization** | **Definition** |
|---|---|
| European Commission (EC) | DERs consist of small- to medium-scale resources connected mainly to the lower voltage levels (distribution grids) of the system or near the end user. Key categories are distributed generation, energy storage and demand response. |
| US Federal Energy Regulatory Commission (FERC) | A DER is any resource located on the distribution system, any subsystem thereof or behind a consumer's meter. DERs may include electric storage resources, distributed generation, demand response, energy efficiency, thermal storage, and electric vehicles and their supply equipment. |
| Australian Energy Market Commission (AEMC) | DERs are devices capable of producing, storing or managing energy at homes and businesses, sometimes referred to as behind-the-meter devices. They include rooftop solar PV, energy storage, demand response, electric vehicles and energy management systems, although many of these technologies are not found exclusively behind the meter. |

As one may see from Table 1, the EU and FERC include resources on both sides of the meter. Meanwhile, the AEMC has more focus on resources located behind the meter, although they do not explicitly exclude those in front.

DG is local production in the distribution grid. Typically DGs have low power outputs compared to big conventional power plants and are situated closer to the consumer. Increased levels of DG and bidirectional power flow between the grid and customers give rise to technical challenges that require greater attention, particularly with regard to system and voltage stability, connection requirements, planning, and operation of the distribution network [25]. There are two types of DG in MGs, dispatchable and non-dispatchable. Dispatchable DGs have the capability to adjust their power output in response to requests from a microgrid controller (MC). Examples of such DGs include diesel generators, fuel cells, and microturbines. On the other hand, wind turbines and PV systems are usually considered non-dispatchable DGs, as their power production is heavily influenced by weather and environmental factors that cannot be fully controlled [26].

Implementing DERs with the use of MGs can lead to more efficient and sustainable use of energy and reduce the need for costly and environmentally damaging grid infrastructure upgrades.

### 2.2.6 Enhancing Resilience in Power Supply for Critical Infrastructure

The power grid supplies many consumers who have loads that are considered critical loads. This could be the military, data centers, certain industries, and hospitals. Since this thesis focuses on hospitals, this section will focus on hospitals as critical infrastructure.

Hospitals are to be considered critical infrastructure and should be prioritized in times of energy shortage. The healthcare sector is one of the most vulnerable sectors to electricity outages, and in the worst case, a loss of energy could mean a loss of life. This is what happened in India at the Gandhi Hospital in 2016, where 21 patients died due to a power outage [27].

It is natural and expected that hospitals and medical centers have electricity infrastructures that are equipped with backup systems such as generators and uninterrupted power supply (UPS) units. Despite having generator backup power systems, the best generator in the market has a startup time of approximately 8 to 10 seconds, which may fall short of the needs of the healthcare industry [27].

Hospitals are one of the building types with the highest energy consumption per square meter [28]. This is due to the energy-intensive technical equipment used in hospitals as well as the general high usage time. One may think of critical loads in a hospital as intensive care units, resuscitation units, and operating rooms, which are important to ensure an uninterrupted power supply.

## 2.3 Emerging Solutions to Address Challenges in the Power Grid

Several solutions and technical advancements are emerging to address the previously presented challenges in the power grid. In this section, some of the promising solutions are presented.

### 2.3.1 Smartgrid

Today's power grid has been created through developments and adaptations over many decades. But social development is taking place faster than ever, and so must the development of the power grid. If the grid does not keep up with the changes, it will not be able to handle tomorrow's electrified society where cars, industry, and households run on energy derived from DER.

An essential part of this is to develop new technologies to make the operation and planning of future grids more automated and digitalized than today's grid. By making the grid smarter, one can detect faults before they happen, and consumers can utilize their energy more efficiently. In addition, one would also be able to utilize the existing capacity much more efficiently [29].

Taking Norway as an example, the implementation of the advanced metering system (AMS) was an essential step toward a smarter grid. This was implemented in all households in 2019 and allowed for automatic hourly recording of electricity consumption [30]. The installation of new AMS meters meant that consumers no longer had to take manual readings of their energy consumption. Frequent, automatic readings will also result in better data quality and more accurate electricity bills.

Using AMS meters will result in far more accurate information about the current state of the power grid, including consumption, load, and voltages. This information can be used in analyses allowing the grid companies to operate and design the grid in a more efficient way [31]. Implementing AMS meters also increases the resiliency of the distribution power grid. Presently, fault detection in the low-voltage grid is primarily reliant on consumers reporting issues to grid companies. However, this approach may not be ideal, as damage to consumer electronics and appliances may already have occurred by the time the grid company has been made aware of the fault. Voltage control by AMS can help prevent this. In addition, the AMS enables rapid detection of interruptions such as power outages, ground faults, or voltage quality issues. This enhances the grid company's capacity to promptly and accurately pinpoint faults [31].

The utilization of AMS meters also benefits consumers in several ways. The meters are equipped with a home area network (HAN) port, and by connecting to this port, the consumers gain access to information about their electrical system. The information is updated every 10 seconds and includes data about power output, energy consumption, voltage level, and surplus power (e.g. from PV systems) delivered to the grid [30].

### 2.3.2 Energy Storage Systems and Electric Vehicle Batteries

ESSs are essential in an MG because of the intermittent nature of renewable DERs such as solar power and wind power. By implementing ESSs one can ensure a more stable and uninterrupted power flow to the loads when the power from the DERs is insufficient to supply the loads [9]. Several different ESS technologies are available and vary by the physical form and mechanism in which energy is stored. Some of the technologies could be flywheel energy storage systems, compressed air energy storage systems, electrostatic energy storage systems using capacitors, hydrogen energy storage systems, pumped hydropower or electrochemical energy storage systems using conventional rechargeable batteries [9].

Batteries can serve as an important alternative for the DSO in comparison to constructing new transmission lines or expanding transformer capacities, as they lead to more efficient use of grid capacity. Such batteries can be owned by prosumers for example commercial building owners or even residential households. The distribution grid operator may benefit from congestion management through the reduction of load and generation peaks, loss minimization by controlling power flow to reduce losses in distribution grid lines, and power quality improvements by smoothing fast changing DERs. However, communication technologies and control strategies must also be developed to leverage these advantages fully. Moreover, the use of distributed batteries may also be advantageous for consumers and prosumers as it can reduce the electricity cost by consuming power at lower prices and utilizing this during times with high prices. It can also reduce tariffs based on maximum power usage and serve as backup power [32].

The most widely used electrochemical battery technology at the moment is the Lithium-Ion (Li-Ion) battery. In 2022 the Li-Ion battery demand was 550 GWh, an increase of 65 % from 330 GWh in 2021 [12], a year where the battery demand more than doubled compared to 2020 [33]. This increase is driven primarily by the increase in EVs [33]. There are several subcategories of the Li-Ion battery primarily dependent on what cathode chemistry are used. For EV applications, the three most common ones are lithium nickel manganese cobalt oxide (NMC), lithium nickel cobalt aluminum oxide (NCA), and lithium iron phosphate (LFP) [33]. In general, the Li-Ion battery has high cell voltage, good charge retention, high depth of charge, long cycle life, high power density, high energy density, high specific power, and high specific energy [9]. Nevertheless, it also has some disadvantages. As with many other batteries, the high cost is a drawback, especially in large-scale applications. Batteries also degrade over time, and the net storage capacity will decrease as the battery undergoes charge-discharge cycles. Aging and thermal overheating can also be problematic. Some technical characteristics of the general Li-Ion battery can be seen in Table 2.

**Table 2:** *Technical characteristics of Lithium-Ion batteries [9].*

| | **Lithium-Ion (Li-Ion)** |
|---|---|
| Energy Density [Wh/L] | 94-500 |
| Power Density [W/L] | 1300-10000 |
| Specific Energy [Wh/kg] | 30-300 |
| Specific Power [W/kg] | 8-2000 |
| Response Time | Milliseconds |
| Discharge Time | 15 min - 8 hours |
| Lifetime | 8 - 15 years |

Traditionally, the cost of investing in batteries for energy storage use has been prohibitive for consumers. This has changed now that electric cars have become commonplace. Nowadays, individuals who own an EV possess a relatively large battery that is readily available while the car is parked at home and charging. According to Statistics Norway (SSB), household electricity consumption was approximately 16000 kWh in 2016 [34]. On average, this translates to 45 kWh per day. Most EVs today are equipped with a battery capacity ranging from 20 kWh to 100 kWh [11]. This means that most fully charged EVs will be able to supply a household with electricity for approximately one day, while some could cover the energy demand in your house for several days.

The increasing deployment of EVs may pose a challenge to the distribution grid due to the more unpredictable load profiles and higher load peaks. However, it could also be beneficial to the distribution grid as it can be utilized for power balancing and other benefits associated with battery integration previously mentioned. An additional advantage of EV implementation is its mobility, allowing the battery to be relocated to various locations to supply power or alleviate load demands since EVs are essentially a highly mobile energy package. Moreover, the total storage capacity can be conveniently adjusted by adding or removing EVs from the charging infrastructure. To leverage these benefits, the advancement of smart charging and vehicle to grid (V2G) technology is vital as it leads to improved utilization of the existing grid. This could potentially transform EVs into a valuable asset rather than a liability for the grid operator. Nevertheless, with EVs, factors such as conflicting usage, availability, and battery degradation must also be taken into account.

In order to provide power from an electric vehicle to the power grid, it is a prerequisite that the vehicle supports V2G charging. V2G charging is a two-way communication system that allows the vehicle to communicate with the power grid enabling charging from and discharging to the grid [35]. Currently, few electric vehicles support V2G charging, and only the CHAdeMO charging system allows for two-way charging. However, this is expected to increase significantly in the future as the CCS charging system is expected to support bidirectional charging [35]. Also, when a residential load is connected to the EV charger, Vehicle to Home (V2H) can be implemented by supplying power from the EV battery directly to the load. This would be the preferred operation during a grid outage where the grid is disconnected. As of March 31, 2022, only six car models supported V2G charging, namely Nissan Leaf, Nissan eNV200, Kia Soul, Mitsubishi Outlander, Volkswagen ID.4, and Volkswagen ID.5 [36].

According to the National Grid ESO's 2020 "Future Energy Scenarios" report, they predict that by 2050, 45 % of households will actively provide V2G capabilities. These capabilities will reduce the demand for the power grid and allow EV owners to use greener, cheaper electricity, which is seen as an important step toward the net-zero 2050 scenario [37]. At the same time, they also emphasize that there is a wide range of uncertainty in the development of V2G technology. A figure illustrating the different operational modes for a bidirectional charger is seen in Figure 2.

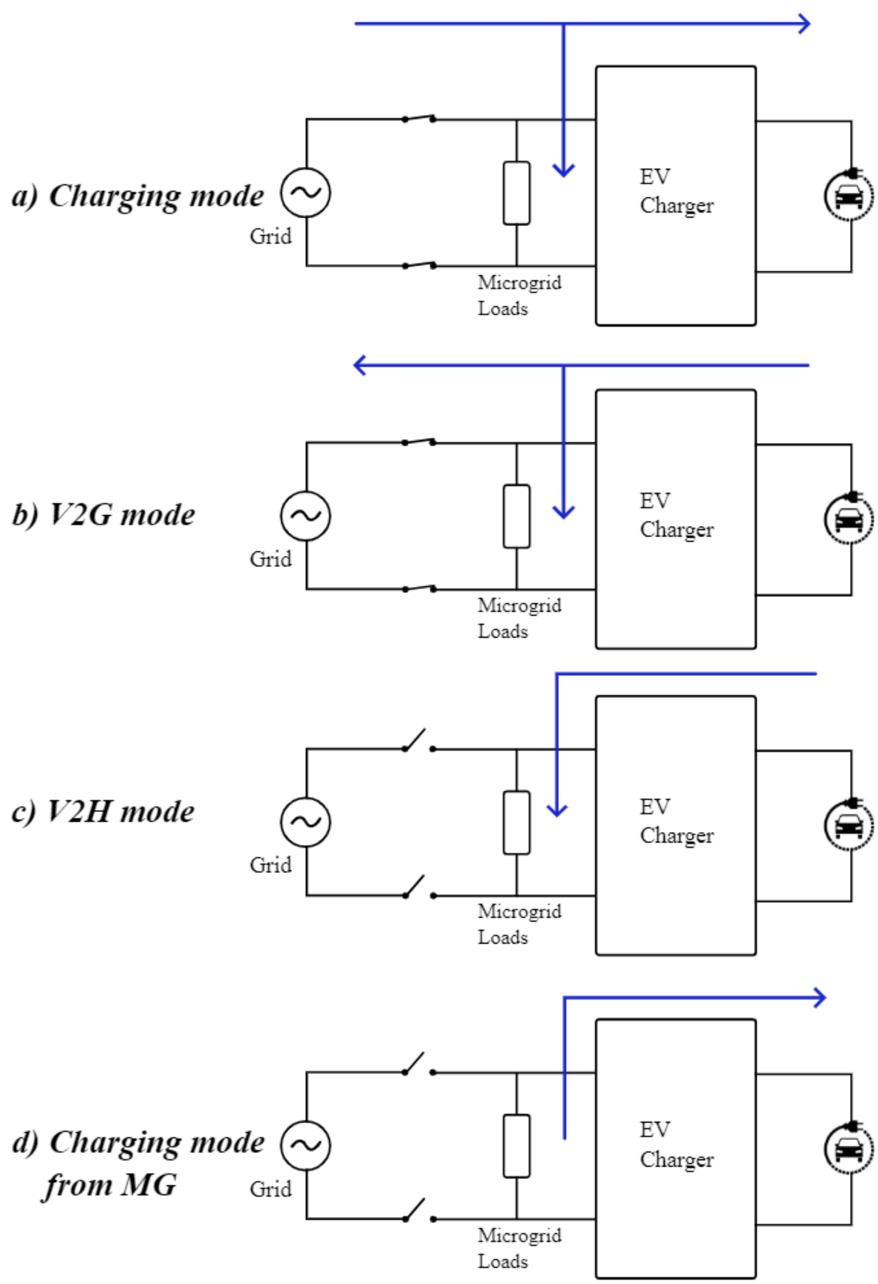


**Figure 2:** *Bidirectional EV charging.*

### 2.3.3 Microgrids

A common definition of an MG developed by the U.S. Department of Energy Microgrid Exchange Group is;

*"a group of interconnected loads and distributed energy resources with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or islanded modes."*[4].

The definition can be further defined by a peak output power of a maximum of 10 MW [6]. As stated in the definition, MGs can operate in grid-connected or islanded modes. Local energy production is a critical requirement for an MG to supply enough power to its loads while operating in islanded mode. Additionally, energy storage serves as a vital component in MGs. Energy storage provides generation smoothing for intermittent renewables. In islanded mode, load shedding or generation shedding can be used to maintain the balance between production and consumption. A generic illustration of an MG is seen in Figure 3.

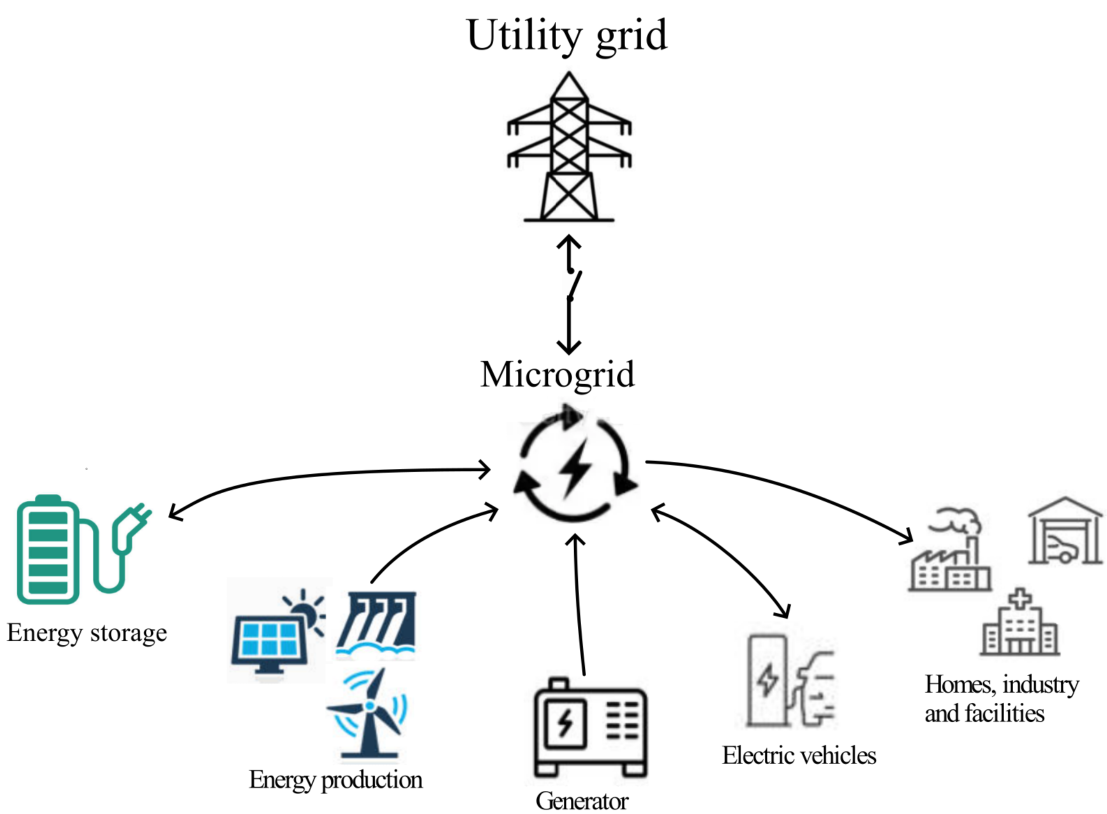


**Figure 3:** *Generic illustration of an MG.*

### 2.3.4 Networked Microgrids

There is no single explicit definition of an NMG in the literature, but NMGs generally refer to two or more MGs interconnected with each other. They can operate both independently and collaboratively. By connecting at least two MGs together, NMGs have the potential to increase resiliency and decrease costs by sharing the same loads and DGs. Consequently, this increases the likelihood of balancing electricity supply and demand within the NMG [38]. An illustration of what an NMG can look like is shown in Figure 4.

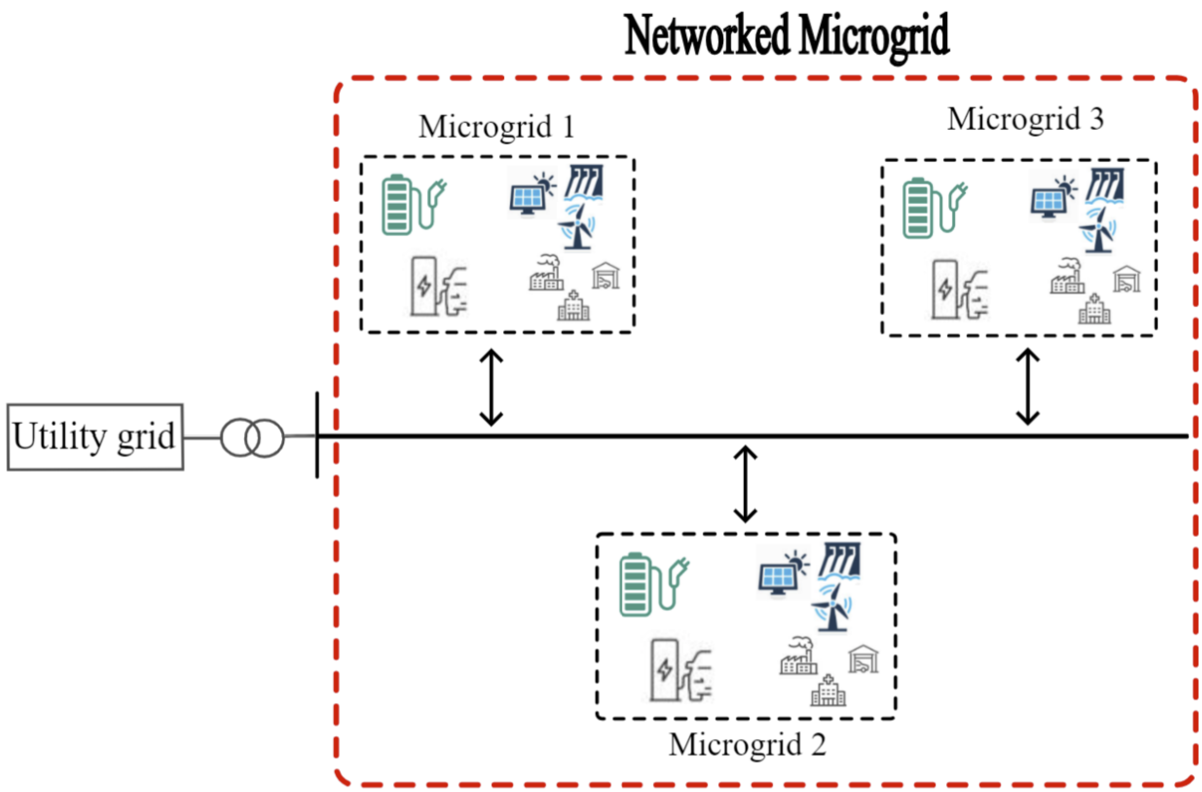


**Figure 4:** *Generic illustration of an NMG.*

Under normal conditions, NMGs operate connected to the distribution grid. And during abnormal situations, such as a power outage, they could operate disconnected from the grid but still interconnected to each other. They also have the ability to work entirely isolated as two or more separate MGs.

The MGs, either connected together or not, are connected to distribution feeders through the points of common coupling (PCC). NMGs can be coordinated at a higher level to function as an integral part of grid operations, or they can be operated and controlled by local DSOs. This enables them to offer ancillary services and deliver operational benefits to stakeholders [39].

The different operational modes of NMGs can be utilized to improve the resilience, robustness, and efficiency of the power grid, depending on the system's control philosophy and specific operational conditions. These operation modes include *centralized dispatch mode* where a centralized controller, e.g. a distribution management system can manage NMGs through the utility Supervisory Control and Data Acquisition (SCADA) system. *Distribution operation mode* with no centralized controller and coordination achieved through a variety of methodologies. *Ride-through mode* where NMGs ride through disturbances or *black-start mode* where large-scale power outages with the power network completely de-energized is supplied by MGs that support with cranking power to DGs in the other MGs, as well as energizing the power network [39].

NMGs can be divided between NMGs with fixed boundaries and NMGs with dynamic boundaries. NMGs with dynamic boundaries can be formed by adjusting the boundaries of MGs and power sources in a dynamic manner using frequency and voltage regulation capabilities [39]. By allowing both individual MGs and NMGs to adjust their electric boundaries dynamically, NMGs with dynamic boundaries offer a more flexible operational paradigm. This thesis will focus on NMGs with fixed boundaries.

The connection of several MGs in an NMG facilitates coordination between the MGs enabling the surplus power sources to be utilized more efficiently for load demand balancing. In addition, NMGs could be designed to protect not only critical loads inside the NMG but also neighboring loads as well.

NMGs can also improve grid efficiency and reduce system losses by actively coordinating with other resources and this way work as controllable loads or dispatchable power sources. Furthermore, NMGs can contribute to the effective integration of DERs by locally addressing uncertainties arising from DERs and loads. This, in turn, simplifies the modeling and computation requirements for optimal power flow [39].

# 3 Method

Chapter 3 outlines the approach taken to address the research questions. First, an introduction of the methodology is given, secondly, a description of the model and its working principles is presented, followed by three sections describing each MG, the MGs data input, and parameters. Lastly, the three simulation scenarios examined in this case study are presented.

## 3.1 Introduction to Methodology

The research questions in this thesis were explored through the following processes.

1. Decide the outlines of the simulation. How many MGs should be connected, and what components should each MG contain?

2. Conduct a literature search and find appropriate simulation values, parameters, and input data.

3. Create an NMG with the decided components from point 1 and focus on power balance. Add all the data found in point 2.

4. Simulate normal operation mode and export all results.

5. Implement a power failure in the utility grid resulting in a disconnected breaker to the utility grid. This will be a comparison scenario to the traditional standalone MG. See how the model responds to this failure, and implement load - and generation shedding if needed.

6. Again implement a power failure in the utility grid, but now keep the interconnections between the MGs connected. Use the same load and generation algorithms to compare the two scenarios. Create a power-sharing algorithm to ensure sufficient power flow to MG1.

7. Compare the results from the scenarios to each other.

The constructed case study is purely theoretical. It focuses on power flow and does not consider synchronization processes, specifics of power electronics, or reactive power.

## 3.2 Description of Model

The simulation consists of an NMG composed of three MGs. The first MG contains a hospital, the second an office building, and the third a residential area with 60 households. The MGs are interconnected through breakers. All MGs have PV systems for energy production, EVs for energy storage, and loads. The hospital is considered a critical infrastructure and should always strive to be supplied with power.

The simulation time is set to three days or until the simulation stops due to insufficient power flow to the critical loads. The simulation is phasor-based, and the power system operates at 50 Hz with an 11000 line-to-line root mean square (RMS) voltage.

Figure 5 shows a block diagram of the top level of the NMG and the connection to the utility grid. Figure 6 shows a generic block diagram of each MG.

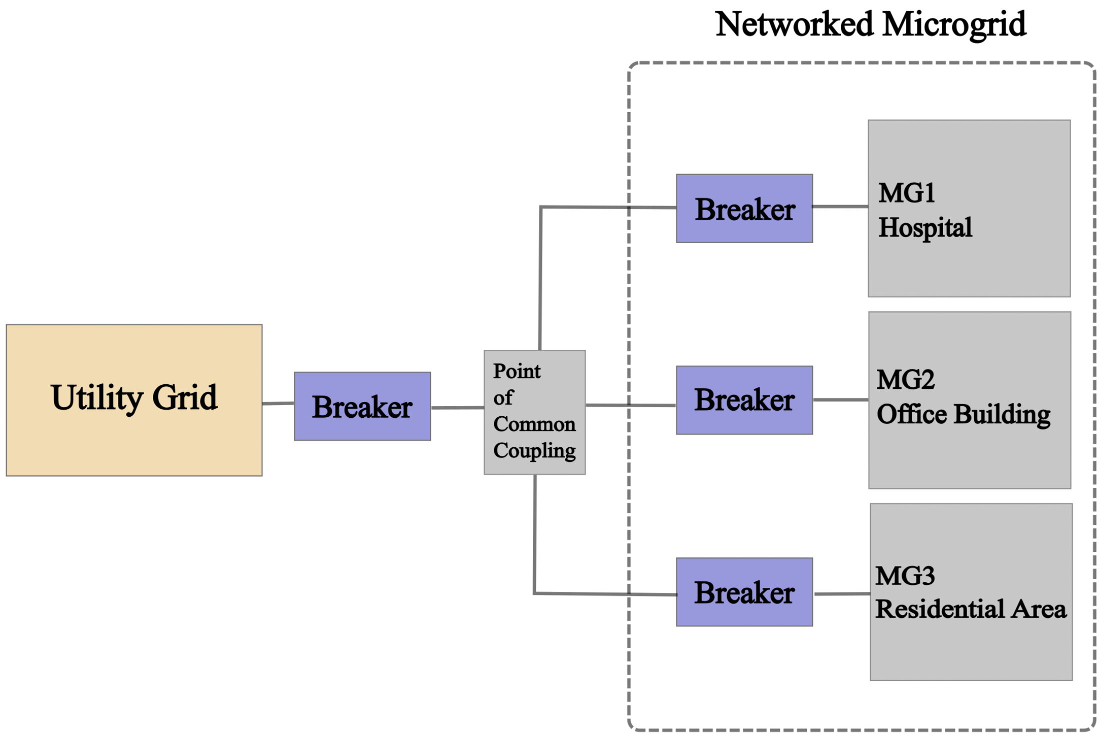


**Figure 5:** *Block diagram of NMG model.*

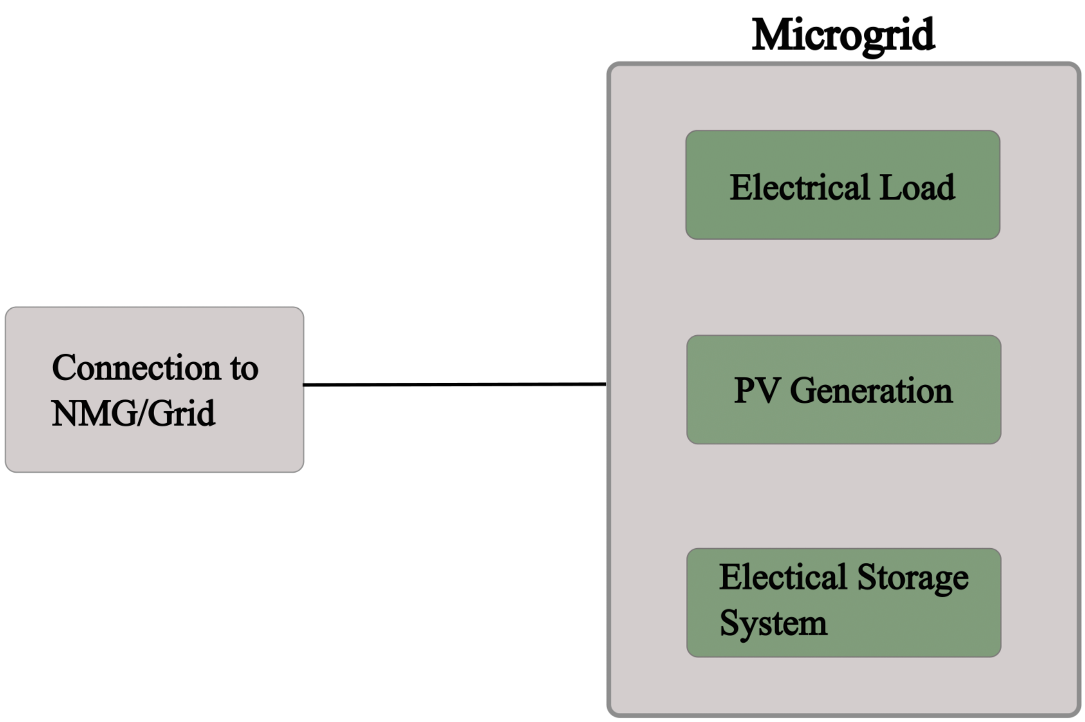


**Figure 6:** *Block diagram of MG model.*

### 3.2.1 Working Principles

**Battery charging:** The normal working instructions for the battery is to balance the difference between the load demand and PV production in each MG. This means that $BatteryPower = LoadBalance$, where $LoadBalance$ is defined as $PowerPV - Load$.

**Scheduled charging:** The exception from the charging rule mentioned above is when EVs are experiencing scheduled charging. In MG1 and MG2, the scheduled charging initiates two hours before the EV owners would need their car to travel back home from work. In MG3, the charging starts two hours before the EV owners need their car to leave for work. This charging lasts for two hours and follows a Gaussian distribution curve. The purpose of the scheduled charging is twofold: to guarantee that EV owners have an adequate SoC when they need their vehicles and to ensure that the SoC of the EVs is higher post-charge compared to pre-charge. The algorithm for the scheduled charging is seen in Appendix A: Simulink Model, Figure 27, and the MATLAB code following the figure.

**Change in storage capacity as a consequence of a change in the number of EVs**: The total battery storage capacity will change throughout the simulation. This is a consequence of EVs arriving or leaving the V2G chargers in the MGs. When cars arrive or leave, it is assumed that the first cars arrive one hour before work time and that the rest arrive linearly until all cars have arrived. Because of this, all changes in battery capacity take one hour and occur linearly. How the number of EVs, and so the capacity, changes in each MG is explained in Sections 3.4, 3.5 and 3.6.

**Load shedding and generation shedding:** During times when the grid is disconnected and the battery can not balance out the power imbalance between production and consumption, load shedding or generation shedding is necessary. The equation used for calculating load shedding is seen in Equation 1, and the equation for calculating generation shedding is seen in Equation 2.

$$L_{shed} = 1 - \left( \frac{(SoC_{lower} + SoC_{threshold} - SoC)}{SoC_{threshold}} \right) \tag{1}$$

where $L_{shed}$ is the factor of load shedding, $SoC_{lower}$ is the lower state of charge (SoC) limit of the battery, $SoC_{threshold}$ is the SoC threshold above the minimum SoC when the load shedding should start, and $SoC$ is the instantaneous SoC of the battery at the given time.

$$G_{shed} = 1 - \left( \frac{SoC - (SoC_{upper} - SoC_{threshold})}{SoC_{threshold}} \right) \tag{2}$$

where $G_{shed}$ is the factor of generation shedding, $SoC$ is the instantaneous SoC of the battery in the respective MG, $SoC_{upper}$ is the upper SoC limit of the battery and $SoC_{threshold}$ is the threshold below the maximum SoC when the generation shedding should start.

The equations are only in effect when the SoC is below $SoC_{lower} + SoC_{threshold}$ for load shedding and above $SoC_{upper} - SoC_{threshold}$ for generation shedding. Using these equations, the amount of load and generation shedding would regulate according to the current SoC level. The full algorithm can be seen in Appendix A: Simulink Model.

**Power sharing:** A power-sharing algorithm was developed to prioritize power flow to MG1, ensuring the battery in MG1 doesn't deplete and trigger a hospital blackout while other MGs still have energy remaining. This is done by increasing the power flow from a battery with remaining energy above what is needed to keep the power balance in the respective MG. With the utility breaker disconnected, this energy would have to be consumed in another battery. Equation 3 is the main equation used to achieve this. The example is from power sharing from MG3.

$$P_{added} = \frac{P_{max}}{SoC_{upper}} \times (SoC_{upper} - SoC_{MG1}) \tag{3}$$

where $P_{added}$ is the additional power from MG3, $P_{max}$ is the is maximum power delivery limit in MG3, $SoC_{upper}$ is the upper SoC limit of MG1 before MG3 should start sharing power, $SoC_{MG1}$ is the instantaneous SoC of the battery in MG1. This equation is part of a bigger algorithm and will only run when the SoC of MG1 is below the $SoC_{upper}$ value. Also, since one knows from the battery capacity of MG1 that the battery has sufficient capacity to supply the loads during day and evening shifts, the power-sharing algorithm was only applied during night shifts at the hospital. Furthermore, as the capacity in MG2 is zero outside of office hours, which stretches beyond the night shift at the hospital, the power-sharing algorithm was only applied to MG3. It should also be noted that in scenarios with power sharing, the threshold limit for load shedding was set at a higher SoC in the MG exporting power. This approach makes more power available for dispatch to the MG that's been prioritized. The full algorithm can be seen in Appendix A: Simulink Model, Figure 32, and the MATLAB code following the figure. A summarization of the SoC thresholds for load shedding, generation shedding, and power sharing is seen in Table 3 below.

**Table 3:** *SoC limits for load shedding, generation shedding, and power sharing.*

| **Parameters** | **Value** |
|---|---|
| SoC threshold before load shedding initiates | 40 % |
| SoC threshold before load shedding initiates with power sharing enabled | 70 % |
| SoC threshold before generation shedding initiates | 60 % |
| SoC threshold before power sharing initiates | 50 % |

## 3.3 System Parameters and Data

This section provides an overview of the key parameters, data inputs, and assumptions valid for all MGs in the model. Each parameter has been chosen to ensure that the model reflects real-world conditions as closely as possible.

### 3.3.1 Load Data

All load data were originally extracted for one day. The extension from one to three days was done using MATLAB. From the first original day, two consecutive days were added with a randomization of 3.5 %. This approach was used for all the MGs.

### 3.3.2 PV System

The power from the PV system is calculated by using Equation 4

$$P_{pv} = G * \eta * A \tag{4}$$

where $G$ is the solar irradiance, $\eta$ is the efficiency, and $A$ is the area of the PV modules.

The solar irradiation used in the thesis is from Ås, Norway spanning from June 4th to June 6th. These dates were chosen as PV production is the only production source in the MGs, and one would therefore choose a time of year when solar irradiance is high. The simulated NMG is not bound to any specific geographical place, but Ås is located in one of the most populated areas in Norway and is situated at a latitude of 59 degrees north, roughly the same as the majority of the Norwegian population. As such, Ås would work as a strong reference location. One can see the solar irradiance curve in Figure 7. As some of these values are negative during nighttime caused by more outward radiation than inward, these values were set to zero when imported in Simulink. The PV system will not work as a load even if the net radiation is negative.

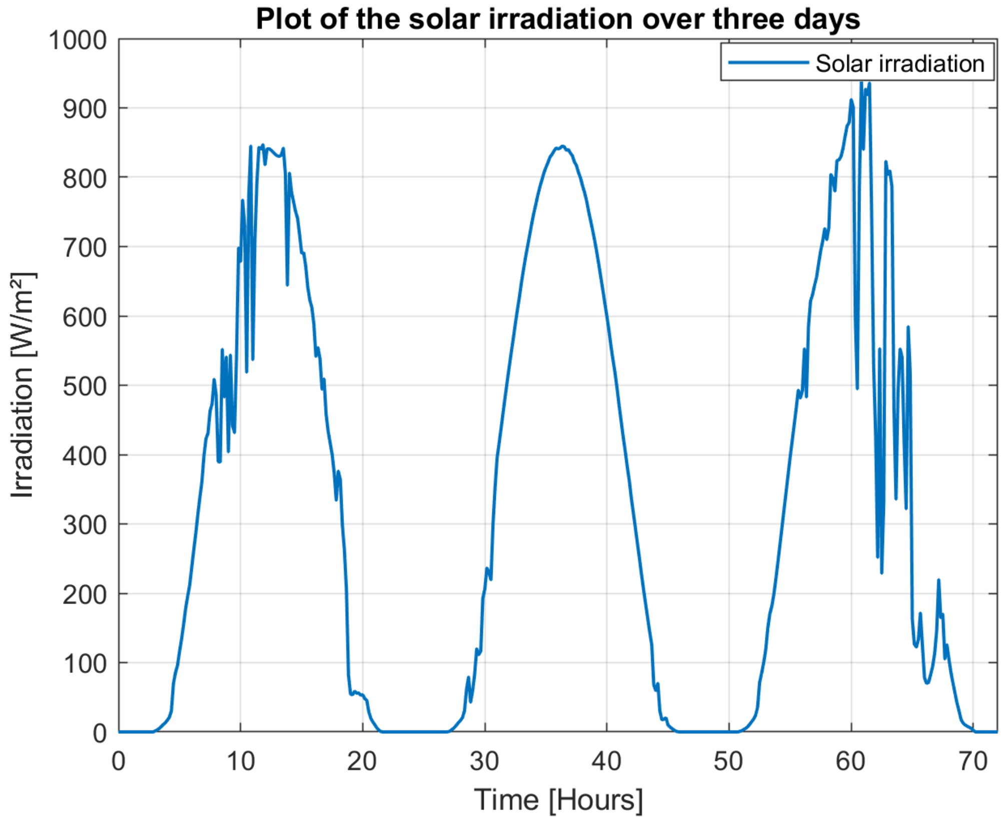


**Figure 7:** *Plot of the solar irradiation in Ås from June 4th to June 6th.*

According to S. Dubcy et al. [40] the efficiency of typical PV panels ranges from 6 % to 20 % dependent on factors such as the type of solar cells and temperature. Norway's generally low temperatures make it well-suited for achieving high efficiencies. Consequently, this thesis utilizes a constant efficiency of 18 % for the PV systems in all the MGs. One could further calculate the installed capacity of each PV system in the MGs using the 1 kW per square meter standard test value for irradiation, but as it is assumed the inverters are oversized, this installed capacity value would be of no practical matter in this thesis. Instead, area and efficiency are used to calculate power production.

### 3.3.3 Storage Capacity

Due to the rapid increase in the share of EVs, using the current ratio for the number of EVs will not be appropriate. It has therefore been determined that a 50 % share of electric cars will be utilized, as projected by NVE to exist in Norway in 2030 [11]. According to Statistics Norway [41], 80.9 % of all travel takes place by the use of cars in Norway.

One important parameter to decide on is the electrical storage capacity in EVs. According to Innovation Norway [42] today's average capacity is 50-60 kWh. The IEA has projected that the average capacity in 2030 will be between 70 kWh and 80 kWh [43], while NVE has projected between 80 kWh and 100 kWh in 2030 [44]. This thesis uses an average capacity of 80 kWh in each EV.

Even if the EVs have a total capacity of 80 kWh when fully charged, all of this can not be utilized. The EVs should retain some capacity for when the owner requires the vehicle, and battery degradation becomes more noticeable when charged or discharged to either of its SoC limits. The EVs will therefore only be charged or discharged when the SoC is between 10 % and 90 %, and the scheduled charging is set to 80 %. Further, it is assumed that since the EVs work together as an aggregated battery, the individual EVs' maximum charging rate will not equal the aggregated batteries' maximum charging rate. This is because when an EV charge at a rapid charger station, it usually only reaches its maximum charging rate in a very short amount of time. Because of this, it is assumed that the maximum charge/discharge rate of the aggregated battery is 60 % of the individual EV's maximum charge/discharge rates.

A summary of all the collective parameters is shown in Table 4.

**Table 4:** *Collective parameters for all MGs.*

| **Parameters** | **Value** |
|---|---|
| PV system efficiency | 18 % |
| Battery SoC [min, max] | [10, 90] % |
| Single EV battery capacity | 80 kWh |
| Fraction of employees using cars as transportation to work | 80.9 % |
| Fraction of cars being EVs | 50 % |
| Randomization added load on days two and three | 3.5 % |

## 3.4 Microgrid 1 - Hospital

The following subsections are a description of the data and assumptions used in MG1.

### 3.4.1 MG1 Load Curve

Since there is limited data for Norwegian hospitals' hourly load consumption, the load curve in this thesis is based on the pattern from an average winter business day load pattern from a hospital in the Castilla y Léon region in Spain [45]. One may assume the winter climate in Spain is somewhat similar to the yearly average in Norway.

According to A. S. Abrahamsen et al. [28], the yearly electrical energy consumption in a Norwegian hospital is 238 kWh/m$^2$ and the average area is 20000 m$^2$. This gives a daily energy consumption of 13041 kWh. By using this number to scale the previously mentioned load curve from Spain [45], one obtains a load curve as in Figure 8.

It should be noted that both [45] and [28] are using data from 2011, but as there is limited available information online, it was decided that this data is sufficient.

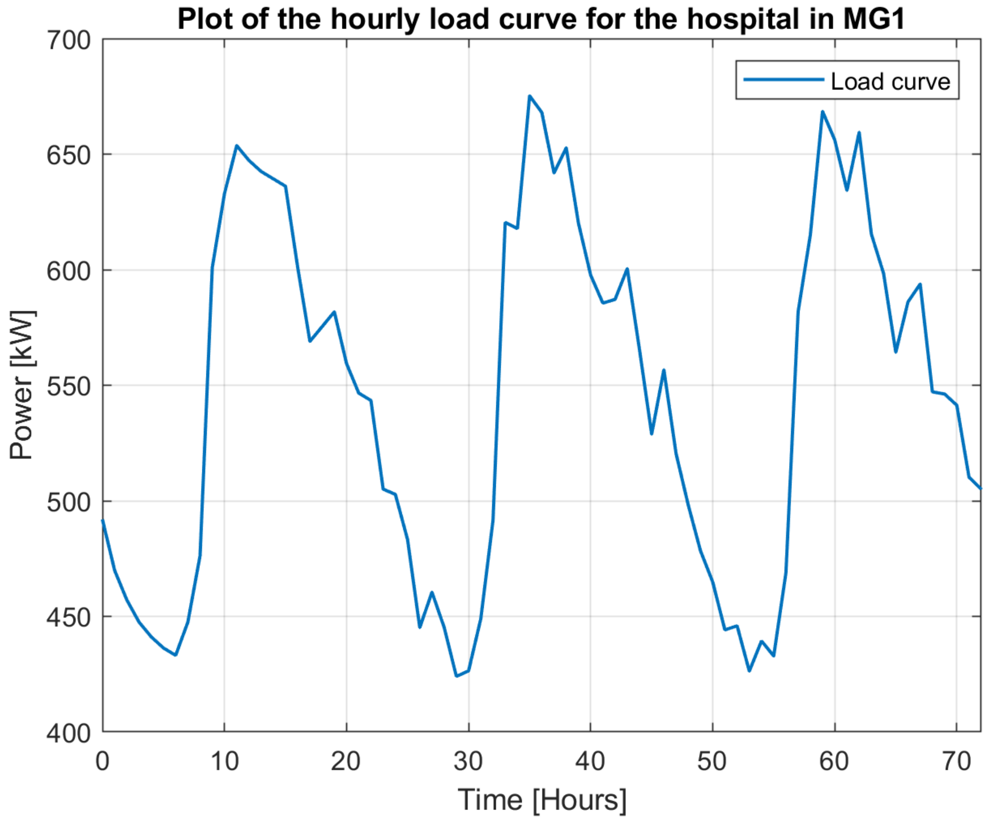


**Figure 8:** *Graph displaying the hourly load curve over a span of three days for the hospital located in MG1.*

#### 3.4.2 MG1 PV System

Building on the assumption that a typical Norwegian hospital is 20000 m$^2$ [28], and assuming the average hospital consists of fours floors, one can estimate the potential for PV installation. If 75 % of the roof can be utilized for PV installation, this results in a usable roof area of 3750 m$^2$.

The equation used to calculate the power production is Equation 4, the same as in Section 3.3.2. Since the NMG is in a bound geographical area, it is assumed that all the areas in the NMG have the same solar irradiance. A plot of the solar irradiance can also be seen in Section 3.3.2 in Figure 7.

#### 3.4.3 MG1 Energy Storage System

As mentioned in Section 3.2, the ESS system in this simulation consists solely of EVs. As there is limited information about the size and number of employees in Norwegian hospitals, one may assume that the relationship between the number of employees and size is the same as in Drammen Hospital, where there are 3000 employees and the hospital is 80000 m$^2$. Using this ratio and scaling this to a hospital of 20000 m$^2$ yields 750 employees. We further assume 50 % are working daytime shifts from 07-15, 35 % work evening shifts from 15-22, and 15 % are working night shifts from 22-07.

With the assumptions mentioned in Section 3.3, the number of employees at the hospital correlates to 152 EVs during the daytime, 106 EVs during the evening, and 45 EVs during the nighttime.

A summary of the data and assumptions used for the ESS in MG1 is seen in Table 5. A plot of the total storage capacity, accessible capacity, and maximum charge/discharge rates can be seen in Figure 9.

**Table 5:** *Summary of data and calculation used in the ESS in MG1.*

| | **Day 07-15** | **Evening 15-22** | **Night 22-07** | **Assumptions** |
|---|---|---|---|---|
| Number of employees | 375 | 263 | 112 | Total number of employees is 750. 50 % are working daytime shifts, 35 % work evening shifts and 15 % are working night. |
| Number of EVs | 152 | 106 | 45 | 80.9 % uses cars as transport to work [41], whereas 50 % have EVs [11] |
| Total capacity | 12160 kWh | 8480 kWh | 3600 kWh | Average capacity in an EV is 80 kWh [43] |
| Accessible capacity | 9728 kWh | 6784 kWh | 2880 kWh | Since the employee needs energy to commute between work and back home, the battery will only be utilized when the SoC is between 90 % and 10%. |
| Max power delivery | 22800 kW | 15900 kW | 6750 kW | Average power delivery is 60 % of the 250 kW maximum power. Giving a maximum power delivery of 150 kW for the aggregated battery. |

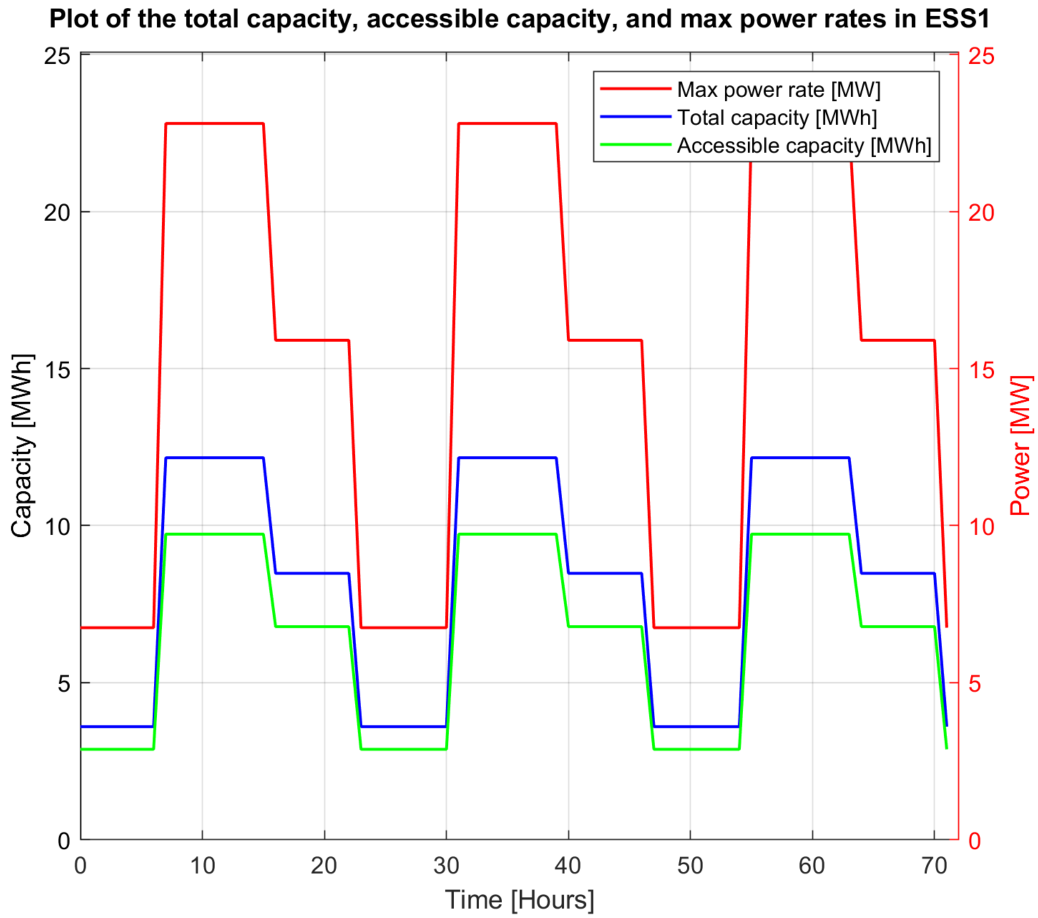


**Figure 9:** *Plot of the total storage capacity, accessible capacity, and maximum power delivery in ESS1.*

## 3.5 Microgrid 2 - Office Building

The following subsections are a description of the data and assumptions used in MG2.

### 3.5.1 MG2 Load Profile

The shape of the load profile for the office building (OB) is based on an average load curve from seven OBs in Trondheim [46]. The load curve is then scaled according to an average-sized OB of 7000 $m^2$ with an electrical consumption of 176.5 kWh/$m^2$year [28]. This gives a daily electrical consumption of 3384 kWh/day for the OB designed in this thesis. The load curve for the OB is shown in Figure 10.

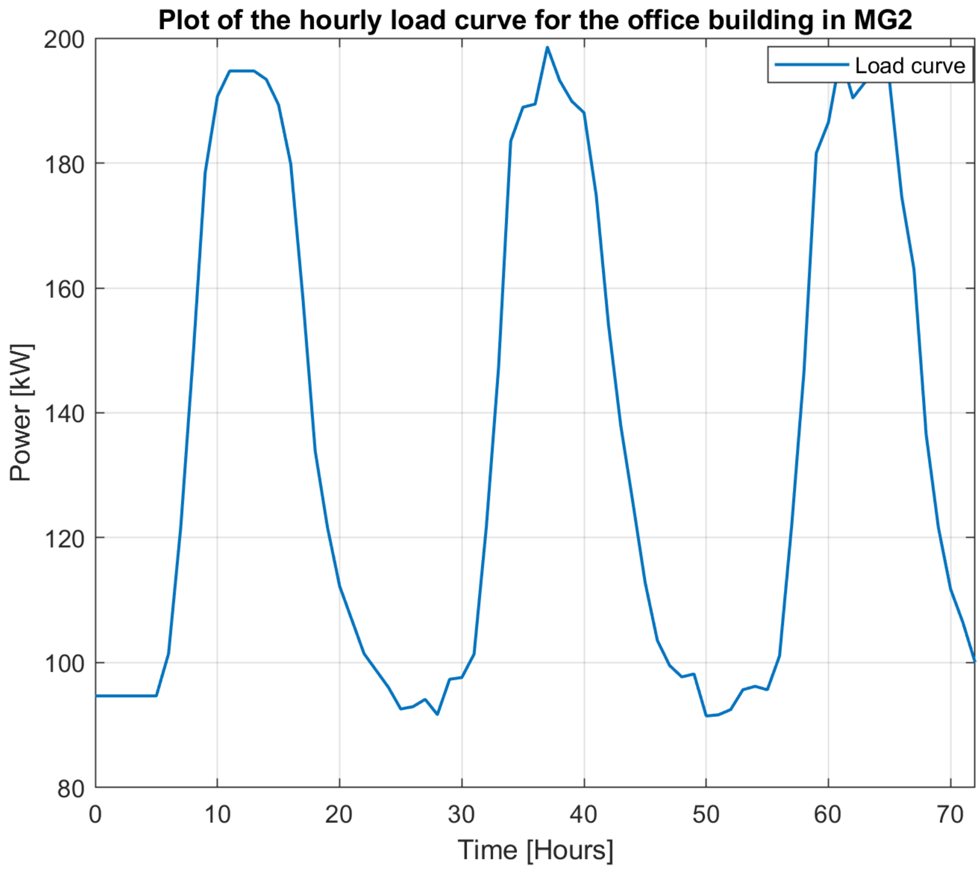


**Figure 10:** *Plot of the three-day load profile for the OB in MG2.*

### 3.5.2 MG2 PV System

The OB also has a PV system on the roof. The building has an area of 7000 $m^2$, and it is assumed the average OB in Norway has four floors. It is further assumed that 75 % of the roof can be utilized for PV installation. This gives a roof area of 1313 $m^2$ available for PV installation.

Equation 4 is the equation used to calculate power production. Since the NMG is in a bound geographical area, it is assumed that all the areas in the NMG have the same solar irradiance. A plot of the solar irradiance can also be seen in Section 3.3.2 in Figure 7.

### 3.5.3 MG2 Energy Storage System

The capacity of the ESS in the MG is proportional to the number of EVs that can supply power to the grid. The number of EVs available is dependent on the number of employees. According to NVE, it was 36 $m^2$/employee in an OB in 2012 [47]. Since the size of the OB is 7000 $m^2$, this translates to 194 employees. With the same assumptions as mentioned before, where 80.9 % of the employees are using cars as transport to work, and 50 % of these car owners have EVs, one ends up with a total of 78 EVs.

A summary of the data and assumptions is shown in Table 6. A plot of the total storage capacity, accessible capacity, and maximum charge/discharge rates is seen in Figure 11.

**Table 6:** *Summary of data and calculation used in the ESS in MG2.*

| | **08:00** | **09:00-15:00** | **16:00** | **17:00** | **Outside office hours (18-07)** | **Assumptions** |
|---|---|---|---|---|---|---|
| Number of employees | 97 | 194 | 107 | 19 | 0 | Total number of employees is 194. |
| The proportion of employees at work | 50 % | 100 % | 55 % | 10 % | 0 % | 50 % of the employees arrive at work between 07 and 08, the next 50 % arrive between 08 and 09. 100 % of the work stock is at work from 09.00-15.00, 45 % leaves between 15.00-16.00, another 45 % leaves between 16.00-17.00, and the last 10 % leaves between 17:00 and 18:00. After these hours, 0 employees are at work. |
| Change in the proportion of employees at work | +50 % | +50 % | -45 % | -45 % | -10 % | Relative change in employees. |
| Number of EVs | 39 | 78 | 43 | 8 | 0 | 80.9 % uses cars as transport to work [41], whereas 50 % have EVs |
| Total capacity | 3120 kWh | 6240 kWh | 3463 kWh | 640 kWh | 0 kWh | Average capacity in an EV is 80 kWh [43]. |
| Accessible capacity | 2496 kWh | 4992 kWh | 2770 kWh | 512 kWh | 0 kWh | Batteries are only utilized between 10 % and 90 % |
| Maximum power delivery | 5850 kW | 11700 kW | 6450 kW | 1200 kW | 0 kWh | The combined power delivery is 60 % of an individual EVs' charge/discharge rate. An individual EVs' maximum rate is assumed to be 250 kW. |

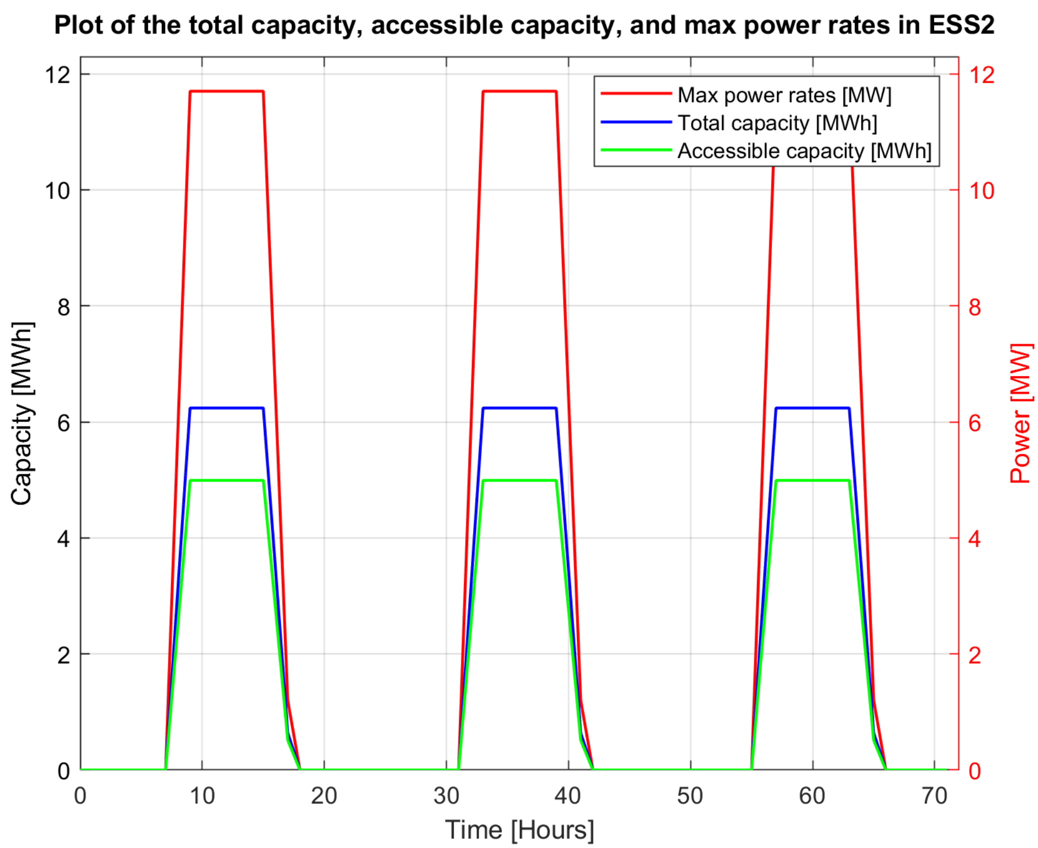


**Figure 11:** *Plot of the total storage capacity, accessible capacity, and maximum charge/discharge rates for the ESS in MG2.*

## 3.6 Microgrid 3 - Residential Area

The third MG in the NMG is a residential area with 60 households. The following subsections are descriptions of the data and assumptions used in this MG.

### 3.6.1 MG3 Load Profile

Based on the average load curve for a household in Norway [48] and scaled according to the daily consumption in 2022 of 38.1 kWh/day [49], the load curve seen in Figure 12 is obtained.

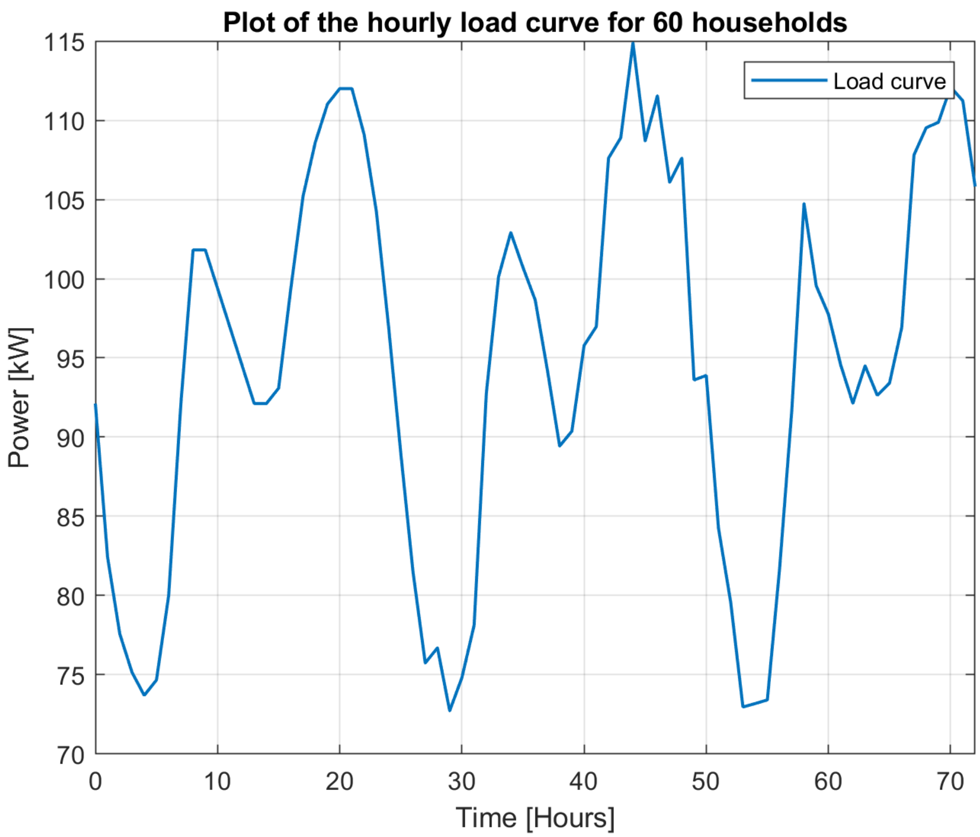


**Figure 12:** *Plot of the load curve for 60 households in MG3*

### 3.6.2 MG3 PV System

It is assumed that 80 % of the 60 households have PV systems installed. This is based on the understanding that these households are not a representative sample of society, but rather a subset of the NMG where PV panels provide a substantial added benefit. Each roof has 50 $m^2$ available for PV panels. This yields a total of 2400 $m^2$ with PV panels distributed on 48 households.

Equation 4 is the equation used to calculate power production. Since the NMG is in a bound geographical area, it is assumed that all the areas in the NMG have the same solar irradiance. A plot of the solar irradiance can also be seen in Section 3.3.2 in Figure 7.

### 3.6.3 MG3 Energy Storage System

In the residential area, it is not as easy as in the OB and hospital to scale the system for high-power rapid charging. The households in the residential area are more distributed and closely interconnected to the distribution grid. It is assumed that all the households in the NMG have three-phase wiring and 32 amperes (A) fuse. This enables all households to draw or deliver 22 kW.

A summary of the data and assumptions is seen in Table 7.

**Table 7:** *Summary of data and calculation in the ESS in MG3.*

| | **07:00-08:00** | **08:00-15:00** | **15:00-16:00** | **16:00-17:00** | **Outside office hours** | **Assumptions** |
|---|---|---|---|---|---|---|
| Percentage of homes with residents present | 50 % | 7 % | 50 % | 80 % | 100 % | 50 % is still at home between 07.00-08.00, 5 % from 08.00-15.00, 50 % from 15:00-16:00 and 80 % from 16.00-17.00. After these hours, all households are occupied |
| Number of homes with residents present | 30 | 4 | 30 | 48 | 60 | Total number of households are 60. |
| Number of EVs | 12 | 2 | 12 | 20 | 24 | 80.9 % uses cars as transport to work [41], whereas 50 % have EVs |
| Total capacity | 960 kWh | 160 kWh | 960 kWh | 1600 kWh | 1920 kWh | Average capacity in an EV is 80 kWh [43]. |
| Accessible capacity | 768 kWh | 128 kWh | 768 kWh | 1280 kWh | 1536 kWh | Batteries are only utilized between 10 % and 90 % |
| Maximum power delivery | 264 kW | 44 kW | 264 kW | 440 kW | 528 kW | Maximum power delivery is 22 kW for one EV |

A plot of the total capacity, accessible capacity and maximum charge/discharge rates is seen in Figure 13.

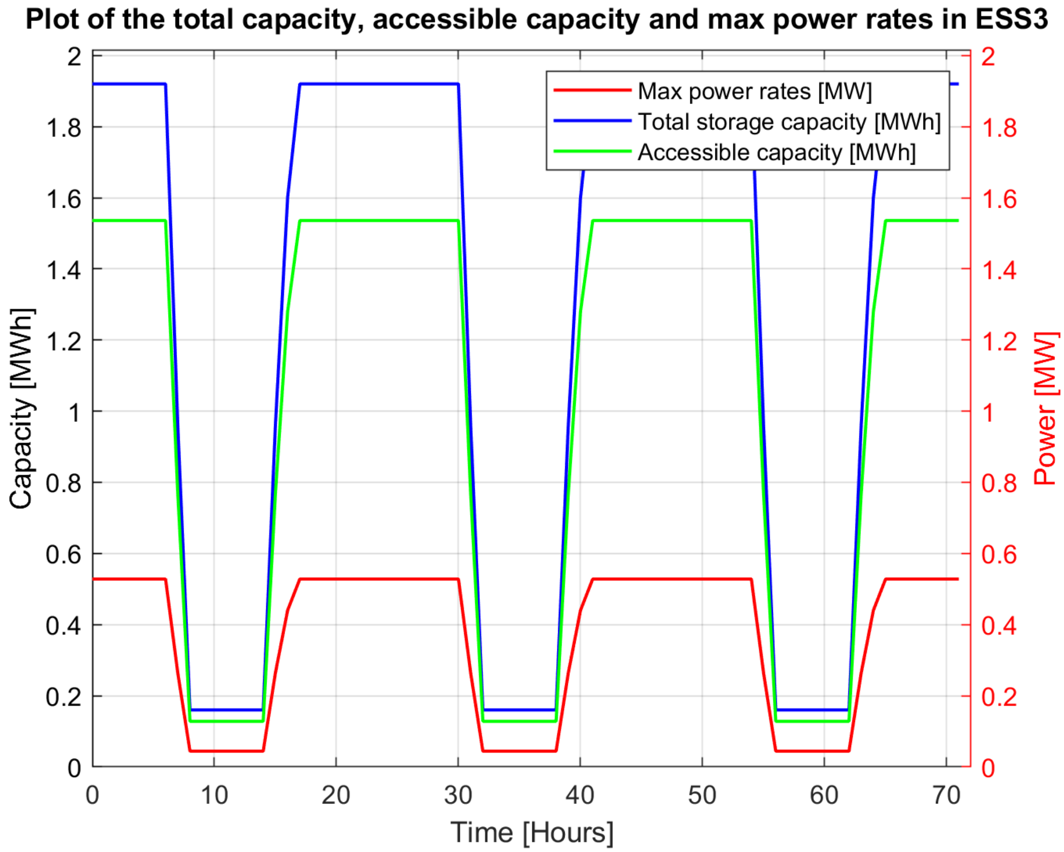


**Figure 13:** *Plot of the total storage capacity, available capacity, and maximum charge/discharge rates in ESS3.*

## 3.7 Summary and Comparison of the Data in the three MGs

This section presents a comparison of the hourly load curves as well as the capacities and charge/discharge rates in the MGs.

Figure 14 presents the load curves from MG1, MG2, and MG3.

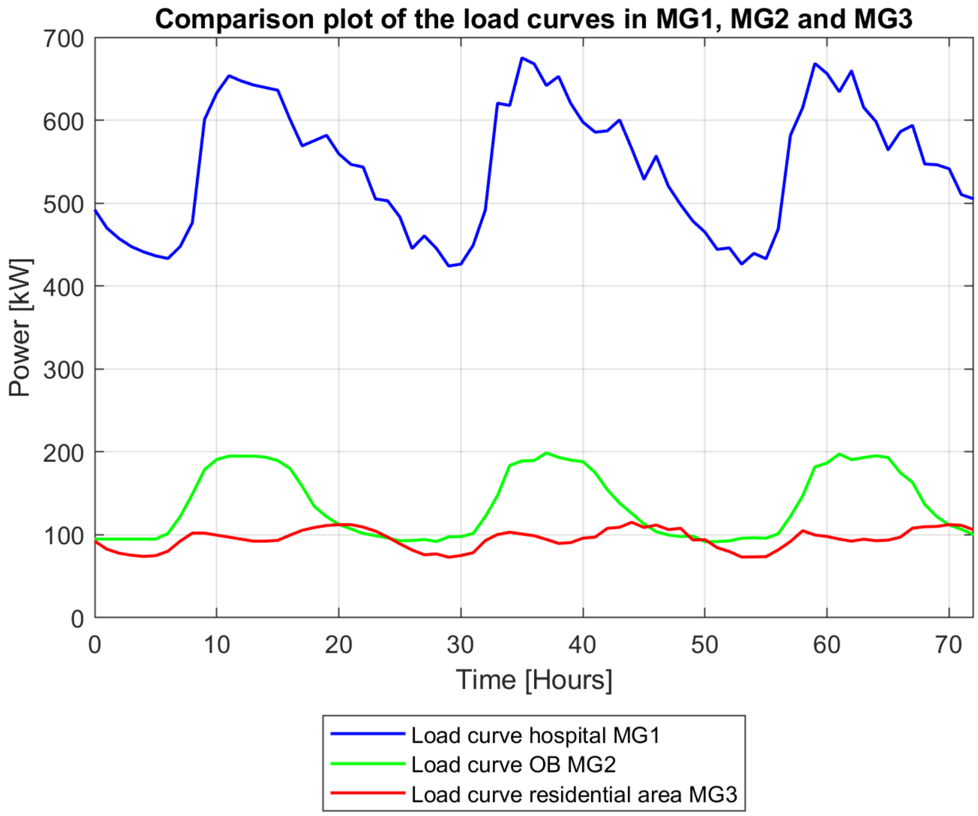


**Figure 14:** *Plot of the load curves in MG1, MG2 and MG3.*

As one can see from Figure 14, the hospital in MG1 had a significantly higher load demand compared to MG2 and MG3. The load demand in MG1 is about twice as high as MG2 and MG3 combined, underlining the high energy consumption in hospitals. One can also observe that while the hospital in MG1 and the OB in MG2 had large fluctuation between daytime and nighttime, this was not as prominent in the residential area in MG3. Figure 15 presents the total capacity, accessible capacity, and maximum charge/discharge rates in the MGs.

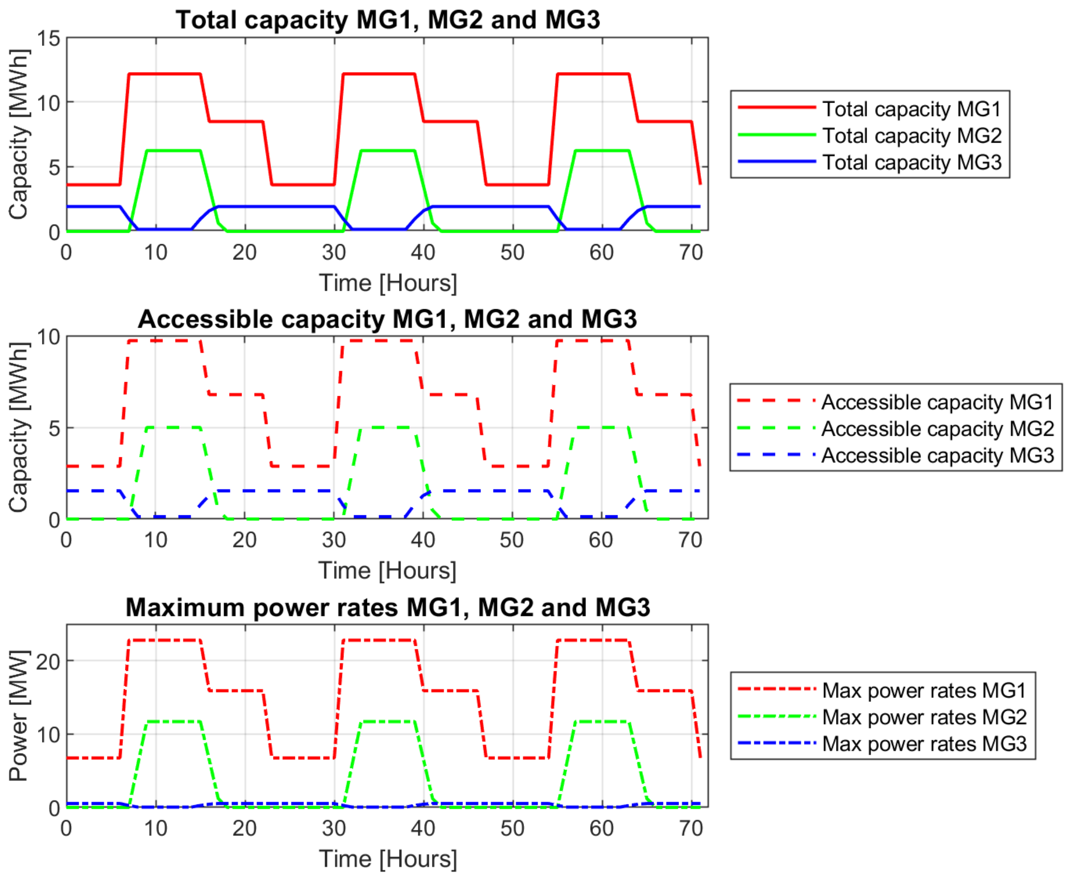


**Figure 15:** *Plot of the total capacity, accessible capacity, and maximum power rates in MG1, MG2, and MG3.*

MG1 carried the highest storage capacities and power rates, followed by MG2 and MG3. One also notices that while the values are high for MG1 and MG2 during daytime, the opposite is true for MG3. This is a natural consequence of the fact that MG1 and MG2 contain workplaces, while MG3 is a residential area.

## 3.8 Simulation Scenarios

Three simulation scenarios were created to test how the model responded under different conditions. The following subsections provide an overview of the three simulation scenarios.

### 3.8.1 Scenario 1 - Grid-Connected

In the first scenario, the NMG is grid-connected. In this operation mode, the power is free to flow in all directions, both between the NMG and grid and also inside the NMG between the MGs. This is considered the normal operation mode.

### 3.8.2 Scenario 2 - Grid Failure - Islanded Mode

The second scenario is presented as a comparison scenario. This scenario will represent the more traditional MG usage with islanded MGs during a power failure. In this scenario, a grid failure has resulted in the NMG disconnecting from the grid. In addition to this, the MGs are disconnected from each other. This makes all three MG operate in islanded mode.

### 3.8.3 Scenario 3 - Grid Failure - NMG Mode

In the third scenario, a grid failure has also resulted in the NMG disconnecting from the grid. But the MGs are interconnected with each other and have power exchanges between them. As the hospital is defined as a critical load, this load is prioritized.

## 3.9 Choice of Modeling Software

Simulink was chosen as the most suitable software program to create and perform the simulation in. Simulink is a simulation and modeling software tool developed by MathWorks. It is based on graphical block diagramming and allows users to simulate the behavior of their models and analyze their performance. Since Simulink is integrated with MATLAB, one can share data between the two seamlessly. This feature makes data from Simulink easy to analyze, and one can write custom blocks in Simulink as MATLAB code.

# 4 Results

This chapter will present the results from the three simulation scenarios. The results will focus on the power flow between the MGs and the power flow between the NMG and the utility grid.

## 4.1 Scenario 1 - NMG is Grid-Connected

This section presents the results from the first simulation scenario where the NMG is grid-connected.

### 4.1.1 Power Flow

Power flow is the main energy variable in this thesis. Figure 16 shows the power flow in all three MGs. Positive values indicate that a component works as a power source, while negative values indicate that a component works as a power sink. It is worth noting that the grid variable is not necessary to or from the utility grid, but power flow in or out of the respective MG.

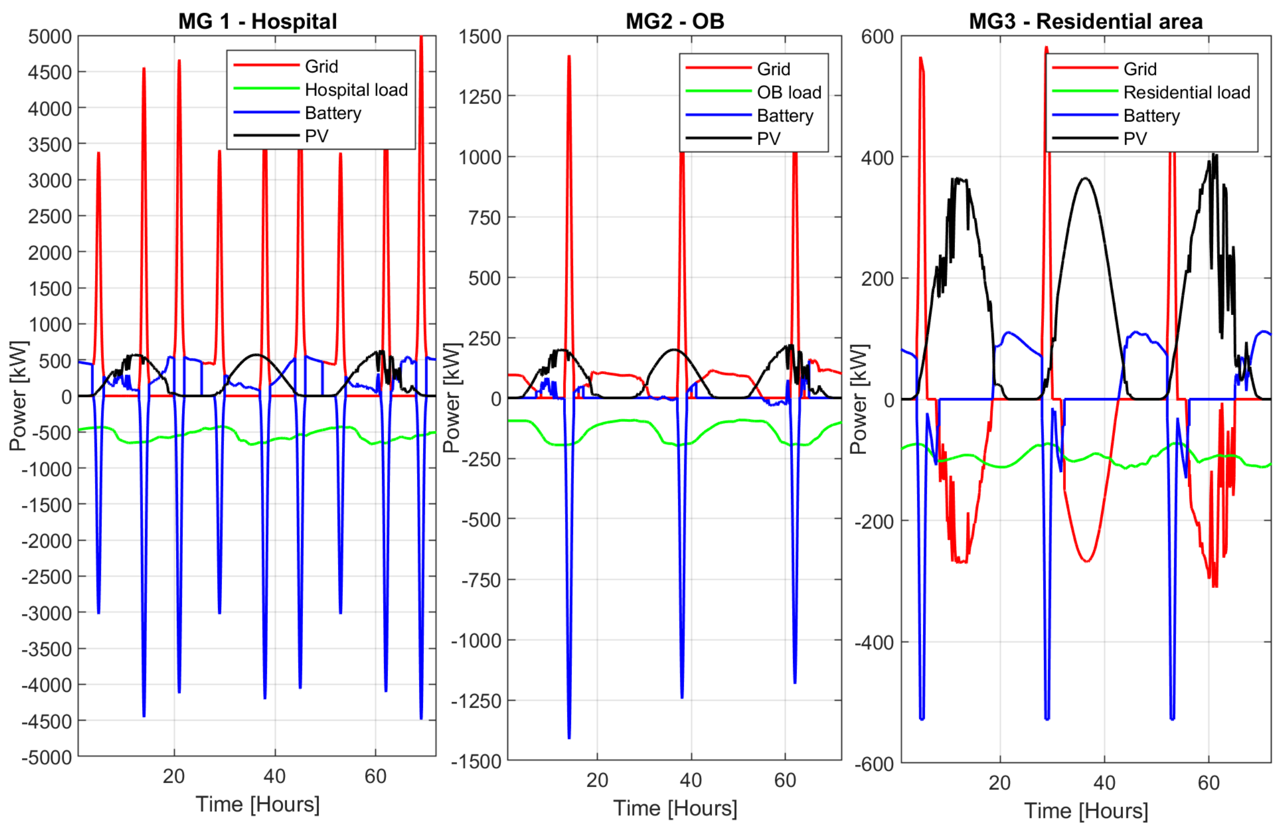


**Figure 16:** *Power flow in the MGs in Scenario 1.*

The charging of EVs is very dominant as this demands a lot of power in a short time span. The charging peaks are especially noticeable in MG1 because of the charging pattern involving three charges each day, unlike the OB and residential area where charging occurs once daily. The large storage capacity in MG1 necessitated by the numerous employees, further accentuates this. At times during scheduled charging, the grid also has to supply the variable load in the MG with power if this is not supplied by PV production.

Looking closer at the battery power, one can see that the battery balances the differences between the PV production and the load consumption, except during scheduled charge or when the power from the battery is zero. Zero battery power is caused by the battery being at either of its SoC limits. The power equilibrium achieved by the battery leads to a situation where the power drawn from the grid is effectively zero.

Another noticeable difference between the MGs is that the charging peaks in MG3 are less prominent than in MG1 and MG2. This is caused by the fact that while MG1 and MG2 have charge/discharge rates of 150 kW for each EV, MG3 is limited to 22 kW.

### 4.1.2 Battery Performance

The component bringing the most uncertainty to the system and the most variable and dynamic one is the battery storage from the EVs. The behavior of the battery is affected by several variables, such as capacity, max power delivery, and SoC. Figure 17 shows how these variables change throughout the three days of simulation. All the SoCs have been put inside a single plot due to the difference in the order of magnitude compared to the other variables. In the power, capacity, and energy plots, one can read the energy and capacity values on the left y-axis and the power values on the right y-axis. Positive power indicates discharging, i.e. power flow from the battery, while negative power values indicate charging, i.e. power flow to the battery.

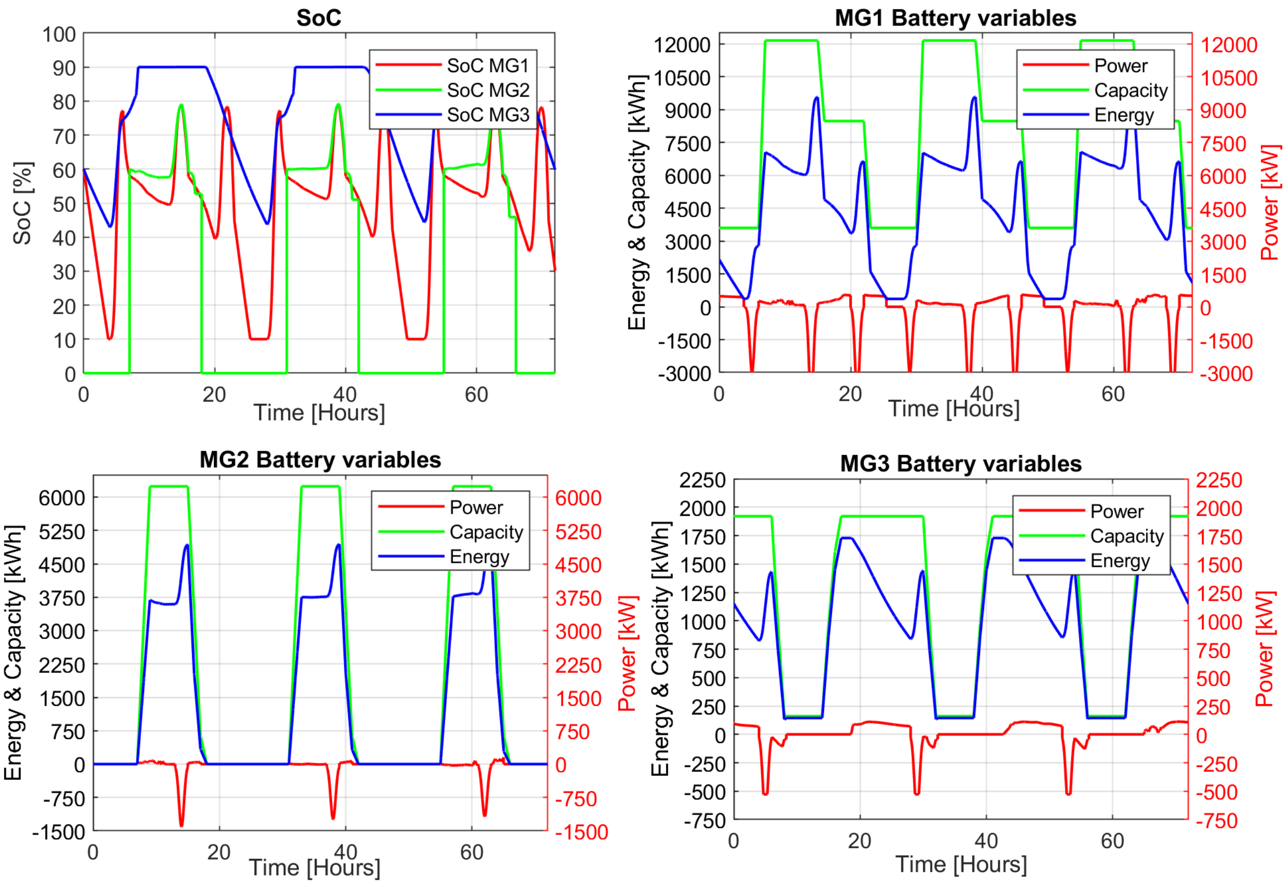


**Figure 17:** *Battery performance of Scenario 1.*

In the SoC plot, one can clearly see how the batteries charge and discharge during the day. The zero SoC for MG2 should not be mistaken for an empty battery but is zero because of the lack of battery. Outside office hours in the OB, there are no EVs available, resulting in zero capacity, zero energy, and, consequently, zero SoC.

Another interesting observation is that the only MG where the battery is fully discharged and reaches its minimum SoC is MG1. This happens in the early morning during the night shift at the hospital and lasts about 1.5 hours. This repeats again on day three. This does not happen on the first day because the simulation starts at 00:00, while the night shift starts at 22:00. Consequently, the EVs used during the night shift miss out on two hours of discharge time.

One should also notice that the energy increase or decrease could be a result of two mechanisms. One is the fact that EVs are arriving or leaving, which adds to or subtracts their energy from the aggregated energy level. This creates big linear increases or decreases that coincide with the capacity decrease or increase. The other mechanism is the charging or discharging of the batteries. This typically creates less steep and more variable changes in the energy amount in the batteries.

### 4.1.3 Grid Power and Energy

As the NMG is connected to the utility grid and the MGs are interconnected to each other in Scenario 1, it is interesting to look at how much power is drawn from or delivered to the utility grid and the power flow in and out of the individual MGs. The plot in Figure 18 shows the power flow from each MG and the utility grid. Positive values indicate power flow to the MGs, while negative is from the MGs. For the utility grid, this translates to power flow from the utility grid during positive values and power flow to the utility grid during negative values.

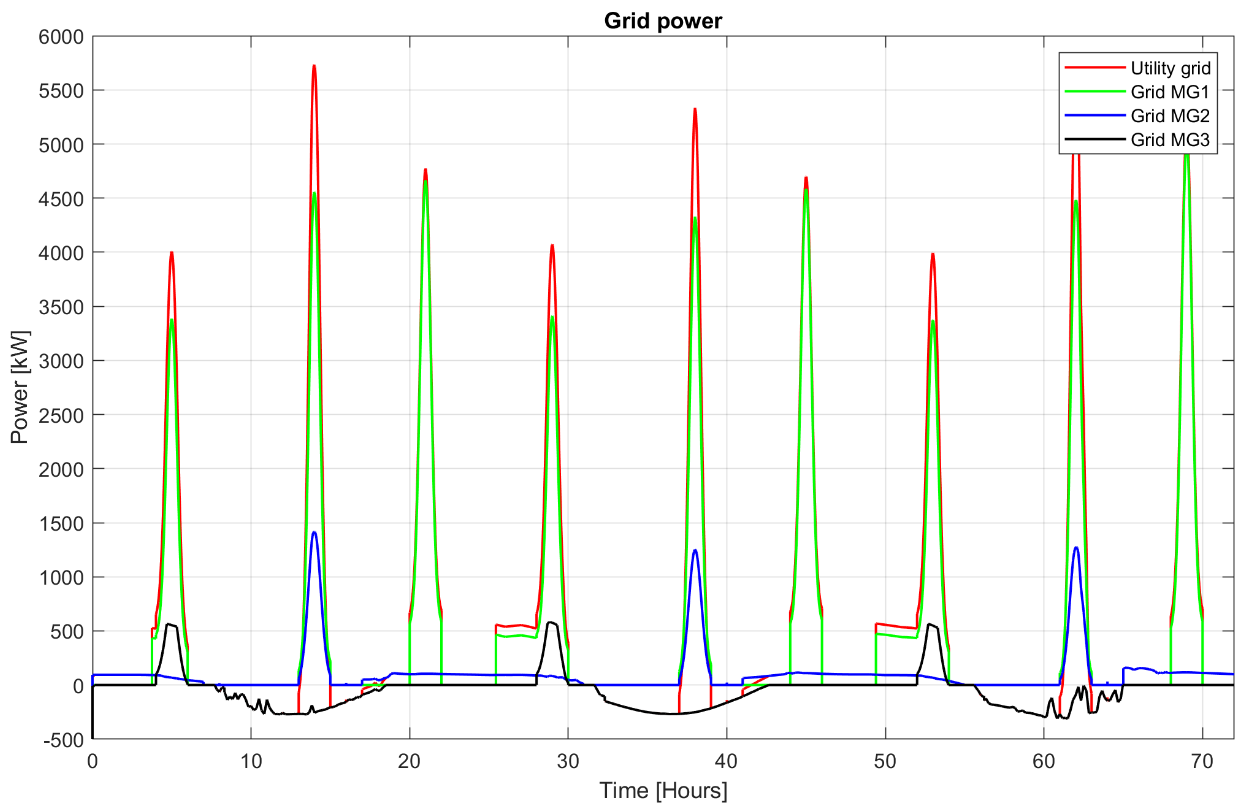


**Figure 18:** *Power flow between the MGs and the utility grid.*

In the incoming power flow to the MGs, one can not say for sure if this power is drawn from the utility grid or is coming from an MG in power surplus. Despite this, one can see a clear connection between the charging times and the power drawn from the utility grid. This is because there is not enough power available in the other MGs to support the charging power peaks, maybe unless one would draw power from one MG battery to another.

A summarization of the energy usage from the utility grid and in or out of each MG is shown in Table 8. Row one shows the net energy consumption for the utility grid and all the MGs. Row two and three distinctly differentiate between energy import and energy export. The duration of power flow in the grid cables is represented in the fourth and fifth rows.

**Table 8:** *Grid reliance during the three days of simulation.*

| | **Utility Grid** | **MG1** | **MG2** | **MG3** |
|---|---|---|---|---|
| Net energy | 41666 kWh | 37468 kWh | 7718 kWh | -3529 kWh |
| Energy imported | 4131 kWh | 37468 kWh | 7718 kWh | 2052 kWh |
| Energy exported | -45797 kWh | 0 kWh | 0 kWh | -5580 kWh |
| Time connected to grid | - | 33.5 % | 66.7 % | 51.6 % |
| Time NMG connected to utility grid | 96.5 % | - | - | - |

The time the MGs can operate self-sufficient without shedding is generally high. MG1 has the lowest total time connected to the grid, with 33.5 % translating to 24 out of the total 72 hours. Followed by MG3 with 51.6 % and lastly MG2 with 66.7 %. The high grid reliance in MG2 is likely a result of a lack of battery capacity outside office hours, making it entirely reliant on the grid during these hours. But even with relatively low grid dependency for the individual MGs, one can see that because of the variable nature between the MGs, the total time with power flow through the utility grid is high at 96.5 %.

## 4.2 Scenario 2 - Grid Failure - Islanded operation

This section presents the results from Scenario 2 with full grid failure. In this scenario, a power blackout occurs at simulation time 28800s, corresponding to 08:00 in the morning on the initial day. This power failure results in disconnection from the utility grid and between the MGs. Consequently, all the MGs operate in islanded mode with the battery as the voltage source. In this scenario, load shedding and generation shedding are also implemented.

### 4.2.1 Power Flow

The power flow from Scenario 2 is shown in Figure 19.

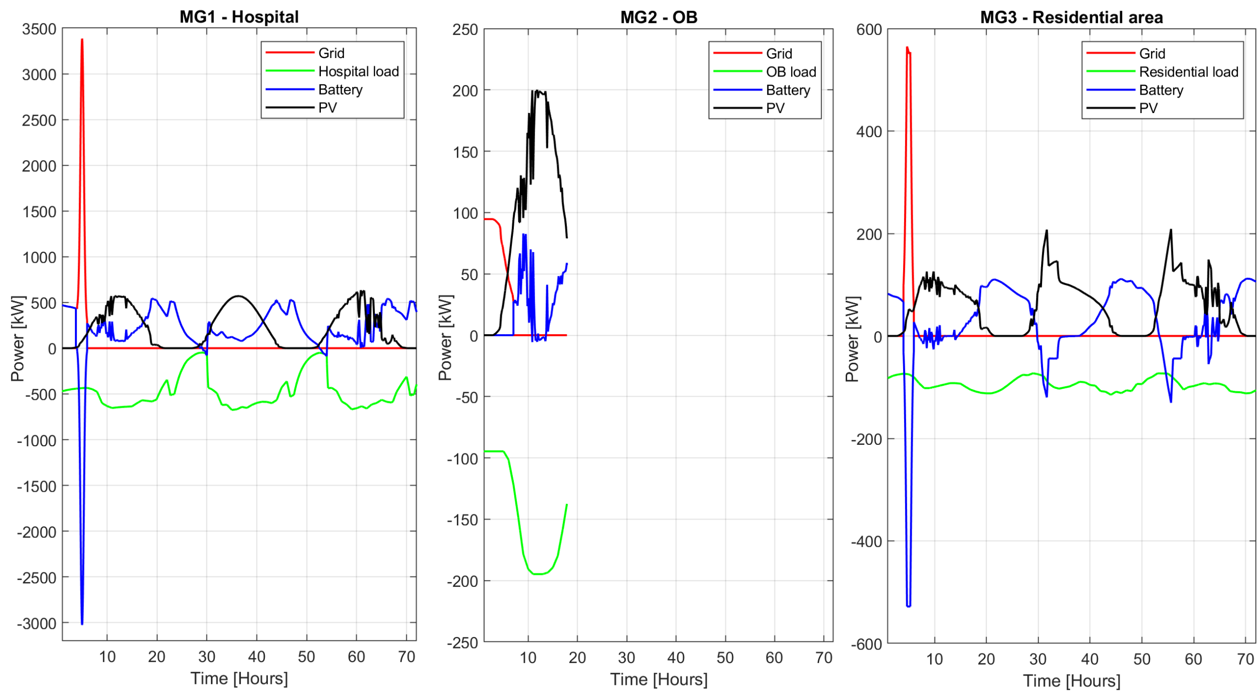


**Figure 19:** *Power flow in the MGs in Scenario 2.*

One immediately notices that MG2 experienced a failure at 18:00 on the initial day. This was as one would expect since the capacity from 18 is 0 kWh until the next day. With no battery, there is no way to balance out the imbalance between the PV production and the load consumption and the MG has no voltage source, resulting in a blackout.

Further, one can see that there is only one charge peak in MG1 and MG3. This charge peak was before the blackout. After the blackout, the batteries operate in voltage mode and the power flow to or from the batteries can no longer be manually controlled, and scheduled charging is not possible. The battery will now only deliver or consume power to balance out the imbalances inside the MG.

### 4.2.2 Battery Performance

Battery variables are shown in Figure 20. In the power, capacity, and energy plots, one can read the energy and capacity values on the left y-axis and the power values on the right y-axis. Positive power indicates discharging, i.e., power flow from the battery, while negative power values indicate charging, i.e., power flow to the battery.

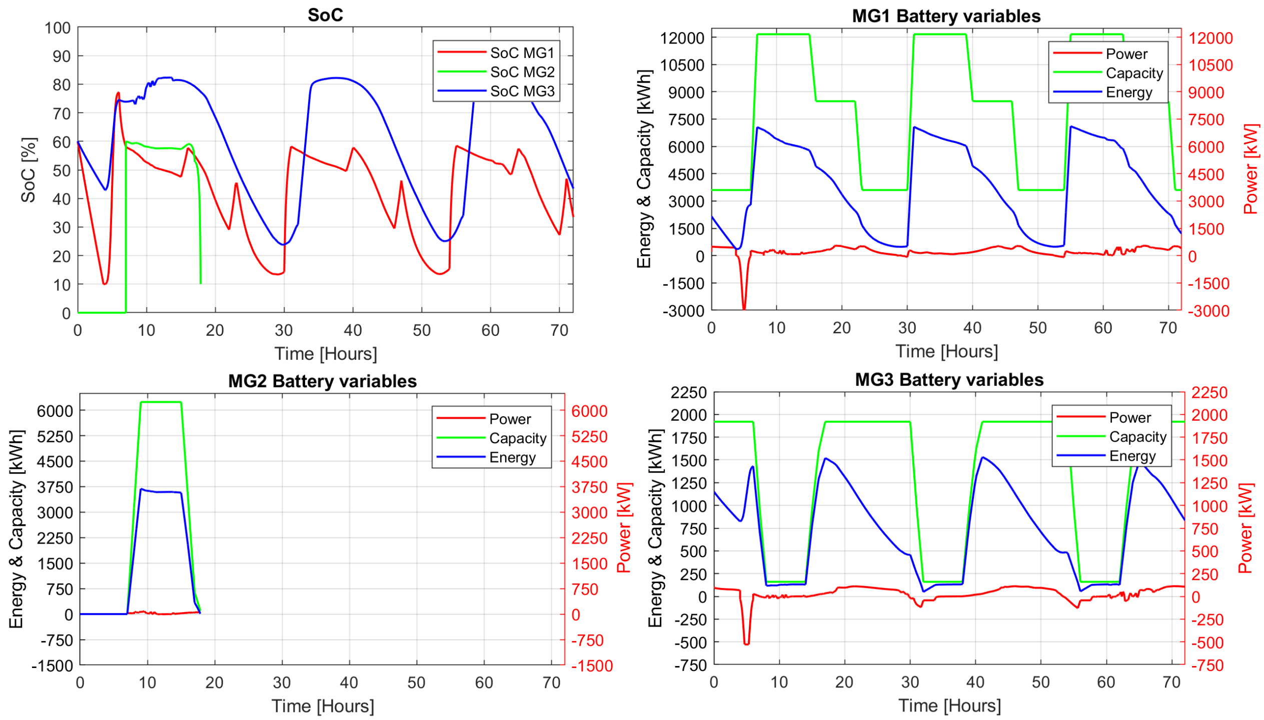


**Figure 20:** *Battery performance of Scenario 2.*

In this scenario, it is important that the SoC does not reach any of its limits. This would result in a situation where the battery is not able to store more excessive energy or deliver power to balance out the power imbalance between consumption and production, resulting in a potential blackout in the MG. And as one can see, neither MG1 nor MG3 reaches any of its limits. MG1 reaches a minimum value of about 14 %, while MG3 reaches a maximum SoC of just over 80 %. In MG2 on the other hand, the SoC reaches 0 % outside of office hours. This is because there are no EVs in the OB outside office hours, effectively resulting in a power blackout.

The sudden increase in SoC occurring three times each day in MG1 is a result of shift changes, where EVs with lower SoC leaves and EVs with an SoC of 60 % arrive. The same mechanism occurs once a day in MG3. It might appear like the SoC of the EVs arriving in MG1 at the night shift, namely at hours 22, 46, and 70 have a lower than 60 % SoC. However, this is a result of the batteries in the already-arrived EVs being discharged during the one-hour linear arrival period of the vehicles. This effect happens during all the shift changes but is more noticeable at the night shift because of the smaller total capacity combined with significant power demand, resulting in a high discharge rate from the batteries.

### 4.2.3 Generation Shedding and Load Shedding

The results show that as opposed to Scenario 1, where no shed was needed, now shedding is crucial.

Figure 21 shows the significant shedding values needed to keep balance in MG1 and MG3. The values represent how much the load or power generation decreases, matching the shed's percentage. For instance, a load shed of 80 % results in a load decrease by the same percentage.

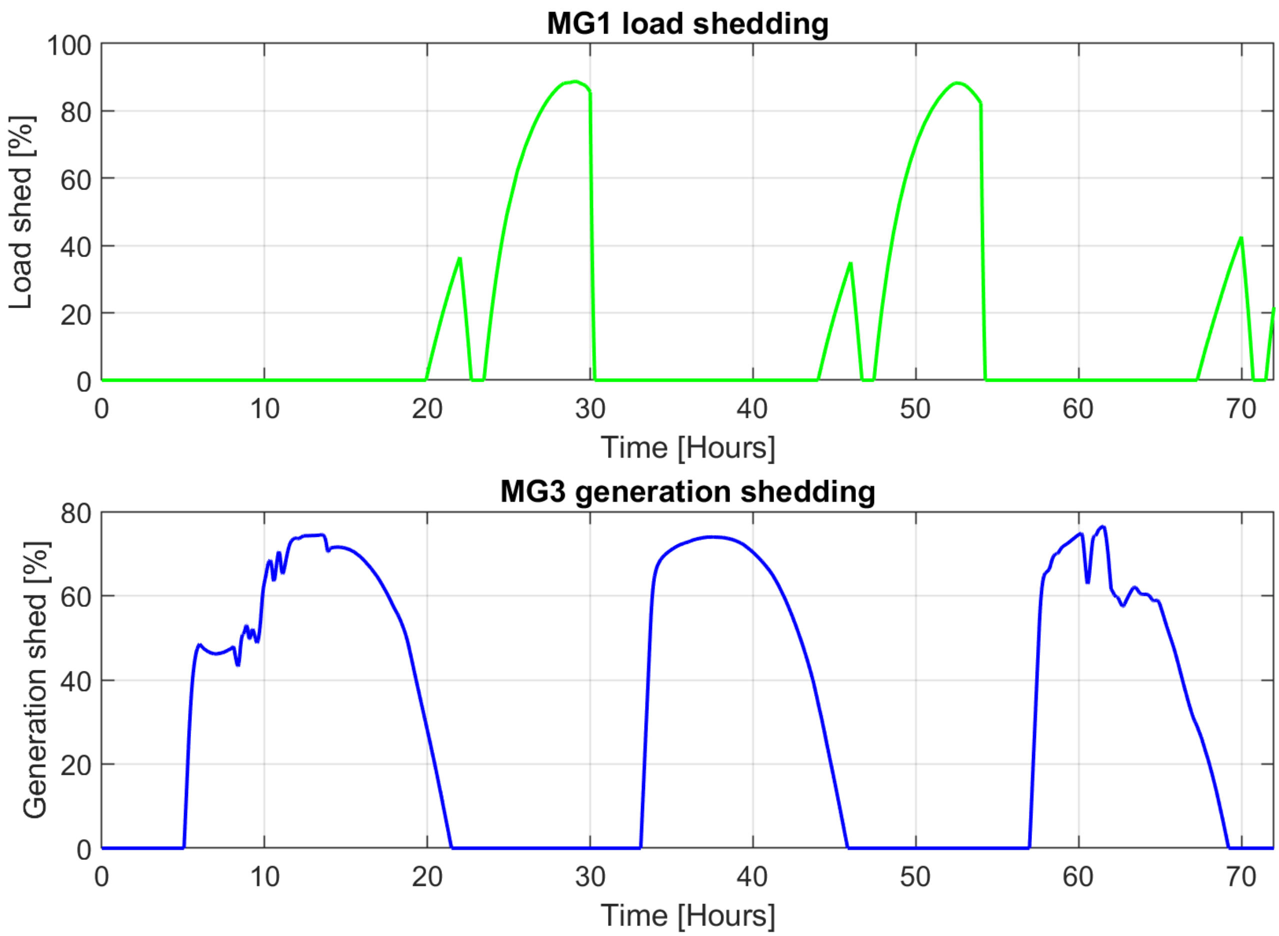


**Figure 21:** *Generation shedding for MG3 and load shedding for MG1 in Scenario 2.*

Load shedding is the most crucial aspect to consider as it directly influences the capacity to maintain continuous operation for the consumer. A big load shedding indicates that the battery is closing in on its lower SoC limit, therefore having to shed load. Contrary, a big generation shed indicates that the battery is getting close to its maximum SoC and need to shed generation. One variable one should look closely at is the amount of time shedding was needed. Table 9 shows the duration of load shedding in each MG.

**Table 9:** *Overview of shedding values for simulation Scenario 2 in islanded mode.*

| | **MG1** | **MG2** | **MG3** |
|---|---|---|---|
| Time with load shedding | 31.7 % | 0 % | 0 % |
| Time with generation shedding | 0 % | 0 % | 57.3 % |
| Time with power supply below critical limit (40 %) | 13.0 % | N/R[1] | N/R |

As one can read from the table above, load shedding was active 31.7 % of the time, and 13.0 % of the time, the load shedding was larger than 40 %. In MG3 generation shedding was applied

[1]Not relevant as the 40 % critical load demand limit only apply to MG1.

57.3 % of the time, and MG2 used no shedding at all. The reason for MG2 not using shedding was because of the failure at 18:00 initial day.

## 4.3 Scenario 3 - Grid Failure - NMG Operation

In this scenario, a power failure also starts at 08:00 initial day. But in this scenario, only the utility grid is disconnected. Meaning the MGs are still interconnected in the NMG. Since the hospital contains critical loads, power flow to the hospital will be prioritized. Because the grid is now experiencing a power failure, the charging of the EVs is removed as this is a highly power-demanding process. After the power failure, the battery in MG1 operates as a voltage source.

### 4.3.1 Power Flow

The power flows from Scenario 3 are seen in Figure 22. As before, positive values indicate that a component works as a power source to the respective MG, while negative values indicate that a component works as a power sink.

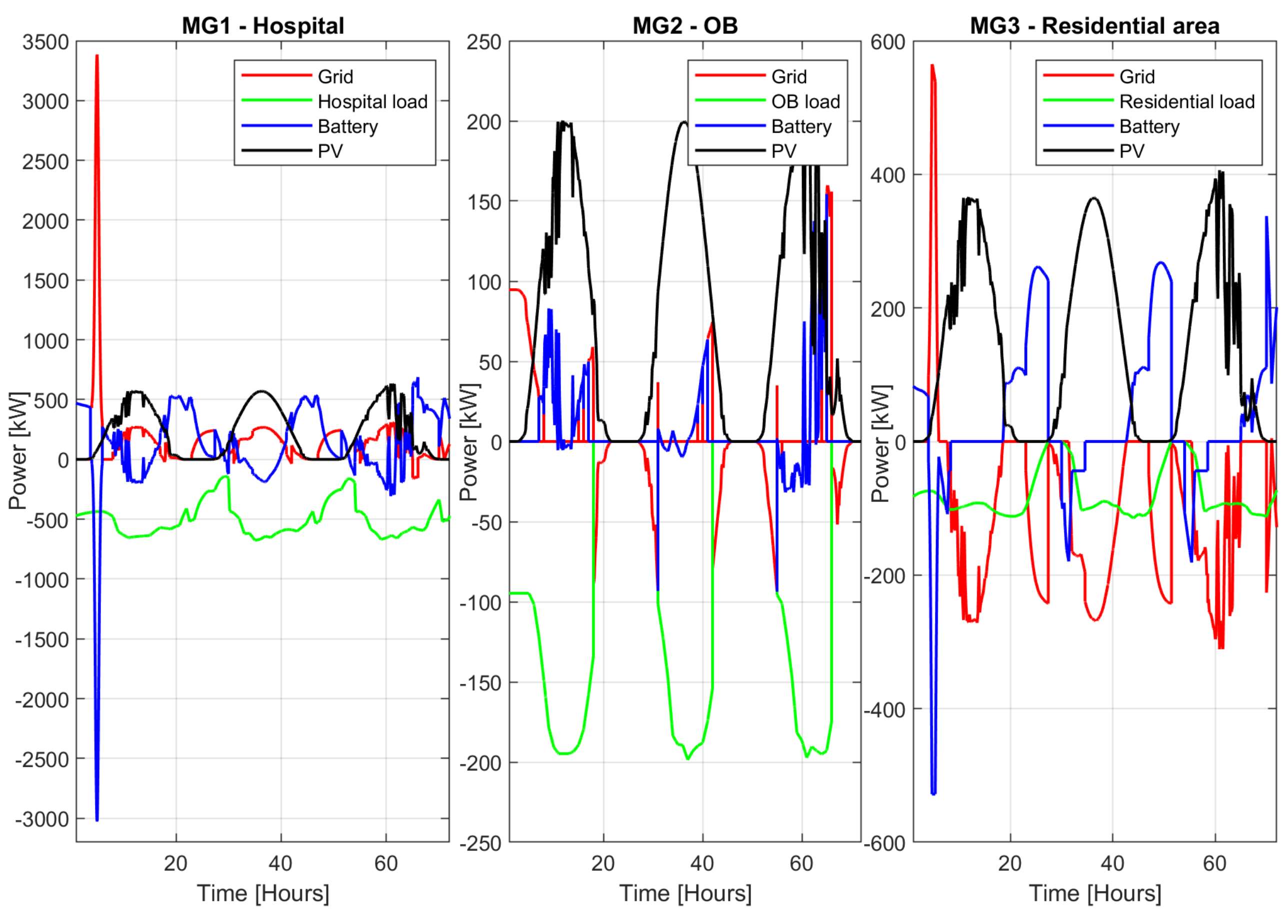


**Figure 22:** *Power flow in the MGs in Scenario 3.*

The power flow is similar to scenarios 1 and 2 until the power failure occurs at 08:00. MG1 and MG3 charge once before the failure, but since MG2 has its first charge at 13:00, it doesn't get the opportunity to recharge before the power failure occurs. Since power flow to MG1 was prioritized, and MG3 had significant time in power surplus, power was shared from MG3 to MG1. One can see this power transfer in the power peaks in MG3 at hours 22-30 and 46-54 where the battery was delivering more than 200 kW, and since there was a very low load in MG3 at this time as a result of load shedding, most of this power was sent to MG1. One can see this both because the grid in MG3 was exporting roughly the same amount as the battery delivers, and MG1 had positive power peaks at the same times in the same magnitude. This effect is harder to see in MG1 because of the much rougher y-axis scale. MG2 was only in operation during the daytime as the battery capacity was zero after office hours. And since all power flow was prioritized to MG1, no power was shared from the other MGs to MG2.

### 4.3.2 Battery Performance

This section focuses on the battery variables SoC, capacity, energy, and power flow for the batteries in the NMG. The battery in MG1 was switched to voltage mode following the utility grid's power failure at 08:00 on the initial day. Figure 23 illustrates the mentioned variables for all batteries.

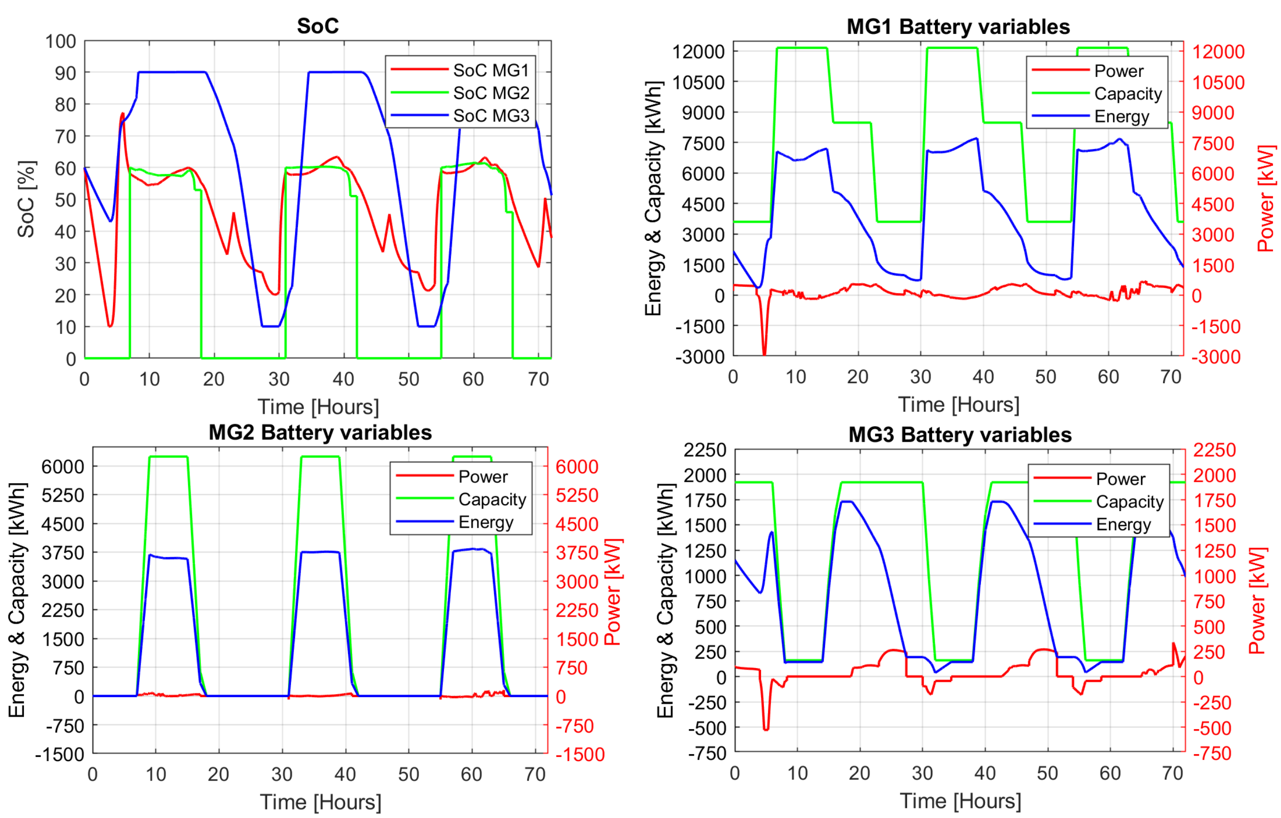


**Figure 23:** *Battery performance of Scenario 3.*

As one can see the SoC in MG3 is once again at its maximum during daytime. This time however the excess production in MG3 did not go to the utility grid but was used to charge the battery in MG1. After the sun sets, the SoC in MG3 quickly drops to its minimum value of 10 %. This is in contrast to what we have seen before and occurs since at the same time while there is no power production and significant load, MG3 also supplies MG1 with significant power with the help of Equation 3, the power-sharing algorithm presented in Section 3.2.1. This is to make sure the MG1 battery does not reach its minimum level, causing the hospital to MG1 to experience a complete blackout. As one can see MG1 reached a minimum of 20 % SoC during the power failure, higher than in both the other scenarios. As before MG2 had zero battery capacity and since it was not prioritized, it had no power supply during nighttime. Early the next morning when the employees arrived at work with 60 % SoC batteries, MG2 was up and running again.

### 4.3.3 Load Shedding

No instance of maximum SoC in all batteries alongside a power surplus in the NMG was observed in Scenario 3, thereby eliminating the need for generation shedding. Load shedding on the other hand was very important to keep the power balance during nighttime when there was no PV production. In Figure 24 below one can see the use of load shedding in all three MGs. A higher percentage on the y-axis indicates a higher amount of load shedding.

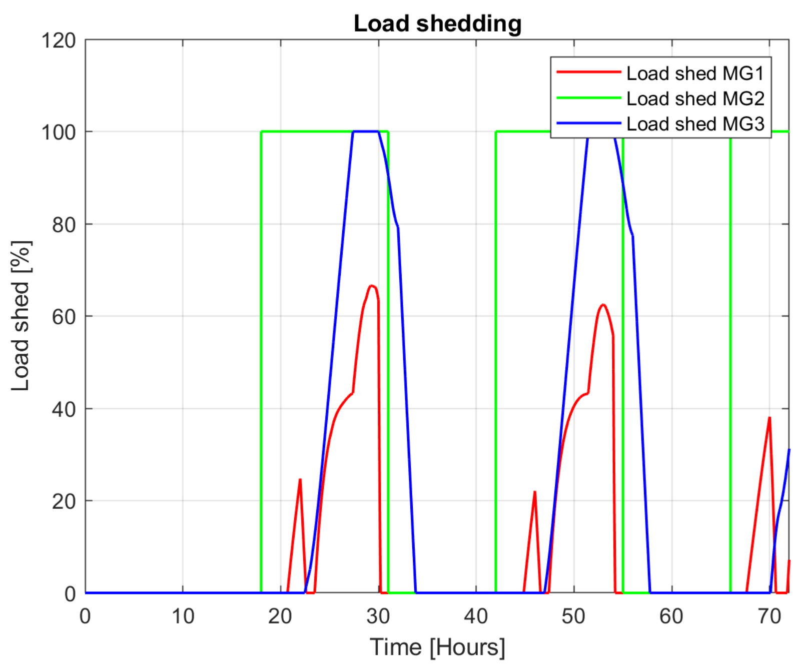


**Figure 24:** *Load shedding in Scenario 3.*

As one can see from the plot above, load shedding was used in all MGs. In MG2 load shedding was at 100 % during nighttime as a result of the lack of any power source in the MG. MG3 also reached times with 100 % load shedding. Meaning there were times when no loads were supplied with power in MG3 as well. In MG1 on the other hand, the MG with the critical infrastructure, the highest load shedding was 66.6 % and only lasted for a very short period. This represents a significant shift from Scenario 2, where the highest level of load shedding was 88.7 %. A shed of 66.6 % leaves 33.4 % of the electrical load remaining. This implies that at the worst point during the simulation, the load shedding was just 6.6 % above the level of critical load. In Table 10 one can see an overview of the amount of shedding and shedding times in the different MGs.

**Table 10:** *Overview over shedding values for simulation Scenario 3.*

| | MG1 | MG2 | MG3 |
|---|---|---|---|
| Time with load shedding | 27.8 % | 44.6 % | 33.1 % |
| Time with generation shedding | 0 % | 0 % | 0 % |
| Time with power supply below the critical limit (40 %) | 4.0 % | N/R[2] | N/R |
| Maximum shedding value | 66.6 % | 100 % | 100 % |

## 4.4 Summary and Comparison Between the Scenarios

As it was decided that the NMG should prioritize power flow to the hospital's critical loads in MG1, this is what will be the main focus of this summary.

The main objective was to supply the hospital with enough power to operate its critical loads, defined as 40 % of the total loads. Table 11 lists the durations of load shedding and the maximum load shed value for all scenarios, while Table 12 lists the differences across the scenarios.

**Table 11:** *Duration and maximum load shedding values for all scenarios.*

**Load shedding values for all scenarios**

| Scenario | MG | Seconds | Fraction | Seconds below 40 % | Fraction below 40 % | Max shed value |
|---|---|---|---|---|---|---|
| 1 | 1 | 0 | 0 | 0 | 0 % | 0 |
| | 2 | 0 | 0 | N/R[3] | N/R | 0 |
| | 3 | 0 | 0 | N/R | N/R | 0 |
| 2 | 1 | 82166 | 31.7 % | 33696 | 13.0 % | 88.7 % |
| | 2 | 0 | 0 | N/R | N/R | 0 % |
| | 3 | 0 | 0 | N/R | N/R | 0 % |
| 3 | 1 | 72058 | 27.8 % | 10369 | 4.0 % | 66.6 % |
| | 2 | 115603 | 44.6 % | N/R | N/R | 100 % |
| | 3 | 85795 | 33.1 % | N/R | N/R | 100 % |

**Table 12:** *Changes between Scenario 2 and Scenario 3 in load shedding.*

**Change in load shedding from Scenario 2 to Scenario 3**

| MG | Seconds | Relative change | Seconds below 40 % | Relative change below 40 % | Max value |
|---|---|---|---|---|---|
| 1 | - 10108 | - 12.3 % | - 23327 | - 69.2 % | - 22.1 % |
| 2 | + 115603 | Undefined[4] | N/R | N/R | + 100 % |
| 3 | + 85795 | Undefined | N/R | N/R | + 100 % |

In Scenario 1, no load shedding was needed as the NMG, and hence all MGs had free access to power from the utility grid. In both Scenario 2 and Scenario 3 where the utility grid was disconnected, the load shedding went above the 60 % load shed limit in MG1. But while it exceeded this limit by 28.7 % in Scenario 2, it only exceeded the limit by 6.6 % in Scenario 3. The amount of time with the load shedding above this limit was also substantially decreased. From 13.0 % in Scenario 2 to 4.0 % in Scenario 3. In seconds this corresponds to 33696 seconds in Scenario 2 and 10368 seconds in Scenario 3, a decrease of 69.2 %. What these load-shedding values correspond

[2] N/R refers to Not Relevant as the 40 % power supply limit only applies to MG1.

[3] Not Relevant as the 40 % power supply limit only applies på MG1.

[4] The relative change is undefined because the initial value was 0.

to in energy consumption is shown in Table 13. Note that the energy consumption values do not consider the load demand of the batteries during charging, only the consumption of the previously defined variable loads in each MG. Scenario 1 is used as a reference for the changes as there was no load shedding in this scenario.

**Table 13:** *Energy load consumption for all scenarios in every MG.*

| Scenario | MG | Energy consumption | Changes relative to Scenario 1 |
|---|---|---|---|
| 1 | 1 | 39224 kWh | 0 kWh |
| | 2 | 9844 kWh | 0 kWh |
| | 3 | 6821 kWh | 0 kWh |
| 2 | 1 | 34152 kWh | - 5072 kWh |
| | 2 | 2613 kWh [5] | -7231 kWh [6] |
| | 3 | 6821 kWh | 0 kWh |
| 3 | 1 | 36082 kWh | - 3142 kWh |
| | 2 | 6377 kWh | - 3467 kWh |
| | 3 | 5605 kWh | - 1216 kWh |

When looking at the load consumption at the hospital in MG1, one can see that while the load consumption was reduced by 5072 kWh in Scenario 2, in Scenario 3, it was reduced by 3142 kWh. This means 1930 kWh more was supplied to the hospital loads in Scenario 3 compared to Scenario 2.

While load shedding applied to all MGs, generation shedding only applied to MG3 in Scenario 2. In this scenario, MG3 operated in islanded mode with a power surplus, resulting in generation being shed. The maximum generation shed value was 76.5 %, and the total time with generation shedding was 148576 seconds. Table 14 summarizes the generation shedding results.

**Table 14:** *Generation shedding in MG3 summarized. No other MGs applied generation shedding.*

| Scenario | MG | Seconds | Fraction | Max value | Energy production |
|---|---|---|---|---|---|
| 1 | 3 | 0 | 0 % | 0 % | 10150 kWh |
| 2 | 3 | 148576 | 58 % | 76.5 % | 4165 kWh |
| 3 | 3 | 0 | 0 % | 0 % | 10150 kWh |

As one can see from the table above, PV production was reduced by 5985 kWh or 59 % in Scenario 2 where generation shedding was applied. This can also be seen as an increase from Scenario 2 with islanded operation to Scenario 3 with NMG operation by 143.7 %.

[5] Since the simulation only covered 18 of the total 72 hours, this value is not a good representation of the energy used in this MG.

[6] Since the simulation only covered 18 of the total 72 hours, this value doesn't accurately represent the change from Scenario 1.

# 5 Discussion

Chapter 5 provides a discussion of the results from Chapter 4. The chapter begins with a discussion on resiliency and utilization of DERs, followed by a consideration of the use of EVs as ESS. The chapter concludes with a general discussion and an examination of the study's findings.

## 5.1 Resiliency

By operating in NMG mode, the hospital was supplied with more power, experienced less time with load shedding, and lowered the levels of load shedding applied. The load demand was, however, still below what was considered a critical threshold for a brief period. But, because it was only 6.6 % below in NMG operation, compared to 28.7 % in islanded mode, the hospital would still be able to maintain a significantly higher operational state.

Moreover, the power exchange from MG3 to MG1 in Scenario 3 led to an increase in the amount of load shedding required to maintain the energy balance in MG3 throughout the night. However, the power production in MG3 also increased during daytime. By examining the results from Table 13 and Table 14, it is evident that while the energy demand, and hence energy supply, decreased by 1216 kWh as a result of load shedding, the energy production simultaneously increased by 5985 kWh compared to Scenario 2 where the MG operated in islanded mode. This shows that by utilizing the power-sharing properties of the NMG, one could increase the utilization of the PV system and create a larger power surplus seen in the NMG as a whole.

Another advantage of the NMG operation mode compared to the islanded one is that in the NMG operation, only one battery must work as a voltage source, while in islanded mode every MG has to use their batteries as a voltage source. Operating just one of the three batteries in voltage mode enhances flexibility, as it provides improved control over the other two batteries that continue to operate in current mode.

## 5.2 EVs used as ESS

Implementing EVs as the only ESS by using V2G technology in an NMG showed possible by the thesis results. How the ESS is utilized in the NMG could be configured in many ways depending on operational mode, system specifications, and requirements. In this case study, it was decided that the EVs should balance out the power imbalance between the production and consumption inside each MG. This could in many ways not necessarily be the most optimal way to operate the MGs during normal operational mode, as this puts a lot of stress on the EV batteries and provides uncertainty to the EV owners of the current SoC of their vehicle. But since this case study was purely theoretical, and the EVs were a central component in the NMG one wanted to test the very extremes of the batteries. This thesis focuses on the technological possibilities in such projects, but by a realization of projects using EVs as ESS, economic compensations to EV owners for the battery degradation, reduced lifespan, and uncertainty about their EVs SoC should be considered.

Understanding that the main intent of EV owners is to charge their vehicle when connecting to a charger, one must ensure that the EVs have a higher SoC post-charge compared to pre-charge under normal operation. In this case study, it was assumed that the EVs arrive at 60 % SoC and leave with 80 %. This indirectly means that the EVs are taking energy from the MG, compared to a stationary battery where all energy used to charge the battery is discharged in the MG if one disregards losses. However, when the EVs arrive at the V2G charger connected to the NMG at 60 % SoC, they add energy to the NMG coming from outside the NMG. This addition of energy coming from outside the EVs adds flexibility to the NMG as it adds energy to the system, also outside of times with regular PV production.

One should also pay attention to the very high charge peaks in the power grid during scheduled EV charging in the normal operational mode. In Figure 18 one can see that during the biggest power peaks where all three MGs have scheduled charging at the same time, the peak power demand reaches 5.5 MW. This is a very high power transfer and could cause problems such as voltage drops or grid instability if the grid doesn't have a high enough transmission capacity.

### 5.2.1 EV Availability

During Scenario 2 and Scenario 3 where the utility grid had a power failure, the charging of the EVs was removed as this would be too power-intensive for the generation inside the NMG to handle. In addition, it would have significantly reduced the power available to the loads. The lack of charging again provokes the question of why the EV owners would connect to the chargers during these instances. During daytime with PV production, there might be a power surplus charging the EVs, but during nighttime, one would certainly have a power deficit discharging the EVs. Essentially, the EV owners are giving away energy they have already paid for.

As power failures often occur during crises, either man-made or natural disasters, the question regarding EV availability again arises. During such instances, it is likely to believe that the daily routines of the people connected to the NMG would change. This again creates uncertainty about how many EVs will be present at the chargers. Furthermore, looking at the results from Scenario 2 and Scenario 3, one can see that both in MG1 and MG3 the SoC of the batteries are very low at the end of their working day. This means they have discharged the energy they arrived with and have to leave work with a very low SoC. This can cause problems if they have a long commute home and contradicts the EV owners' purpose of charging their EVs.

Another consideration is that by utilizing EVs as the only ESS in the MGs, the storage capacity changes throughout the day. This carries both advantages and disadvantages. The advantage is that the storage capacity typically coincides with the needs. This is because high load periods often align with the times when EV owners are present at their workspace or home, resulting in a high storage capacity. The disadvantage is that outside of office hours at a workplace, the storage capacity is typically very low or even zero. This is a problem for an MG as it needs a battery to balance out the imbalance between production and consumption and a battery to work as a voltage source when the utility grid and other MGs are disconnected. A possible solution to this issue would be a combined ESS consisting of a stationary battery complemented by EVs. This way, one could always guarantee a minimum storage capacity and a voltage source.

## 5.3 General Discussion

The findings from this thesis have shown that interconnecting MGs in an NMG increases resilience, achieves a higher utilization of DERs, and implementing EVs as ESS in NMFs increases flexibility. To create a well-designed NMG, careful preparations and groundwork must be done.

This model was designed by first deciding how many and what kind of loads should be included, and later a literature search was conducted to find and examine realistic parameter values and data inputs. Due to this working approach, how the requirements and dimensions of the MGs would harmonize was unpredictable. As a consequence of this, MG2's role in the functioning of the NMG is relatively minor. Firstly, the load demand and PV production coincidentally balance each other out very well as seen in the power plots from all scenarios. This can be seen in Figure 16 or Figure 22 and is also reflected by the very minor changes in the battery's SoC during daytime seen in, e.g., Figure 23. This well-balanced energy production and consumption create very small power surpluses or power deficits, making the battery less important and reducing interaction with the other MGs. Secondly, MG2 has only EVs connected to chargers, and hence battery storage, during working hours from 07:00 to 18:00. These are also the hours with PV production and the times with the lowest need for power exchange in the NMG. During nighttime when the need for power exchange is evident, MG2 has nothing to contribute with. This is not ideal, and in this exact three-day simulation, MG2 could be omitted. To avoid such situations, one should do more groundwork and preparations to facilitate good coordination among the MGs in the NMG. Another consideration regarding MG2 and the lack of ESS outside office hours is the effect this has on the MG during nighttime. In Scenario 2 when all MGs were in islanded mode, MG2 had no battery to work as a voltage source causing the entire MG to crash outside office hours. In Scenario 3, the MG1 battery worked as the voltage source, but one still had to shed all loads in MG2 for it not to draw power from the prioritized MG1 battery.

Moreover, the NMG presented in this case study is heavily reliant on PV production as this is the only power production in the NMG. In a real-case scenario, this would be an issue on cloudy days or during winter. It was considered adding wind power as an additional power production to the MGs, but it was decided that since this is just an initial study focusing on the NMG operation and EVs, adding wind power would only increase the complexity of the model without adding substantial value to the results.

One should also remember that the simulated scenario is an extreme case to test the full capabilities of the NMG. In the simulated scenarios, the power blackout lasts for a total of 64 hours. This is extremely rare as consumers in Norway experience on average two longer interruptions per year, each typically lasting for about two hours [3]. The negative results should therefore not be generalized.

A final point to keep in mind is that the results of this thesis are very dependent on the constructed model created for the case study. Its components, parameters, variables, and data inputs substantially impact the results.

# 6 Conclusion

The master's thesis had three primary objectives. The main research question aimed to investigate how NMGs can improve resilience in the power grid, the second research question explored how NMGs can enhance the utilization of DERs and the third research question was how EVs could utilize V2G technology to work as ESSs in NMGs. These questions were explored by creating a Simulink model of an NMG consisting of three interconnected MGs. Three scenarios were simulated. One in normal operation where all breakers are connected, i.e. power flows freely between the NMG and utility grid, but also between the MGs. The second scenario involved a power failure, with the MGs operating in traditional islanded mode, where each MG is isolated. The third scenario involved a power failure in the utility grid, with the MGs operating in NMG operation and the breakers between the MGs connected. During power failure, power flow to the hospital in MG1 was prioritized.

The results from this thesis demonstrated that operating several MGs in an NMG improves resilience, one achieves a higher utilization of DERs, and implementing EVs as ESS in the NMG increases flexibility. Power delivery to the prioritized MG was significantly improved by transitioning from islanded mode to NMG operation. The duration of load shedding, which reduced the load supply to levels below what was deemed critical, decreased by 69.2 %. Furthermore, the total time of load shedding experienced by the hospital was cut down by 12.3 %. The maximum load-shedding value in the hospital was also reduced by 22.1 %. It should be noted that surplus power and battery energy from a non-prioritized MG was delivered to the prioritized MG, resulting in less energy available for the non-prioritized MG. Consequently, this increased the amount of load shedding in the non-prioritized MG.

Further, the results showed that NMG operation increased the overall system efficiency and one could better utilize the PV production and power surpluses. In islanded operation, the PV production in MG3 had to apply generation shedding 58 % of the simulation time, with a maximum generation shed of 76.5 %. While in NMG operation no generation shedding was needed. This increased the PV production in MG3 by 143.7 %.

Using EVs as the only ESS by the use of V2G technology is shown possible by the results of this thesis. This brings both advantages and disadvantages. While each EV carries 80 kWh of storage capacity, the accumulated capacity of all EVs reached its maximum at 12160 kWh during the hospital dayshift in MG1. But, because of the variable nature of the EVs, the lowest capacity was 0 kWh in MG2, meaning no EVs were connected to the chargers. This intermittent utility pattern of EVs may cause uncertainty regarding what storage capacity is available at the given times. However, the EVs also provided a valuable contribution to the system during times of power failures, arriving with an SoC of 60 %, thereby bringing in stored energy to support the system.

This study concludes that NMGs perform better than standalone MGs during power outages. NMGs improve resilience, allow for better utilization of DERs, and EVs used as ESS in NMGs increase flexibility and can balance out intermittent power sources.

# 7 Implications and Future Research

The model solely focuses on power flow and does not take into account aspects such as voltage stability, synchronization processes, reactive power, or the specifics of power electronics. A more thorough investigation and understanding of these factors is essential to uncover the full potential and implications of NMGs.

One of the most important improvements that could be implemented in this model is likely the implementation of optimization to solve for optimal power flow inside the NMG. Mixed-Integer Linear Programming (MILP) was originally intended to be implemented, but because of the time constraints of the master's thesis, this had to be excluded.

The NMG presented in this case study consisted of only three MGs, whereas one of the MGs had a very minor contribution to the NMG in the sense of power exchange. Due to this, the full potential of the NMG could not be completely realized, and future enhancements would involve incorporating more MGs into the NMG. Further, exploring how the NMG would perform during shorter blackouts would also be a valuable contribution as this research only examined the extreme case of a blackout lasting 64 hours.

Moreover, the types of loads in the MGs should be further explored. This includes determining which loads are deemed critical in a hospital, which loads can be dynamically controlled, and which loads must be shed in bulk. In this thesis, it was assumed that all loads could be dynamically shed, which is a bold assumption.

There is also a need to delve deeper into non-technical aspects, like how the extensive use of EV batteries might affect their degradation rate, shorten their lifespan, and have implications for warranty coverage. To motivate consumers to connect their EVs to these facilities, suitable incentive schemes need to be established. It is also clear that a detailed economic analysis should be conducted to examine the economic advantages or disadvantages of NMGs.

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# Appendix A: Simulink Model

Appendix A presents excerpts of the Simulink model and code inside some of the MATLAB Function blocks. Excerpts of the model are added in this appendix to give an understanding of what the Simulink model looks like. It will not provide detailed explanations of the model or the code inside the MATLAB Function blocks.

Figure 25 shows a top-level view of the NMG connected to the utility grid.

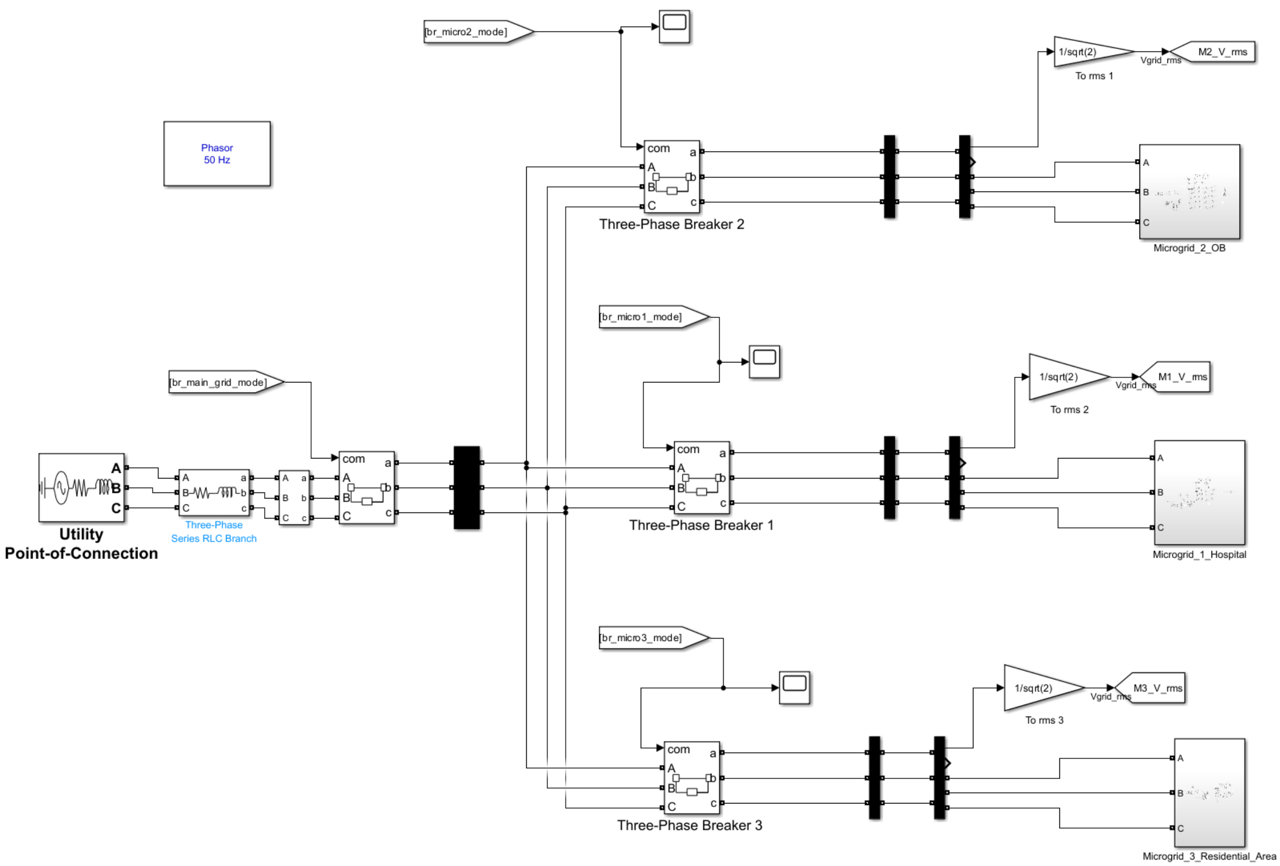


**Figure 25:** *Top-level of the NMG connected to the utility grid.*

The utility grid is connected to the NMG through the PCC. Both the utility grid and each MG are equipped with installed breakers. In Figure 26 one can see what it looks like inside an MG. This example is from MG1.

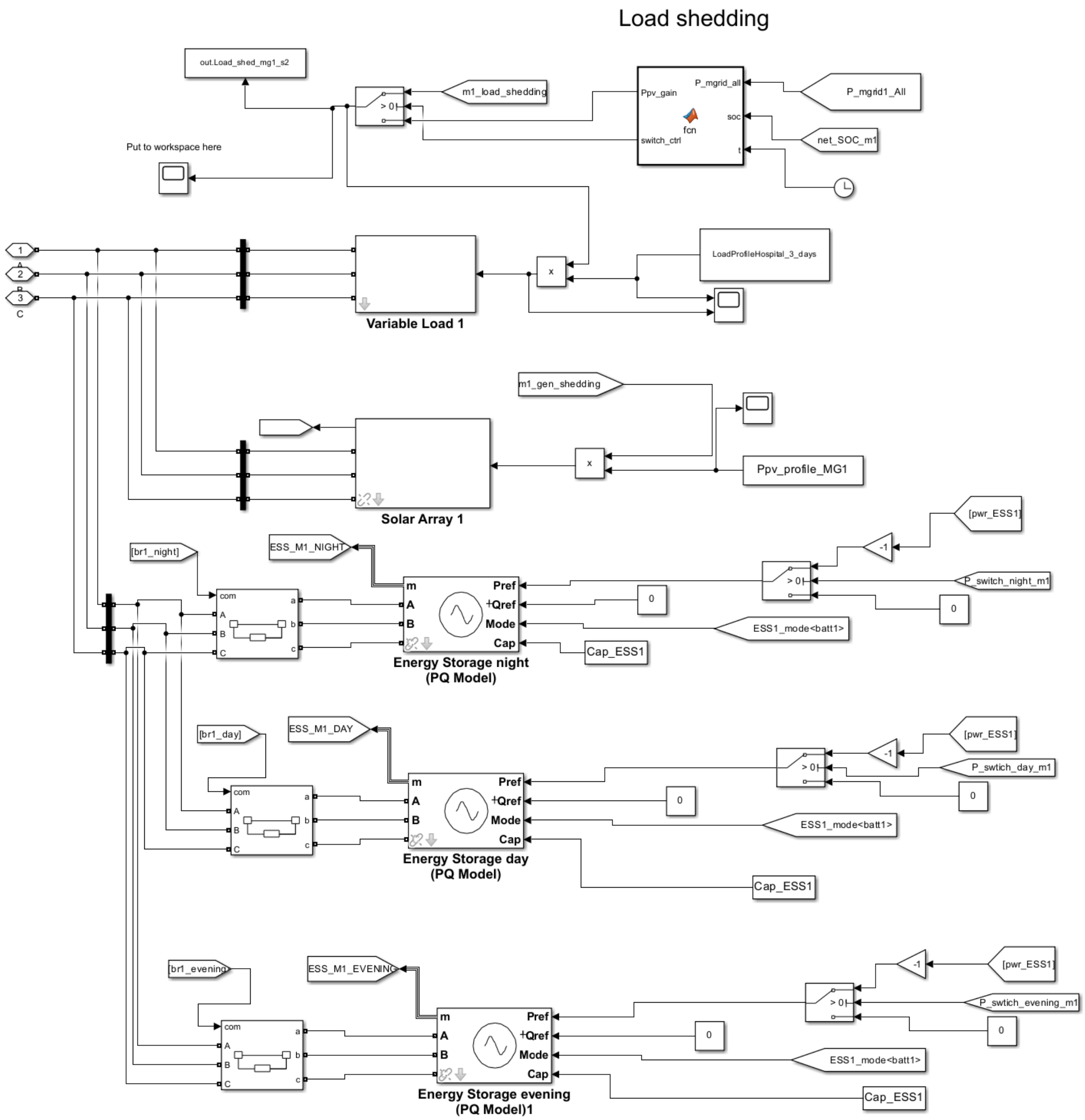


**Figure 26:** *Extract of the inside of MG1.*

Inside each MG there is a variable load, a solar array for PV production, and a battery for energy storage. In MG1, all three shifts at the hospital are modeled as three separate batteries. A simple time-based control system to change between the batteries was created in a MATLAB Function block. The "Pref" input port of the Energy Storage block control the power in and out of the batteries, including the scheduled charging of the EVs. Figure 27 shows the MATLAB Function block and associated Simulink blocks resulting in the "pwr_ESS1" signal used as input for the "Pref" port. The code inside the MATLAB Function block is presented after the figure.

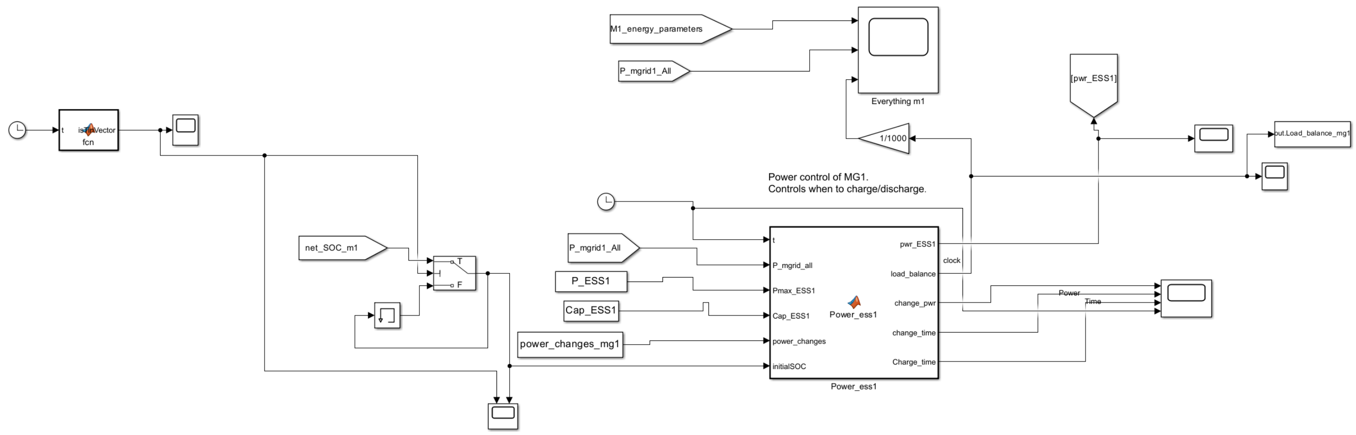


**Figure 27:** *MATLAB Function block and associated blocks to control the power flow on the battery in MG1.*

```
function [pwr_ESS1, load_balance, change_pwr, change_time, Charge_time] = Power_ess1(t, P_mgrid_all, Cap_ESS1, power_changes, initialSOC)
%%% ------------------------------------------------------------
% This function calculates the power balance in the MG. If the MG has a power surplus, then the EVs will charge. If the MG has a power deficit, then the EVs will supply the needed power to the MG. The power delivery and acceptance are limited by the maximum charge/discharge rates of the EVs. The function also controls the two hours of scheduled charging.
%%% ------------------------------------------------------------


Pvar1 = P_mgrid_all(2);

Ppv1 = P_mgrid_all(4);

change_time = power_changes(1); % A list of the time when the power changes
change_pwr = power_changes(2);  % A list of the power changes.
Charge_time = change_time - (3600*2); % When the charge of batteries should start.

load_balance = (Pvar1 + Ppv1)*1000; % Watts

% In ESS1, the load balance is always negative since the negative pvar is larger
% than the Ppv.

if t > (change_time - (3600*2))  && t < change_time && t<252000 %
```

```
    Last hour before shift change charge cars.

    chargeTarget = 0.8; % Charge the battery to 80% of Cap_ESS1
    chargeDuration = 3600*2; % Charge duration is set to two hours
        .

    % Calculate the energy needed to charge the battery to 80%
    targetEnergy = Cap_ESS1 * chargeTarget;
    currentEnergy = (initialSOC/100) * Cap_ESS1;
    energyNeeded = (targetEnergy - currentEnergy);

    % Calculate the time step size
    timeStepSize = 1; % Placeholder value for dynamic step size

    % Normal distribution parameters
    mu = chargeDuration / 2; % Mean
    sigma = chargeDuration / 6; % Standard deviation

    % Calculate the normal distribution curve values
    x = 0:timeStepSize:chargeDuration;
    pdfValues = normpdf(x, mu, sigma);

    % Normalize the normal distribution curve to have the desired
        total energy
    pdfArea = trapz(x, pdfValues);
    pdfValues = pdfValues * (energyNeeded/pdfArea)*3600;

    % Find the charge power for the current time step
    index = max(1, round((t - (change_time - (3600*2)) /
        timeStepSize)));
    pwr_ESS1 = pdfValues(index);


else
     pwr_ESS1 = load_balance;

end

end
```

Further, Figure 28 shows the first layer inside the battery. This layer conducts several operations, but one of the most important operations is differentiating between when the battery is in voltage mode or in current mode. This is controlled through a set of breakers that will not be discussed in detail. A MATLAB Function block was incorporated to stop the simulation if the SoC exceeds its boundaries during voltage mode operation.

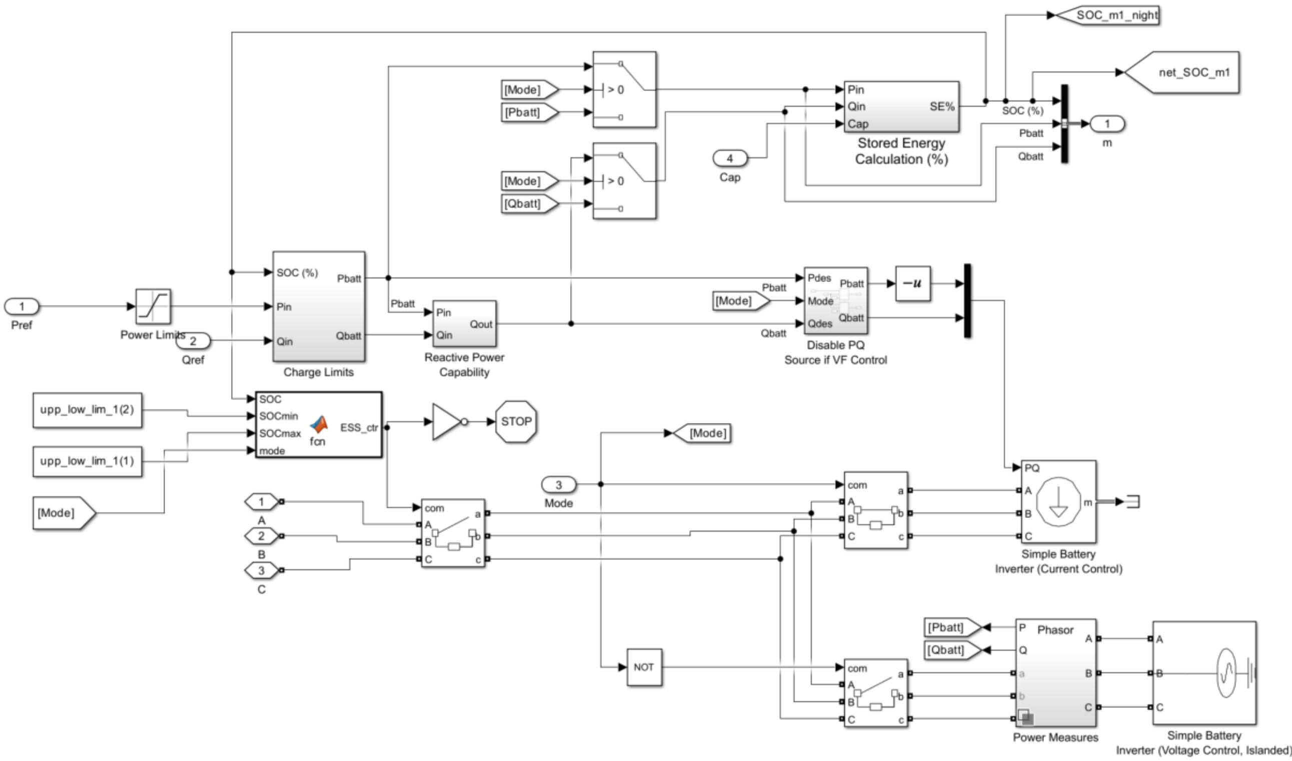


**Figure 28:** *First layer inside the night battery in MG1.*

The "Stored Energy Calculation (%)" was a central part of the model since this is where the SoC was calculated. In this block, the power was integrated, and the instantaneous energy of the battery was calculated. Figure 29 shows the inside of the "Stored Energy Calculation (%)" block. An enabled subsystem was used to reset the battery's energy (and hence the SoC) when the next batch of EVs arrived with 60 % SoC. A look inside the enabled system is seen in Figure 30. The SoC calculation can be seen in the area marked in blue.

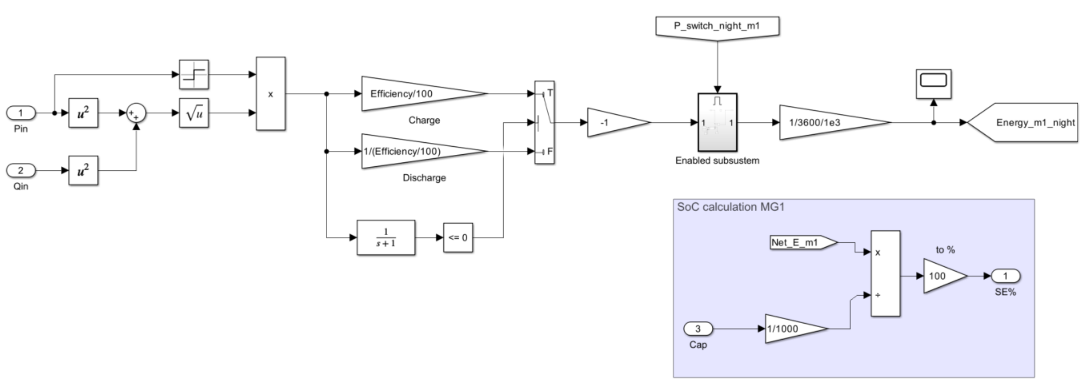


**Figure 29:** *Power integration and SoC calculation in MG1 night battery.*

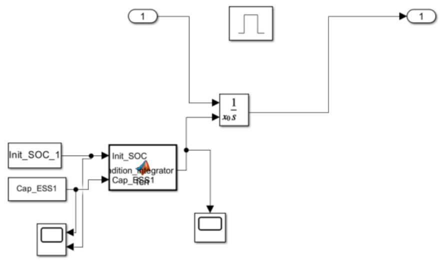


**Figure 30:** *A look inside the enabled subsystem to reset the battery's energy.*

The sample rate of the capacities in the batteries is hourly based, while the instantaneous energies are calculated for every simulation time-step in the simulation. When the capacities change, there is a one-hour linear change in capacity, and since the SoC is calculated by dividing energy with capacity, a linear one-hour transition had to be created in the energies as well. And at the same time, creating a "Net Energy" corresponding to the energy of the battery in use at a given time. Figure 31 below shows the Simulink blocks, and the MATLAB code inside the MATLAB Function block follows the figure.

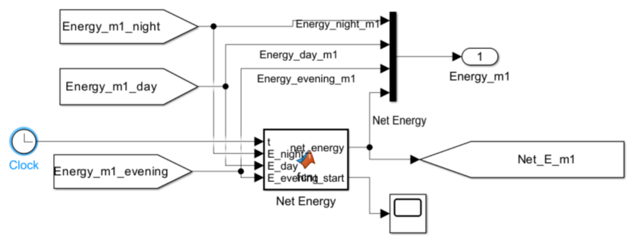


**Figure 31:** *Creating a Net Energy variable and linear energy transitions in MG1.*

```
function [net_energy, t_start] = fcn(t, E_night, E_day, E_evening)
%%
% This function creates linear transitions between the energy
   changes.
%%


% Define energy levels and time intervals:
shift_energy = [E_night E_day E_evening];

time_intervals = [21600 54000 79200 108000 140400 165600 194400
   226800 252000 255600]; % Seconds
transition_time = 3600; % One hour transition time.


% Determine the current energy level and the next energy level
if t < time_intervals(1)+3600 || (t >= time_intervals(3)+3600) &&
```

```
    (t < time_intervals(4)+3600) || (t >= time_intervals(6)+3600 && t < time_intervals(7)+3600) || (t > time_intervals(9)+3600)
    current_energy = shift_energy(1); % E_night
    next_energy = shift_energy(2);    % E_day

    % Find the start time of the current energy transition
    t_start = ((t < time_intervals(1)+3600) * (time_intervals(1))) + (t >= time_intervals(3)) * (t <= time_intervals(4)+3600) * (time_intervals(4)) + (t >= time_intervals(6)) *(t <= time_intervals(7)+3600) * (time_intervals(7));

    % If the time is less than one hour after the transition starts, create a linear transition. If not, follow the current energy level.
    if t >= t_start && t < (t_start + transition_time)
        slope = (next_energy - current_energy)/transition_time;
        net_energy = (slope * (t - t_start)) + current_energy;

    else
        net_energy = current_energy;
    end

elseif (t >= time_intervals(1) && t <= time_intervals(2)+3600) || (t >= time_intervals(4) && t < time_intervals(5)+3600) || (t >= time_intervals(7) && t < time_intervals(8)+3600)
    current_energy = shift_energy(2);       % E_day
    next_energy = shift_energy(3);          % E_evening

    % Find the start time of the current energy transition
    t_start = (((t >= time_intervals(1)) * (t <= time_intervals(2)+3600)) * (time_intervals(2))) + (((t >= time_intervals(4)) * (t < time_intervals(5)+3600)) * (time_intervals(5))) + ((t >= time_intervals(7)) * (t < time_intervals(8)+3600) * time_intervals(8));

    % If the time is less than one hour after the transition starts, create a linear transition. If not, follow the current level.
    if t >= t_start && t < (t_start + transition_time)
        slope = (next_energy - current_energy)/transition_time;
        net_energy = (slope * (t - t_start)) + current_energy;
    else
        net_energy = current_energy;
    end

else
```

```
    current_energy =  shift_energy(3);         % E_evening
    next_energy =   shift_energy(1);           % E_night

    % Find the start time of the current energy transition
    t_start = (((t >= time_intervals(2)) * (t <= time_intervals(3)+3600)) * (time_intervals(3))) + (((t >= time_intervals(5)) * (t < time_intervals(6)+3600)) * (time_intervals(6))) + ((t >= time_intervals(8)) * (t < (time_intervals(9)+3600)) * time_intervals(9));

    % If the time is less than one hour after the transition starts, create a linear transition. If not, follow the current energy level.
    if t > t_start && t < (t_start + transition_time)
        slope = (next_energy - current_energy)/transition_time;
        net_energy = (slope * (t - t_start)) + current_energy;
    else
        net_energy = current_energy;
    end
end
end
```

If one takes a few steps back and looks at Figure 26 again, one can see a Variable Load and Solar Array block. Input data to these blocks are data created and calculated in MATLAB and imported to Simulink through "From Workspace" blocks. At the very top of Figure 26 one can see the load shedding blocks. The code inside the MATLAB Function block in the load shedding system is presented below.

```
function [Load_shed, switch_ctrl] = fcn(soc, t)

switch_ctrl = 1;

soc_upper_lim = 90;
soc_lower_lim = 10;
threshold = 30;
Load_shed = 0;

if t > 28800
    if soc < soc_lower_lim + threshold
        switch_ctrl = 0;
        Load_shed =(1 - (((soc_lower_lim + threshold) - soc) * (100/threshold))/100);
    end

end
```

As the generation shedding is created in a similar fashion as the load shedding, the generation shedding algorithm will not be displayed.

Further, In Figure 32 one can see the power control for MG3 and how the power-sharing algorithm associated with Scenario 3 is implemented to the power control. On the top of the figure, one can see the blue area associated with the power-sharing. The code contained within the 'Additional Energy' MATLAB Function block is provided after the figure.

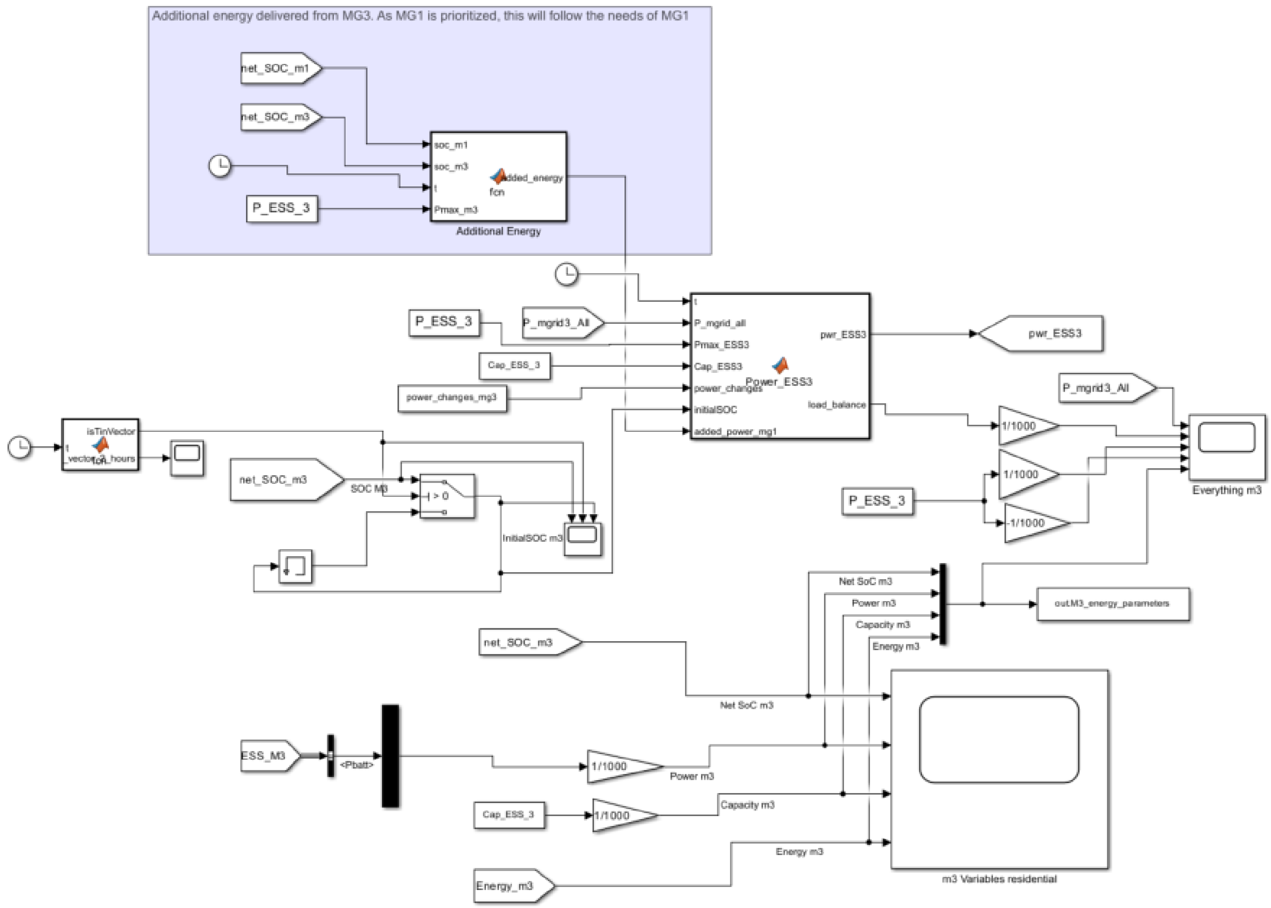


**Figure 32:** *MG3 power control including power exchange to MG1. The power exchange part is marked in blue at the top of the figure.*

```
function added_energy = fcn(soc_m1 , t , Pmax_m3)
upper_lim = 50;

    if soc_m1 < 50 && (t > 28800 && t<= 54000) || (108000 < t && t
        <= 140400) || (194400 < t && t <= 226800) % Day
        added_energy = 0; % No added energy during daytime

    elseif soc_m1 < 50 && t <= 79200 || (140400 < t && t <=
       165600) || (226800 < t && t <= 252000) % Evening
        added_energy = 0; % No added energy during evening

    elseif soc_m1 < 50 && (79200 +3600 < t && t <= 108000) ||
```

```
        (165600 +3600 < t && t <= 194400 +3600 || t>252000 ) %
        Night
            added_energy = Pmax_m3/upper_lim * (upper_lim - soc_m1); %
                During nighttime added energy is delivered from MG3
                when MG1's SoC is below 50 \%.

        else
            added_energy = 0;
        end
end
```

Lastly, to change between the simulation scenarios three MATLAB function blocks were created, one for each scenario. These were simple time-based controllers of the breakers and operational modes on the batteries. An example from Scenario 3 is seen in Figure 33, with the code inside the MATLAB Function block provided after the figure.

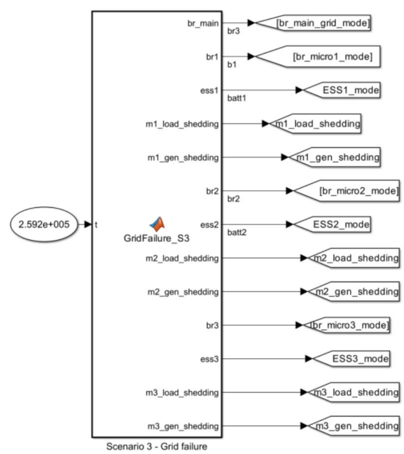


**Figure 33:** *Scenario 3 control system.*

```
function [br_main,br1, ess1,m1_load_shedding,m1_gen_shedding, br2,
    ess2, m2_load_shedding, m2_gen_shedding, br3, ess3,
    m3_load_shedding,m3_gen_shedding] = GridFailure_S3(t)
% Base values for the load shedding, 1 means no load shedding.
m1_load_shedding=1;
m2_load_shedding=1;
m3_load_shedding=1;

% Base values for generation shedding, 1 means no generation
    shedding.
m1_gen_shedding=1;
m2_gen_shedding=1;
m3_gen_shedding=1;

% Breaker control for the MGs and utility grid. 1 indicate
    connected.
```

```
br1 = 1;
br2 = 1;
br3 = 1;
br_main = 1;

% Battery mode control. 1: Current mode, 2: Voltage mode.
ess1=1;
ess2=1;
ess3=1;

% Grid failure occurs at t=28800 seconds, translating to 08:00 initial day.
if t > 28800

    % All M grids are connected to the grid
    br1 = 1;
    br2 = 1;
    br3 = 1;

    br_main = 0; % Utility grid disconnected


    % 1= current mode, 0=voltage mode

    ess1=0;
    ess2=1;
    ess3=1;

end
end
```

MATLAB was used in conjunction with Simulink. All data, parameters, and variables were defined in MATLAB and exported to Simulink. In addition, all plots were created in MATLAB. This section will only show a very limited extraction of the MATLAB code used.

Below it is shown how the load shedding values for MG1 in Scenario 3 were extracted, resampled, and calculated how much of the total simulation time the load shedding was applied. The load-shedding values were exported from Simulink to MATLAB using "To Workspace" blocks.

```
%% Extract load_shed values
load_shed_m1_s3 = out.Load_shed_mg1_s2.Data(:,1);
time_s3 = out.Load_shed_mg1_s2.Time/3600 % In hours

%% calculations load shed:
% Time:
time_seconds = time_s3 * 3600;

```

```
% Resampling
[uniform_shed_sec, uniform_time_sec] = resample(load_shed_m1_s3,
   time_seconds, 1); % seconds

% Calculation of how much of the simulation time the load shedding
    was applied:

% Counter:
seconds_connected = 0;

for i = 1:length(uniform_shed_sec)
    if uniform_shed_sec(i) < 0.99 % If the shed value is below
       this threshold, then load shedding is applied.
        seconds_connected = seconds_connected + 1;
    end
end

seconds_with_shed_m1 = (Seconds_connected/(24*3600*3))*100; %
   Equals 27.8 % of total simulation time with load shedding.
```

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