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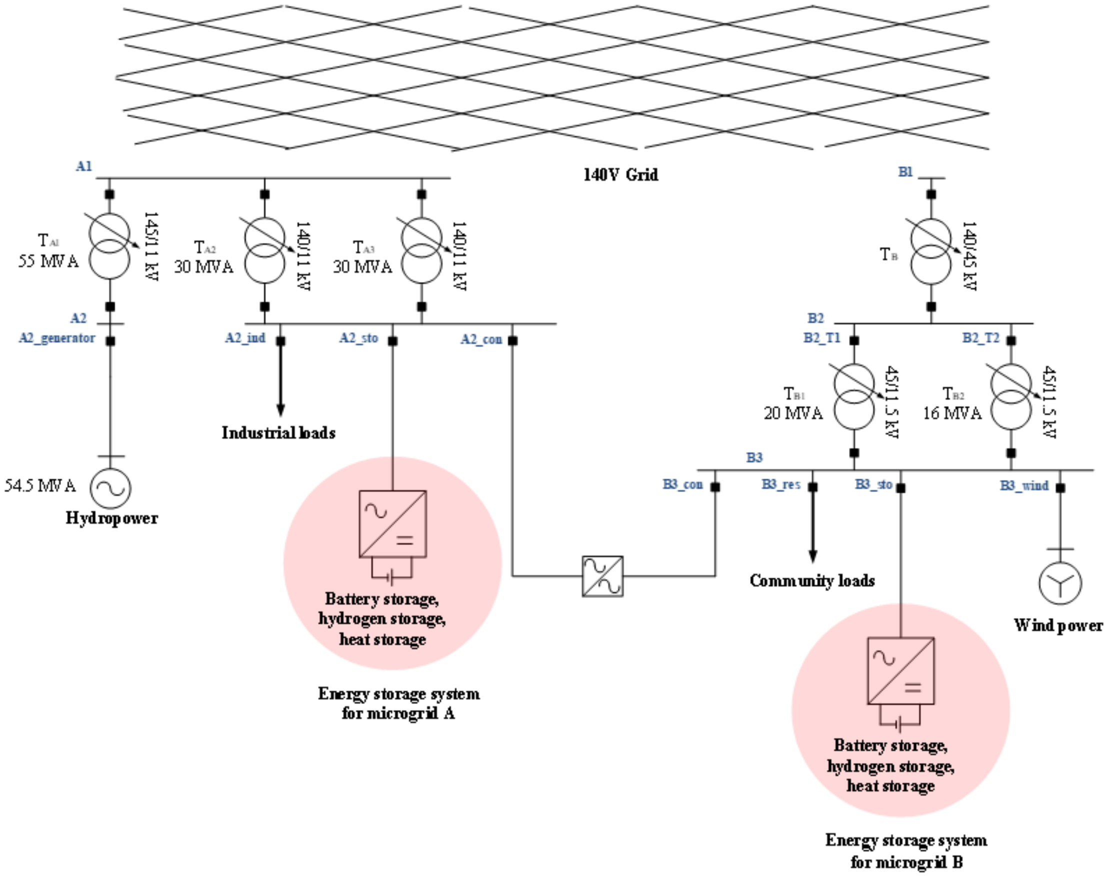

# Design and Analysis of Interconnected Medium-Voltage Microgrids

Department of Space, Earth and environment

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# Abstract

Microgrid is considered as a competitive solution for capacity shortage mitigation and supply reliability enhancement instead of conventional grid upgrade. To handle these two grid issues, techno-economic analysis needs to be carried out on technology solutions available for microgrid development, including different energy storage technologies and the possibility to interconnect adjacent microgrids.

In this thesis, an energy system model is built on the basis of two real medium-voltage local distribution grids in Western Sweden. Different scenarios are analysed, including varying requirements on island operation capability and different levels of load expansion. Four technical options, including battery storage system, hydrogen storage system, heat storage system and microgrid interconnection, are provided as technical options for investment. For each scenario, the running result is an optimization solution combining the technical options. The objective of the optimization is to handle all requirements in each scenario with the minimum total cost. The thesis mainly discuss the driving factors that affect the dimension of the four technologies, especially the investment in different energy capacity and power capacity of these technologies. According to the results obtained, individual microgrids mainly rely on battery to manage the grid capacity shortage during periods of high net load. Battery is also the only technology to handle island mode requirement of short durations. However, as the island mode duration increases, hydrogen storage system becomes a complementary solution to the battery storage system for handling the increasing energy storage demand. For interconnected microgrids, there is a reduction on the total net load of the two microgrids because of their complementary net load profile. The interconnection technology is competitive to replace the energy storage technology, especially the hydrogen storage system for long-term and large volume energy back-up.

Keywords: Microgrid, Interconnected microgrids, Island mode, Energy system modelling, GAMS, Energy storage technology

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Yibo Liu and Ziyao Ma, Gothenburg, June 2022

# List of Acronyms

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

| | |
|---|---|
| PCS | power conversion system |
| RES | Renewable-based Energy Sources |
| CRF | Capital recovery factor |
| O&M | operation and maintenance |
| BESS | Battery Energy Storage System |
| DER | Distributed Energy Resource |
| MG | Microgrid |
| EU | European Union |
| EMS | Energy Management System |
| TES | Thermal Energy Storage |
| LTTES | Low-Temperature TES |
| HTTES | High-Temperature TES |
| SHS | Sensible Heat |
| LHS | Latent Heat System |
| AAS | Absorption and Adsorption System |

# Nomenclature

Below is the nomenclature of indices, parameters, and variables that have been used throughout this thesis.

## Indices

| | |
|---|---|
| $i$ | Indices for energy storage technologies |
| $t$ | Index for time step |
| $m$ | Index for microgrid |
| $r$ | Index for renewable power plant |
| $k$ | Index for island mode duration |
| $x$ | The island mode happens at time $x$ |
| $y$ | The island mode has lasted for $y$ hours |

## Parameters

| | |
|---|---|
| $G_{r,t}$ | Electricity generated in renewable power plant $r$ at time $t$ [kWh] |
| $G_{m,t}$ | Electricity generated in microgrid $m$ at time $t$ [kWh] |
| $D_{m,t}$ | Demand in microgrid $m$ at time $t$ [kWh] |
| $TC_m$ | transformer power capacity between microgrid $m$ and main grid [kw] |
| $\eta_{i,in}$ | charge efficiency of technology $i$ |
| $\eta_{i,out}$ | discharge efficiency of technology $i$ |
| $C_i^{es}$ | Annualized energy storage capacity investment costs of energy storage technology $i$ [Euro/kWh, year] |
| $C_i^{in}$ | Annualized input capacity investment costs of energy storage technology $i$ [Euro/kW, year] |
| $C_i^{out}$ | Annualized output capacity investment costs of energy storage technology $i$ [Euro/kW, year] |
| $C_c^{inv}$ | Annualized investment costs of cable [Euro /(kW*km), year] |

| | |
|---|---|
| $C_{PCS}^{inv}$ | Annualized investment costs of PCS [Euro /kW, year] |
| $C_i^v$ | Variable O&M costs of each energy storage technology [Euro /kWh] |
| $P_t$ | price of electricity at time $t$ [euro/kWh] |
| $C_{m,t}^{net,trans}$ | Transfer fee to receiving electricity from the main grid to grid $m$ at time $t$ [Euro /kWh] |
| $C_{m,r}^{net,gen}$ | Capital compensation for generating in power plant $r$ in grid $m$[Euro /kWh] |
| $LC$ | Length of cable investment [km] |
| $D_m^{peak}$ | Peak net load in microgrid m[MW] |
| $D_{total}^{peak}$ | Peak net load in microgrid m[MW] |
| $ER_m^{peak}$ | Peak energy requirement in microgrid m[MWh] |
| $ER_{total}^{peak}$ | Peak energy requirement in microgrid m[MWh] |

# Variables

| | |
|---|---|
| $EC_{i,m}$ | Installed energy storage capacity in technology $i$ connected to microgrid $m$ [kWh] |
| $IC_{i,m}$ | Installed input power capacity in technology $i$ connected to microgrid $m$ [kW] |
| $OC_{i,m}$ | Installed output power capacity in technology $i$ connected to microgrid $m$ [kW] |
| $E_{m,i,t}^{in}$ | Electricity charged by microgrid $m$ to technology $i$ at time $t$ [kWh] |
| $E_{m,i,t}^{out}$ | Electricity discharged by technology $i$ to microgrid $m$ at time $t$ [kWh] |
| $S_{m,i,t}$ | Storage level in device $i$ connected to microgrid $m$ at time $t$ [kWh] |
| $E_{m,t}^{bought}$ | Electricity purchased by microgrid $m$ from main grid at time $t$ [kWh] |
| $E_{m,t}^{sold}$ | Electricity sold to main grid from microgrid $m$ at time $t$ [kWh] |
| $n_{m,i,t}$ | The maximum electricity output can be provided by technology $i$ in microgrid $m$ at time $t$ [kW] |
| $E_{m,i,t,d}^{is}$ | The maximum electricity can be supplied during island mode by technology $i$ in microgrid $m$ at time $t$ for duration d [kWh] |
| $CC$ | Installed cable power capacity [kW] |
| $E_{m,t}^{tra}$ | Electricity transmitted from microgrid $m$ to another microgrid at time $t$ [kWh] |
| $C_{net}^{ar}$ | Net profit from energy arbitrage [Euro] |
| $C^{ar}$ | Profit from energy arbitrage in normal case[Euro] |

| | |
|---|---|
| $C^{ar}_{without\ storage}$ | Profit from energy arbitrage in no energy storage system case[Euro] |
| $C^{cable,extra}$ | Extra cable cost comparing to no energy storage system case[Euro] |
| $C_{cable}$ | Cable cost in normal case |
| $C^{cable}_{without\ storage}$ | Cable cost in no storage system case |
| $C^{cost}_{battery}$ | Cost of battery in normal case[Euro] |
| $C^{surplus}_{battery}$ | Surplus from battery comparing to no storage system case[Euro] |

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# 1

# Introduction

## 1.1 Background

In recent years, the increase of electricity demand is faster than ever before. The most cost-efficient way to meet this new electricity demand is by installing wind and solar power. The new electricity demand is most cost-efficiently met by varying generation. To add this new load and generation to the grid and make the system operate reliably at every time instant is a challenge. Furthermore, a substantial share of the wind and solar power as well as the new load is connected at the local distribution grids. Therefore, a shortage in grid capacity locally may arise. Also, the lead time to expand the grid capacity is relatively long, which may hinder the renewable integration and electrification process. To handle this, some measures apart from grid capacity expansion is worth consideration, such as interconnecting two local distributed grids, introducing storage technologies and so on. These alternatives are selected and combined to replace or complement the existing connection between the main grid and the local distribution grid. Based on this, a conception, 'microgrid', appears.

Microgrid is regarded as one suitable alternative for operating local electric power systems in several countries. Comparing with the conventional grid, microgrid has the potential to improve supply reliability for its grid users and to mitigate grid capacity shortage with a short lead time. But there are several challenges for microgrid development. It is difficult for microgrid to keep self-sustaining for long time. Self-sustaining is an ability of microgrid to keep the supply-demand balance in a duration without interaction with the main grid. Additionally, the future load expansion will enhance the difficulty for microgrid to manage larger fluctuations in load and generation. To handle these problems, energy storage technologies can be one of the effective alternatives. But at present nearly all energy storage technologies contain one or more expensive part that limits their development. Therefore, it is worthwhile to study on another alternative, microgrid interconnection. Interconnecting microgrids is different with conventional grid upgrade. Interconnection can be built between microgrids which are not far from each other. In this way, the cost is low but the microgrids in both ends can get more self-sustaining. This thesis compares the solutions for individual microgrid and interconnected microgrid in terms of managing island mode operation and sustaining an increase in load.

## 1.2 Aim

The purpose of this project is to find out the optimum design of a microgrid through energy system modelling by considering different technology options for mitigating the local grid capacity shortage and improving the supply reliability for the consumers.

For energy system modelling, four scenarios with different requirements are designed as follows:

1. individual microgrids with varying degree of island mode duration requirements
2. individual microgrids with varying degree of load expansion requirements
3. interconnected microgrids with varying degree of island mode duration requirements
4. interconnected microgrids with varying degree of load expansion requirements

The objective is to find out the optimization way for the four options on investment and coordination, i.e.,to handle all requirements with minimum cost.

## 1.3 Problem description

The problem is proposed for two medium-voltage grids. Figure 1.1 is the electrical diagram of their existing condition. The two grids are anticipated to run as microgrids in the future. For this reason, several scenarios are designed with stricter conditions than now, to enhance the grids' performances on self-sustaining and supply reliability.

There are two situations to be investigated. In one situation, microgrids face a possibility that island mode happens at any time. Island mode means the microgrids loses connection or stops interaction with the main grid. During island mode, the microgrid must depend on the generation and energy storage in itself to keep the demand-supply balance. The longer the island mode duration is, the higher requirement on microgrids' self-sustaining ability. In another situation, the microgrids take the challenge on load expansion. The loads in microgrids are increased to varying extent but the size of generation remains the same. The larger demand and net load variation enhance the difficulty to ensure the supply reliability in microgrids.

Based on the two situations above, several technical options are investigated, including three energy storage technologies and microgrid interconnection. The capacity of energy storage technology contains energy storage, charge power capacity and discharge power capacity. Investments on these parts are individual.

## 1.4 Scope

The two distribution grids under investigation are in Västra Götaland. Grid A contains hydropower generation and industrial loads. Grid B contains wind power generation and community loads. The hourly electricity generation and consumption amount refers the data in 2018.

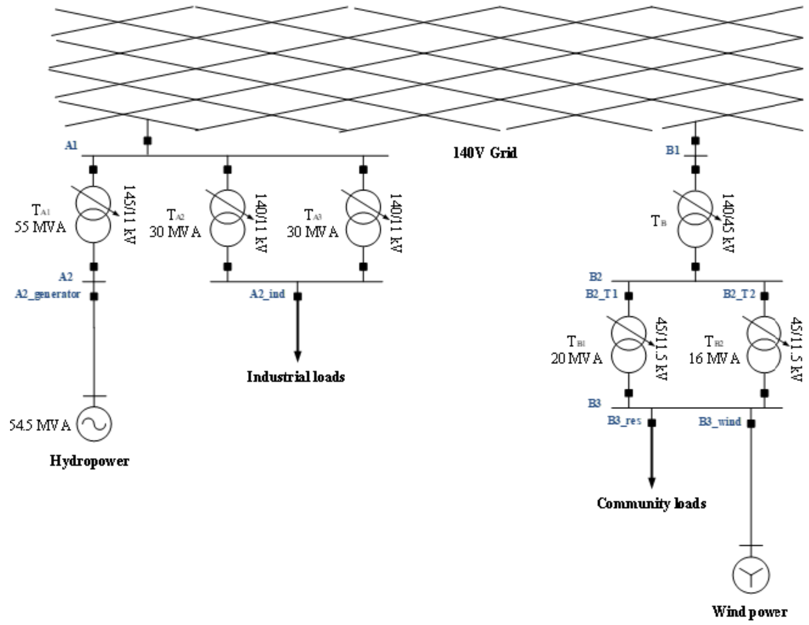


**Figure 1.1:** Existing condition of Grid A and Grid B

Three storage technologies are considered in this work, battery energy storage, hydrogen energy storage and heat energy storage. The battery is Lithium-ion battery. For hydrogen storage, the system contains three parts. The part for charging refers Alkaline electrolysis technology. The part for energy storage is a hydrogen tank. The part for discharging is designed as fuel cells. For heat storage system, it charges with heat exchanger. The energy is stored as high temperature heat in form of aluminum alloy and discharged through Stirling engine.

The evaluation of solutions refers total cost. Total cost consists of several items. As for energy storage technologies, the cost can be divided in three parts, i.e., energy storage capacity, charge power capacity and discharge power capacity. For each part, the investment cost and O&M (operation and maintenance) cost are considered. As for microgrid interconnection, the evaluation refers cable power capacity investment cost and power conversion system (PCS) cost. As for interaction between the microgrid and the main grid, income and expenses to trade with the main grid are counted. Additionally, the network tariff is also taken into consideration.

# 2

# Overview of microgrid and energy storage technologies

## 2.1 Microgrid

According to US. Department of energy, the microgrid is defined as " a group of interconnected loads and distributed energy resources within 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 island-mode."[1] The typical components of a microgrid include: microgrid controller (if necessary, including load/generation forecasting system, and communication system), energy storage system, dispatchable generation, load. [2] Relationship between components of microgrid in grid-connected is shown in Figure 2.1.

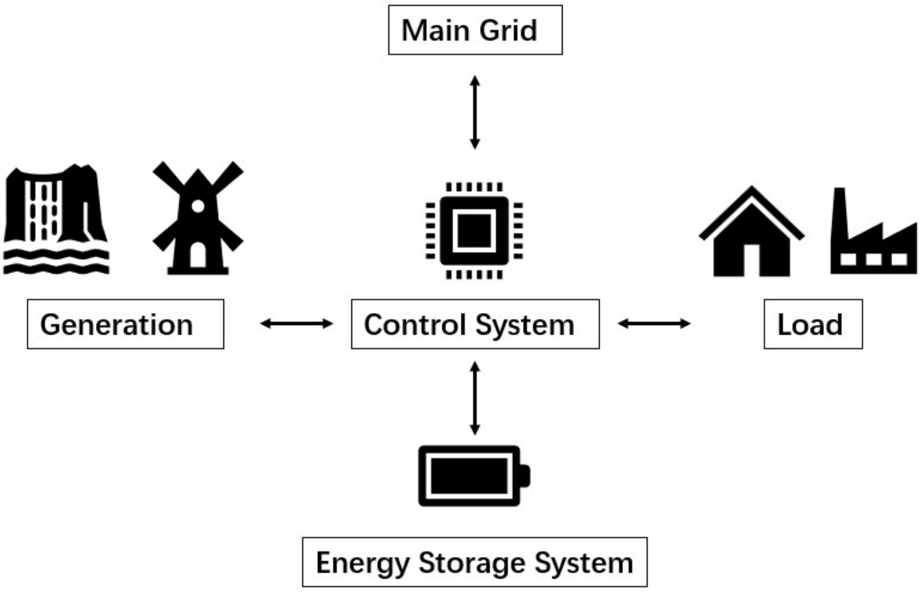


**Figure 2.1:** Illustration of microgrid

A point of common coupling between control system and main grid is used for connecting, which is a switch and can separate the microgrid from main grid, and then it becomes an island.[3]

### 2.1.1 Purpose and value of microgrid research

Sweden has been one of the European Union (EU) member since 1995. Therefore, the rules and regulations of EU should be obeyed. There are some goals published by Publications Office of European Union, which sets ambitious energy and climate targets for 2030. In addition to those targets, it provides a stable legal framework to foster the necessary investment [4]. The main objectives of ref. [4] include improving the European internal energy market, facilitating the transition from fossil energy to renewable energy, and strengthening consumer status in the market. Adjusting trade rules, strengthening connectivity to prepare for future demand, and harnessing intermittent renewable energy are important steps to improve the market. By 2050, 50% of European households are expected to produce their own energy [4].

The implementation of microgrids can help reaching some of the European targets. Microgrid implementation in the University of California, San Diego shows that the microgrid can contribute to reliable deployment of renewable generation, and distributed resources in microgrid can be coordinated to achieve environmental objective [5]. In order to provide energy to customers in an economical and clean way, different technologies and systems are came out in different research [6].

A complex control system could significantly improve the operation of microgrid, which could find a suitable solution for a microgrid system. This solution could achieve the lowest emission by optimal sharing of renewable energy. Also, hybrid optimized techniques which contain renewable generation and energy storage system can achieve optimal scheduling, design, and power sharing from a cost or environmental perspective [7]. Control systems includes forecast system and, energy management system, which are actualized by algorithms. By using forecast system to predict renewable energy source and demand, different strategies could minimize the operational cost [8]. Also, Microgrids could improve the utilisation of renewable energy, reduce blackout and curtailment of renewable energy. If microgrids are combined with forecast systems, users could benefit from shared excesses of renewable resources, and the curtailment of renewable energy could be reduced [9]. In addition, implementation of a microgrid energy management system (EMS) could improve efficiency of microgrid operation. The microgrid platform can communicate with different energy devices and perform an energy management task efficiently [10].

There are several algorithms published for better operation of microgrid. Stefano Leonori proposed a microgrid Fuzzy logic-based EMS which aims to redistribute an intelligent way the prosumers energy balance [11]. Elizaveta Kuznetsova proposed a 2 steps-ahead reinforcement learning for battery scheduling, which is a key role in the achievement of consumers targets [12]. Mohammed H.Alabdullah reported that a deep reinforcement learning-based approach to manage different energy source within a microgrid [13].

In term of economical aspect, From N. D. Hatziargyriou analyses it can be concluded that the cost for the end users is significantly reduced when the demand is met by the Microgrid’s units especially for the cases when the electricity prices are very high [14].

### 2.1.2 Challenges of microgrid development

Although microgrids may benefit the system, there are still some challenges which need to be solved in the reality. First are the technique challenges of microgrids.

1. Autonomous Operation
   When the microgrid transit from grid-connected to island-mode, it should be maintaining suitable voltage and frequency levels for all microgrid loads. Therefore, momentary interruptions may occur during the transitions by the switch technology. If power is lost, the microgrid should be able to restart and supply the island loads [15]. In addition, modern power electronics need to be able to respond quickly to a variety of system conditions and load management.
2. Power and Frequency Control
   According to the literature, the most common way to control microgrid generators is the power – frequency droop control [16]. Normally, when increase the output power, there is a negative slope droop on the frequency. However, the system should keep around 60 Hz frequency. (Figure 2.2). The speed governors should control the machine speed and not let the frequency drop too fast. Of course, for different machines, the frequency droop is differed. Thus, the frequency drop of various units will be complex but slow. [15].

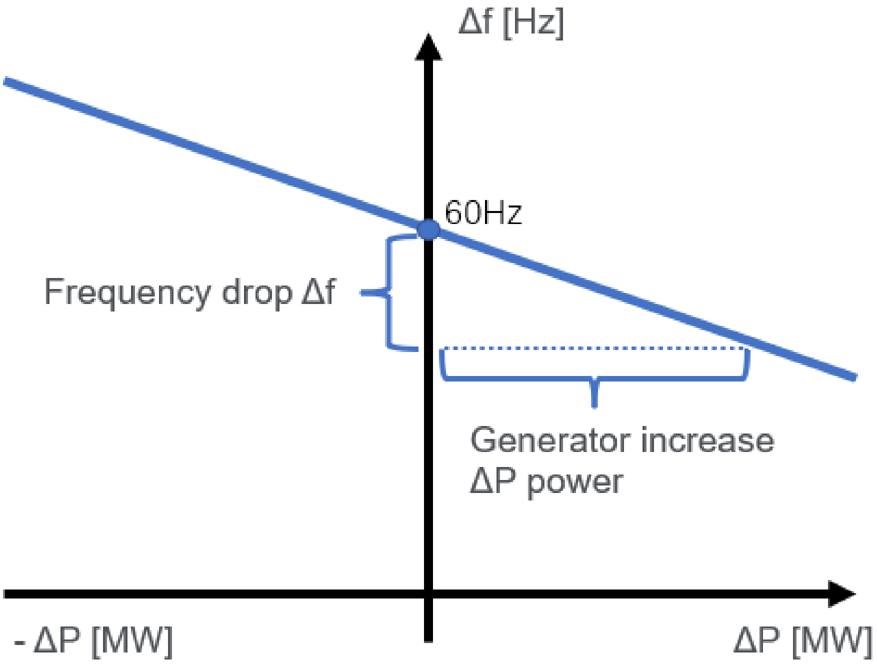


**Figure 2.2:** Frequency droop control principled

Additionally, there are some regular barriers for microgrid which would like to operating as one legal unit. The most common challenges are regulatory policies. As literature shown that, whether a group of people has legal right to build and operate a microgrid depend on one issue: " whether a micro-grid is defined or perceived to be a public utility". The fact is that there still are many companies unclear of the microgrid concept and how the policy developed for this new concept [17]. Also, from this literature, the ownership of the microgrid is also ambiguous. The regulators are not clear about the detail of techniques, but rather in microgrid ownership and business practices. To find the solution of this barrier, reference propose five different models that could find the balance between their ownership and business practices [17]. Besides, reference [17] shown different barriers, choice of voltage level, the legality of microgrids, Service territories, Utility tariffs, Interconnection procedures & technical requirements, Microgrid & customer interaction, Environmental and siting laws.

Microgrid will always contain energy storage system. However, energy storage system still has barriers. As reference [18] says, microgrid has large size of energy storage, which lead to the cost of storage system is quite high. Cost includes installation and maintenance costs. Depending on storage type, storage capacity, C rate of storage system and life cycle, the cost are different. Using suitable energy storage system could minimize the cost. The development of energy storage system is one of the key features for microgrid.

## 2.2 Energy storage technologies

In this section, three different energy storage technologies are introduced. Li-ion battery, Hydrogen storage, Heat storage are chosen to add into this model. of energy storage systems. These technologies have different cost feature in energy storage, charge, and discharge. Also, round trip efficiency has a high impact on how storage are used and operated. See Table 2.1 [19].

**Table 2.1:** Typical Cost for different storage

| | Energy storage cost | Cost of charging | Cost of discharging | Round trip Efficiency |
|---|---|---|---|---|
| Battery system | High | Low | Low | High |
| Hydrogen storage system | Low | High | High | Medium/Low |
| Thermal storage system | Low | Low | High | Medium/Low |

The detail of each technology will describe later.

### 2.2.1 Li-ion battery

Li-ion battery is one of the most popular energy storage technologies in the past decades. Li-ion battery is currently dominant in portable electronic devices, especially in cell phones and laptop computers [20].

Fundamental of Li-ion is shown in Figure 2.3. The illustration of working principle of battery is based on the LixC6/Li1-xCoO2 cathode. Lithium ion move though

the electrolyte which is contained between anode and cathode. When the battery is discharging, lithium ions are released from anode and move to the delithiated cathode [21]. Graphite-based materials are commonly used for anodes, since the low cost and wide availability of carbon. For cathode, it influences the performance of battery deeply. Cathodes consist of a complex lithiated materials, Such as LiCoO2, LiMn2O4, and LiFePO4 [22, 23, 24].
As an energy storage system in a microgrid, Li-ion battery is one of the choices. Energy storage system should convert electricity from grid level power into a storable form and convert it back when the grid needs it. As reference [25] show, large batteries are gradually being implemented in EES applications. However, the increased use of batteries in EES systems is limited by high cost [25].

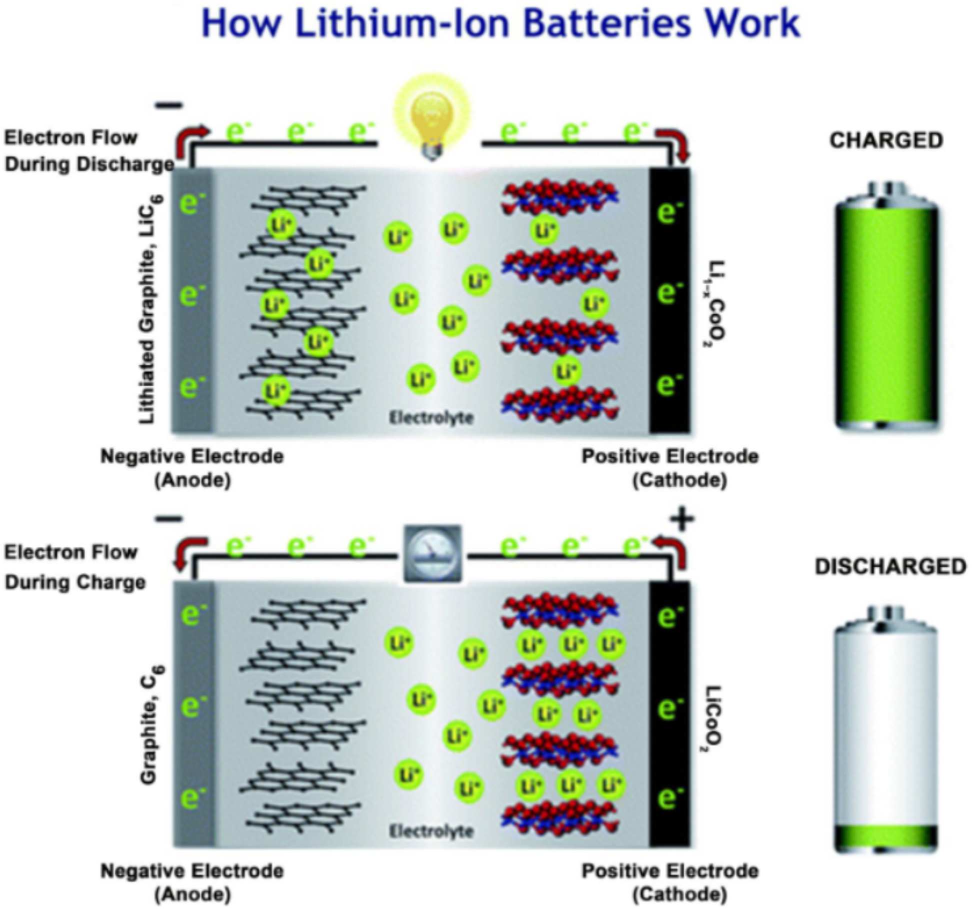


**Figure 2.3:** The principle of Li-ion battery. copyright 2012, The Royal Society of Chemistry

### 2.2.2 Hydrogen storage

In this case, hydrogen storage system contains electrochemical decomposition of water to produce hydrogen, store by tank, fuel cell to discharge.

It is a simple process to produce hydrogen and oxygen by electrochemical decomposition of water. Figure 2.4 illustrates the basic principle of hydrogen production using electrolysis [19].

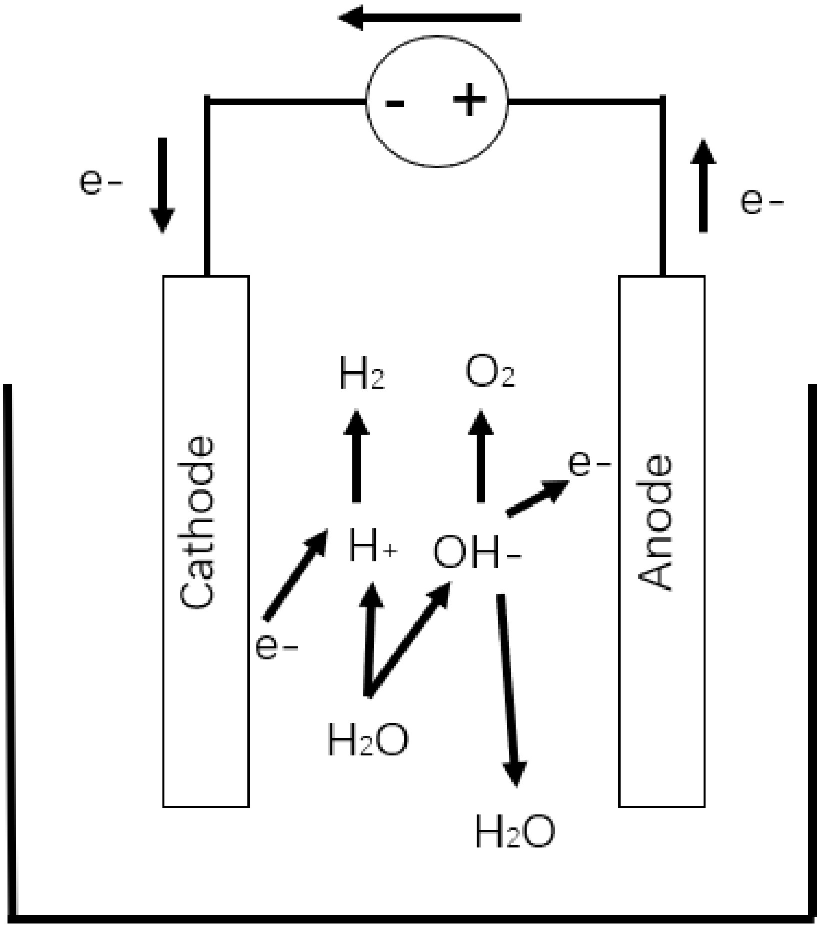


**Figure 2.4:** Basic principle of hydrogen production.

The reaction on cathode is given by 2.1:

$$2H^+ + 2e^- = H_2 \tag{2.1}$$

The reaction on anode is given by 2.2:

$$H_2O = \frac{1}{2}O_2 + 2H^+ + 2e^- \tag{2.2}$$

The overall reaction of water decomposition is given by 2.3.

$$H_2O = \frac{1}{2}O_2 + H_2 \tag{2.3}$$

The basic principle of a fuel cell is a reversible reaction of hydrogen production. As shown in Figure 2.5, hydrogen fuel reaches to the electrode and dissociates into H+

and e-. H+ move to the oxygen electrode through electrolyte. H+, O2, and electrons are combined to form water. The electron travel through the external circuit and provide power.

For Hydrogen storage, there are two group of techniques to store hydrogen. One is physical, and another is material-based storage system. However, both storage system have their limitation. Physical storage needs high pressure or large volume, and material-based hydrogen, like metal hydride, needs high pressure and temperature in order to release hydrogen [18].

Reference [26] studied that hydrogen storage in microgrid which incorporating with renewables was greatly utilized, in order to safely balance all the uncertainties from loads and renewables. Hydrogen storage technology is preferred in the case of load-shifting applications in larger time scale comparing with battery system [27]. However, this technique is costly, because of the cost of electrolysis and the cost of fuel cell. its efficiency is the most critical criteria to develop this technology [27].

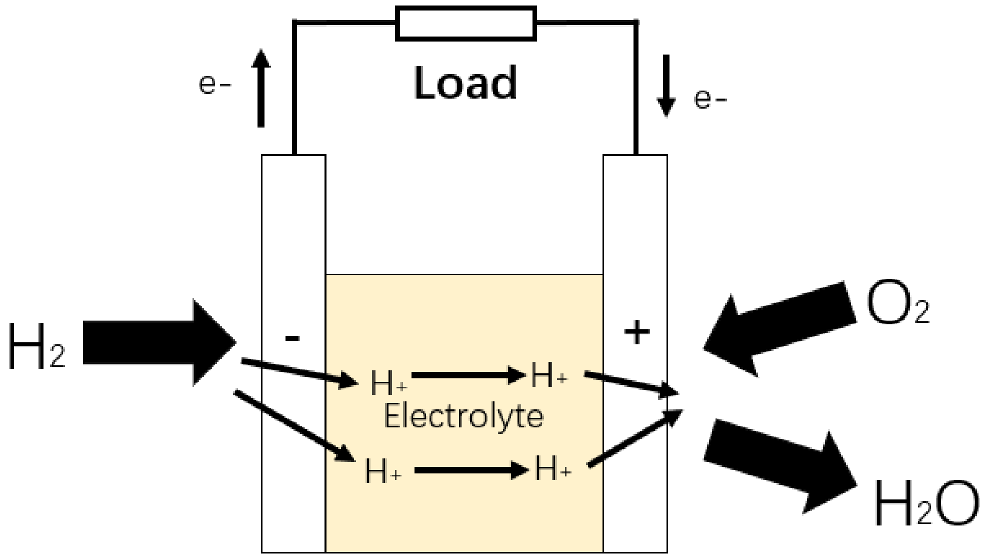


**Figure 2.5:** Basic principle of fuel cell

### 2.2.3 Heat storage

Thermal Energy Storage (TES) systems can store energy in the form of heat or ice, which can be released later if needed. TES can be mainly categorized into two groups: low-temperature TES (LTTES) and high-temperature TES (HTTES), which given by operation temperature. LTTES operates at a temperature below 200 $\circ$C and can be applied to solar cooking and water heating [28]. High-temperature TES can be classified into three categories: sensible heat (SHS), latent heat (LHS), and absorption and adsorption system (AAS). The main types of thermal energy storage are shown in Figure 2.6 [29].

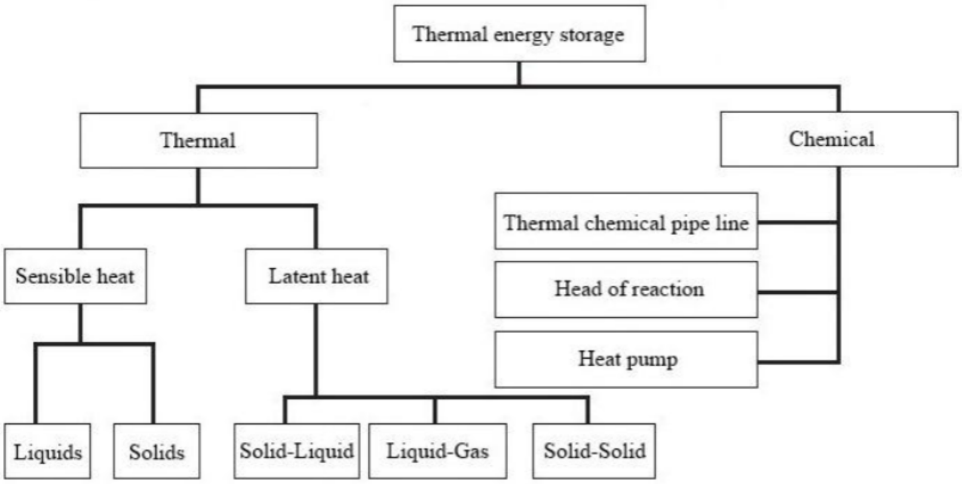


**Figure 2.6:** The main types of thermal energy storage[28]

In this paper, Azelio TES.POD 1.0 is used as thermal energy system, which belong to LHS. The TES.POD 1.0 in standard configuration consists of a Stirling engine as power conversion unit and a thermal energy storage filled with 4,4 tons of PCM AlSi. LHS materials are broadly classified based on their physical transformation for heat absorbing and desorbing capabilities. TES is advantageous with its low charging cost of heat exchanger, low capital cost of heat storage in caverns, low self-discharge rate, secured energy, environment-friendliness, and acceptable energy density [30]. At present, TES systems based on sensible heat are commercially available [29].

# 3

# Methods

## 3.1 Model parameter data collection

The parameter data can be divided in two parts, data of the existing energy system and data of technical options. For existing energy system, there are hourly data on generation, consumption, electricity price and network tariff, which can be obtained directly. The capacity of transformers between microgrids and the main grid is calculated according to the electrical diagram of the real grid.
As for technical options, the significant properties of each technical option should be well investigated before building the energy system model. And the investigation result should be introduced into the model. So that the running results can reflect strengthens and weaknesses of different technical options. To make a better comparison, for each technical option, there is no fixed ratio of different parts' sizes in one unit. Instead, the combination of different capacities for one technical option can be flexible. As for energy storage technologies, the is no limitation on how much power capacities should be attached for a 1kWh of energy storage capacity. The charge power capacity and discharge power capacity can be different as well. And the investment is not on numbers of fixed units. Thus, the installed capacity is not necessarily a multiple of a value, it can be any number instead. As for microgrid interconnection, the installed power capacity of cable and PCS can change flexibly according to system's need. For each technical option, the data collection process may be different. Table 3.1 shows the results of data collection for technical options.

For battery and hydrogen storage system, all the data are obtained directly[31, 32]. Specifically, the investment cost on battery's power capacity is decided by the larger one between installed charge power capacity and installed discharge power capacity. Therefore, there is only one item for investment cost on charge and discharge power capacity.
For heat storage system, the financial data from a commercial product is used [33]. But there is detailed technical data such as the size of each part in one product, indicating the round-trip efficiency. And the data of some parts can be found in other resources with similar technology. Based on this, there is an estimation for distribution of the total product cost on each part.
For microgrid interconnection, the cable cost varies with different diameter and power capacity [34]. And the data selected for simulation is the level for most of the sizes. The financial data of PCS are the same with that of PCS in battery. It is also notable that since time scale of the model is one year, the investment

**Table 3.1:** Parameter data for technical options

| **battery** | |
|---|---|
| Annualized energy storage capacity investment cost(€/kWh/year) | 18.62 |
| Annualized charge/discharge power capacity investment cost(€/kW/year) | 22.21 |
| O&M variable cost(€/kWh) | 0.002 |
| Charge efficiency | 98% |
| Discharge efficiency | 97% |
| **Hydrogen** | |
| Annualized energy storage capacity investment cost(€/kWh/year | 4.04 |
| Annualized charge power capacity investment cost(€/kW/year) | 55.88 |
| Annualized discharge power capacity investment cost(€/kW/year) | 78.09 |
| O&M variable cost(€/kWh) | 0 |
| Charge efficiency | 66% |
| Discharge efficiency | 53% |
| **Heat** | |
| Annualized energy storage capacity investment cost(€/kWh/year) | 4.08 |
| Annualized charge power capacity investment cost(€/kW/year) | 0.00 |
| Annualized discharge power capacity investment cost(€/kW/year) | 119.15 |
| O&M variable cost(€/kWh) | 0.00 |
| Charge efficiency | 100% |
| Discharge efficiency | 28% |
| **Cable** | |
| Annualized cable power capacity investment cost(€/(kW*km)/year) | 0.33 |
| Length of cable (km) | 2.00 |
| Annualized converter investment cost(€/kW/year) | 43.33 |

costs throughout the lifetime are annualized with discount rate of 5%. The detailed calculation can be found in Appendix A.

## 3.2 Energy system modelling

### 3.2.1 Scenario formulation

Considering the potential challenges for the energy system and the microgrids in the future, varying requirements are designed for different scenarios. Also, the mi-

crogrids in scenarios can be separated as individual microgrids and interconnected microgrids, to make a comparison of them through the results. The detailed scenarios are listed below.
Scenario 1a) Individual microgrids facing varying requirement of island mode duration, see Figure 3.1. There is no cable or other connection between microgrid A and microgrid B, the two microgrids meet their constraints individually. Based on this, the duration requirements of island mode changes from 0 to 40 hours. And N-1 criteria should be ensured for all the time except island mode.

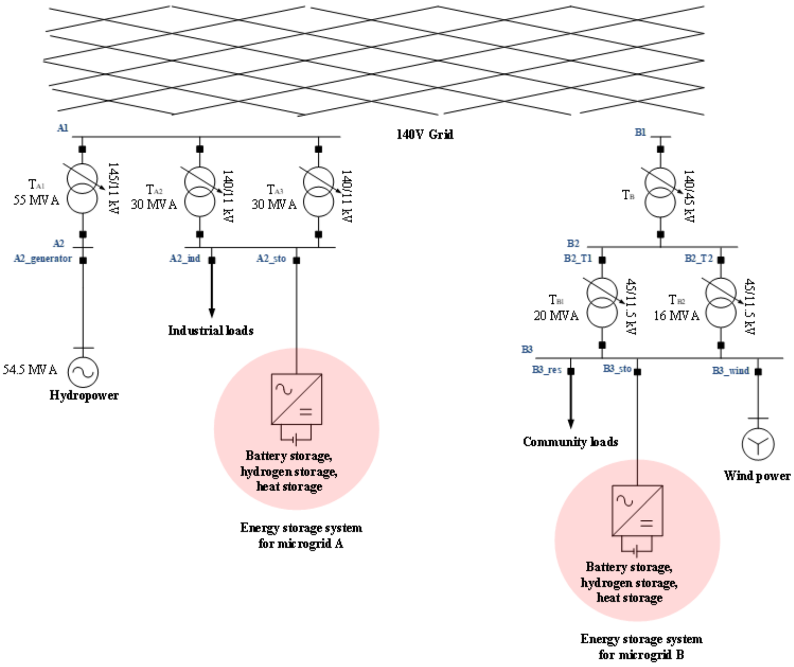


**Figure 3.1:** Electrical diagram of Scenario 1a

Scenario 1b) Individual microgrids with varying extent of load expansion, as Figure 3.2 shows. There is no cable or other connection between microgrid A and microgrid B, which is the same with 1a. But there will be additional load instead of island mode requirements. The load is increased to different size, until double of the original load. And N-1 criteria are one of the constraints for all the time.

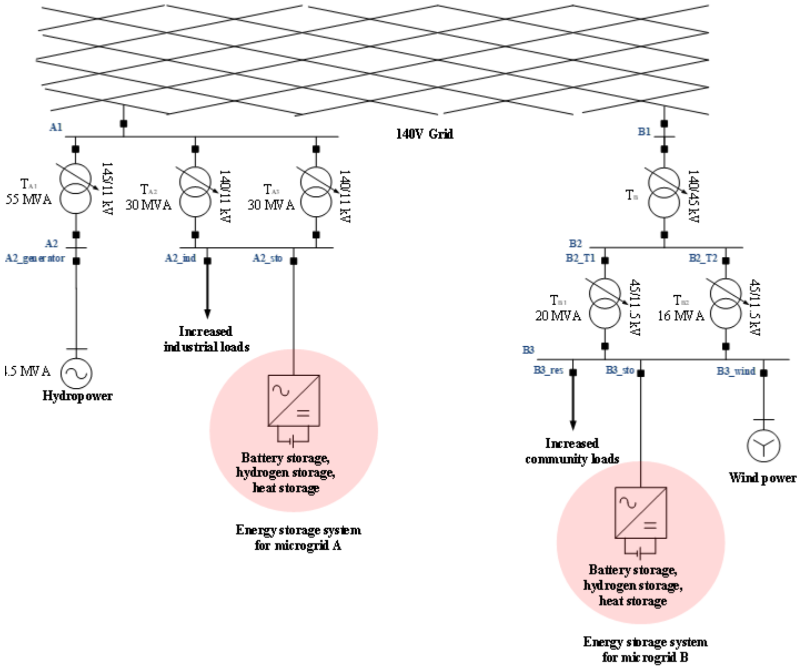


**Figure 3.2:** Electrical diagram of Scenario 1b

Scenario 2a) Interconnected microgrid to manage varying duration of island mode. Allow for investment on cable and power conversion system between microgrid A and microgrid B and enable microgrids to sustain island operation mode for varying durations (0-40 hours). And N-1 criteria should be ensured for all the time except island mode. Furthermore, two situations are considered: a situation when there is a break at one of the microgrids ('single island mode') and a situation when there is a break at both microgrids ('double island mode'). Accordingly, three sub scenarios are derived as followings.

Scenario 2a-A) Only microgrid A loses connection with the main grid during island mode, see Figure 3.3.

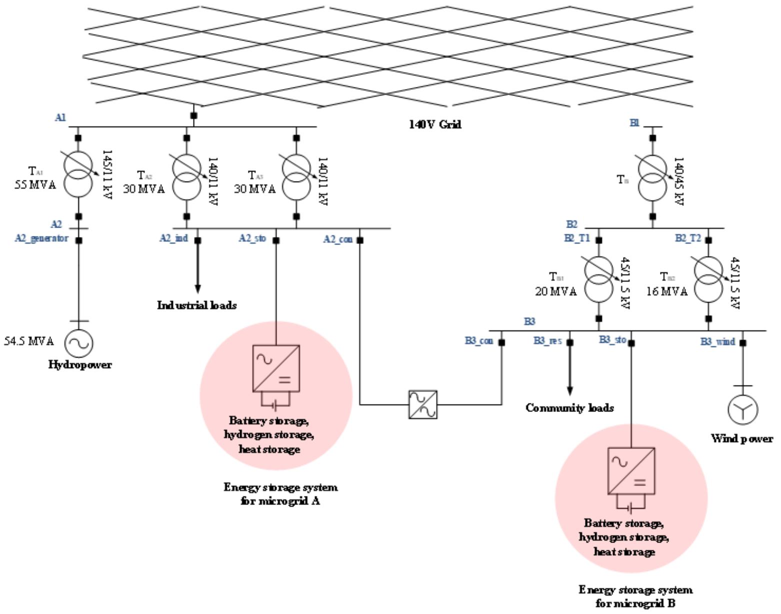


**Figure 3.3:** Electrical diagram of Scenario 2a-A

Scenario 2a-B) Only microgrid B loses connection with the main grid during island mode, see Figure 3.4.
Scenario 2a-AB) Both microgrids lose connection with the main grid during island mode, see Figure 3.5.

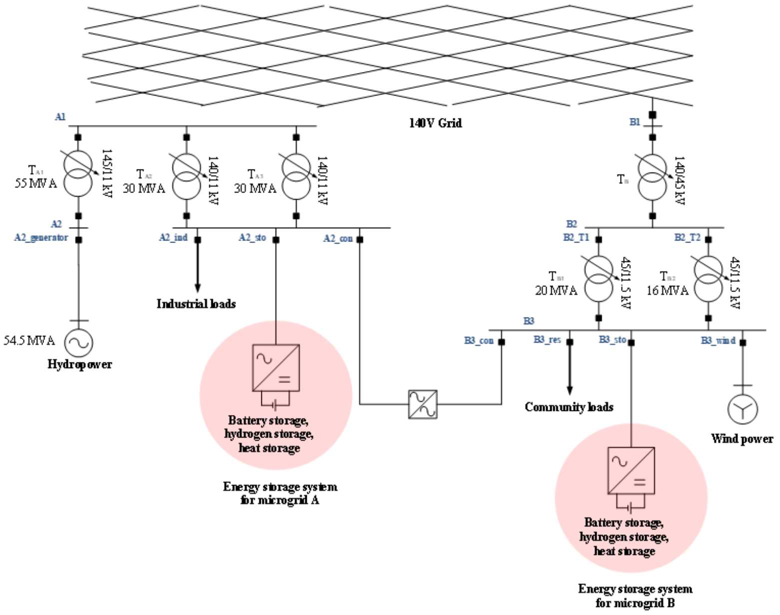


**Figure 3.4:** Electrical diagram of Scenario 2a-B

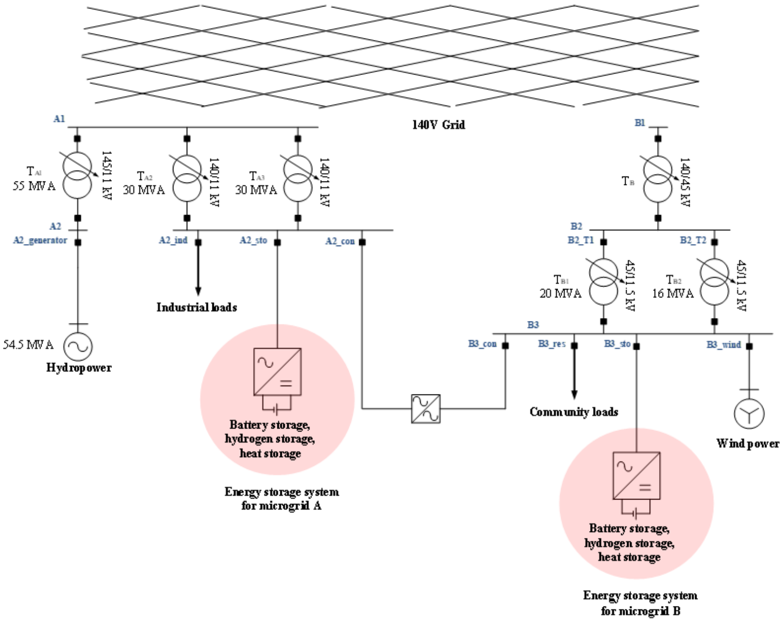


**Figure 3.5:** Electrical diagram of Scenario 2a-AB

Scenario 2b) Interconnected microgrids with varying extent of load expansion, which can be seen in Figure 3.6. Allow for cable and power-electronic converter investment to make microgrid A and microgrid B interconnected. The load is increased step by step until double of the original load. And N-1 criteria are one of the constraints for all the time.

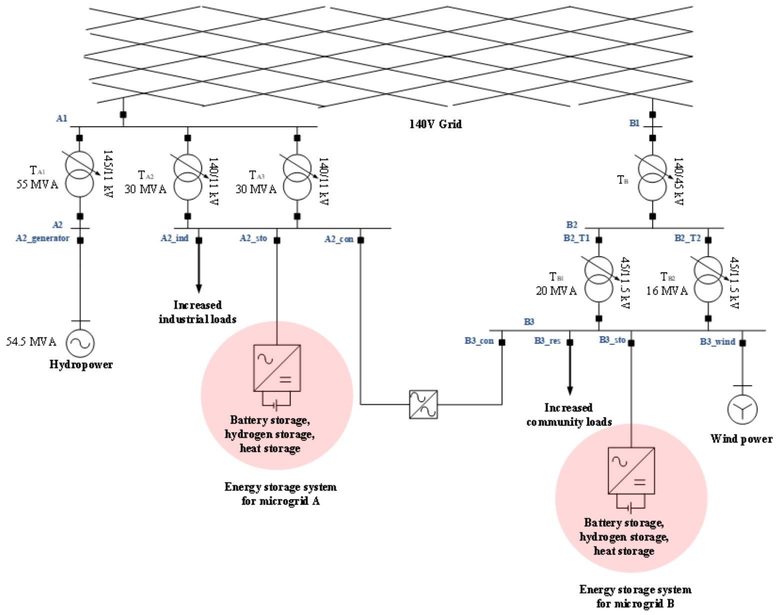


**Figure 3.6:** Electrical diagram of Scenario 2b

The software to optimize the microgrid design is GAMS. To catch up with the operation of different sides along the time, following indexes are attached to detail the parameters and variables.

Time $T$={1,. . . ,8760}
Energy Storage Technologies $I$ = {battery, hydrogen storage, heat storage}
Microgrid $M$ = {A,B}
Renewable power plant $R$ = {hydropower, wind power}
Followings are the parameters and variables included in all scenarios.

**Parameters:**

| | |
|---|---|
| $G_{r,t}$ | Electricity generated in renewable power plant $r$ at time $t$ [kWh] |
| $G_{m,t}$ | Electricity generated in microgrid $m$ at time $t$ [kWh] |
| $D_{m,t}$ | Demand in microgrid $m$ at time $t$ [kWh] |
| $TC_m$ | transformer power capacity between microgrid $m$ and main grid [kw] |
| $\eta_{i,in}$ | charge efficiency of technology $i$ |
| $\eta_{i,out}$ | discharge efficiency of technology $i$ |

**Variables:**

| | |
|---|---|
| $EC_{i,m}$ | Installed energy storage capacity in technology $i$ connected to microgrid $m$ [kWh] |
| $IC_{i,m}$ | Installed input power capacity in technology $i$ connected to microgrid $m$ [kW] |
| $OC_{i,m}$ | Installed output power capacity in technology $i$ connected to microgrid $m$ [kW] |
| $E^{in}_{m,i,t}$ | Electricity charged by microgrid $m$ to technology $i$ at time $t$ [kWh] |
| $E^{out}_{m,i,t}$ | Electricity discharged by technology $i$ to microgrid $m$ at time $t$ [kWh] |
| $S_{m,i,t}$ | Storage level in device $i$ connected to microgrid $m$ at time $t$ [kWh] |
| $E^{bought}_{m,t}$ | Electricity purchased by microgrid $m$ from main grid at time $t$ [kWh] |
| $E^{sold}_{m,t}$ | Electricity sold to main grid from microgrid $m$ at time $t$ [kWh] |

Accordingly, there are some constraints that work for all scenarios.
**Supply-demand balance constraint:**

$$G_{m,t} + E_{m,t}^{bought} - E_{m,t}^{sold} + \sum_{i \in I} E_{m,i,t}^{out} \times \eta_{i,out} \geqslant D_{m,t} + \sum_{i \in I} E_{m,i,t}^{in} + E_{m,t}^{tra}, \forall m \in M, t \in T \tag{3.1}$$

**Storage constraints:**

$$S_{m,i,t} = S_{m,i,t--1} + E_{m,i,t}^{in} \times \eta_{i,in} - E_{m,i,t}^{out}, \forall i \in I, m \in M, t \in T \tag{3.2}$$

$$S_{m,i,t} \leq EC_{i,m}, \forall i \in I, m \in M, t \in T \tag{3.3}$$

$$E_{m,i,t}^{in} \leq IC_{i,m}, \forall i \in I, m \in M, t \in T \tag{3.4}$$

$$E_{m,i,t}^{out} \times \eta_{i,out} \leq OC_{i,m}, \forall i \in I, m \in M, t \in T \tag{3.5}$$

**Transmission constraints:**

$$E_{m,t}^{bought} \leq TC_m, \forall m \in M, t \in T \tag{3.6}$$

$$E_{m,t}^{sell} \leq TC_m, \forall m \in M, t \in T \tag{3.7}$$

**Individual microgrids**

For individual microgrids, the N-1 criteria is ensured separately in microgrid A and microgrid B. In case the energy storage level in a device is lower than the installed discharge power capacity, a variable $n_{m,i,t}$ is introduced.

| | |
|---|---|
| $n_{m,i,t}$ | The maximum electricity output can be provided by technology $i$ in microgrid $m$ at time $t$ [kW] |

$$n_{m,i,t} = Min(S_{m,i,t} \times \eta_{i,out}, OC_{i,m}) \tag{3.8}$$

For microgrid A, since hydropower production and main grid both transmit electricity through transformer $T_{A2}$ or $T_{A3}$ to loads and energy storage system, the transformer to test N-1 criteria is $T_{A2}$ or $T_{A3}$. If either of them is disconnected, there is no more than 30 MW electricity can be supplied by hydropower and main grid to industrial loads.

$$30000 + \sum_{i \in I} n_{A,i,t} \geqslant D_{A,t}, \forall t \in T \tag{3.9}$$

For microgrid B, the device to test N-1 criteria is the largest one among transformers and wind power plant. The largest hourly wind power is 11.9 MW. Therefore, the 20 MW transformer $T_{B1}$ is the standard for N-1 criteria test. If $T_{B1}$ is disconnected, there is no more than 16 MW electricity can be supplied by main grid to community loads.

$$16000 + G_{B,t} + \sum_{i \in I} n_{B,i,t} \geqslant D_{B,t}, \forall t \in T \tag{3.10}$$

Furthermore, for Scenario 1a, there are constraints for the island mode requirement. The island mode does not happen in an appointed period during a year. The connection between the microgrids and the main grid is allowed to be used all the time. But there must be enough backup, both for energy and power, to sustain the microgrid at any time when island mode happens. The microgrids depend on energy storage system to cover the net load during island mode. The output electricity amount of energy storage system is not only decided by the storage level, but also the installed output capacity. Therefore, a new variable $E^{is}_{m,i,t,d}$ is introduced.

| | |
|---|---|
| $E^{is}_{m,i,t,d}$ | The maximum electricity can be supplied during island mode by technology $i$ in microgrid $m$ at time $t$ for duration d [kWh] |

During the island mode, not only the total energy requirement needs to be satisfied. There may be cases that the accumulated netload is positive for a few hours during the island mode but falls to zero only in final hours. To avoid this, the energy requirement of each hour during island mode needs to be handled. Following is the constraint based on this consideration. Assume the island mode requirement duration is $k$ hours. The island mode happens at time $x$. And it has lasted for $y$ hours.

**Island mode requirement constraint for Scenario 1a:**

$$E^{is}_{m,i,x,y} = Min(S_{m,i,x} \times \eta_{i,out}, y * OC_{i,m}) \tag{3.11}$$

$$\sum_{t=x}^{t=x+y} G_{m,t} + \sum_{i\in I} E^{is}_{m,t,x,y} \geqslant \sum_{t=x}^{t=x+y} D_{m,t}, \forall m \in M, x \in [1, 8760-k], y \in [0,k] \tag{3.12}$$

**Interconnected microgrids**

For interconnected microgrids, there is transmission between microgrid A and microgrid B. Thus, extra variables and constraints are introduced for microgrid interconnection.

**variables:**

| | |
|---|---|
| $CC$ | Installed cable power capacity [kW] |
| $E^{tra}_{m,t}$ | Electricity transmitted from microgrid $m$ to another microgrid at time $t$ [kWh] |

**Interconnection transmission constraints**

$$E^{tra}_{A,t} = -E^{tra}_{B,t}, \forall t \in T \tag{3.13}$$

$$-CC \leq E^{tra}_{m,t} \leq CC, \forall m \in M, t \in T \tag{3.14}$$

Since the two microgrids can supply electricity to each other, the N-1 criteria refers only one device to be disconnected in the whole system. The device to test N-1 criteria is the largest one among transformers, interconnection cable and the wind power plant. Here the 30 MW transformers are taken as attempt firstly. According to the running results, the cable capacity is no larger than 10.4 MVA (while the load is 200%). The largest hourly wind power is 11.9 MW. Therefore, the 30 MW transformer, $T_{A2}$ or$T_{A3}$, is standard of N-1 constraint in all the interconnected cases. If either of them is disconnected, there is no more than 66 MW (30 MW +20 MW +16MW) electricity can be supplied by hydropower and main grid to loads. Besides, although microgrid A and microgrid B is seemed like a whole. There is still a power capacity constraint for the cable between them. Therefore, there are individual constraint for each microgrid for N-1 criteria.

**N-1 constraint**

$$66000 + G_{B,t} + \sum_{i \in I, m \in M} n_{m,i,t} \geqslant \sum_{m \in M} D_{m,t}, \forall t \in T \tag{3.15}$$

$$30000 + \sum_{i \in I} n_{A,i,t} + CC \geqslant D_{A,t}, \forall t \in T \tag{3.16}$$

$$36000 + \sum_{i \in I} n_{B,i,t} + G_{b,t} + CC \geqslant D_{B,t}, \forall t \in T \tag{3.17}$$

For Scenario 2a, there are three sub scenarios. Firstly, Scenario 2a-AB with 'double island mode' is discussed. Because there is no difference between constraints for microgrid A and microgrid B, which can supply basis for 'single island mode' to make change on one of the microgrids. For both microgrids, not only the energy storage system supply electricity to consumers, but also, they can get electricity from each other. And the extreme case is one microgrid supply electricity to the other with whole interconnection cable capacity all over the island mode. The first constraint below considers this case for each microgrid. But it may lead the transmission on both directions to be positive at the same time. Thus, there is an extra constraint to ensure the supply-demand in sum during island mode, as the second one. Assume the island mode requirement duration is $k$ hours. The island mode happens at time $x$. And it has lasted for $y$ hours.

**Island mode requirement constraint for Scenario 2a-AB**

$$\sum_{i \in I, m \in M} E^{is}_{m,i,x,y} + CC \times y \geqslant \sum_{t=x, m \in M}^{t=x+y} D_{m,t} - \sum_{t=x, m \in M}^{t=x+y} G_{m,t}, \forall m \in M, x \in [1, 8760-k], y \in [0, k] \tag{3.18}$$

$$\sum_{t=x, m \in M}^{t=x+k} G_{m,t} + \sum_{t=x, m \in M, y=k} E^{is}_{m,i,x,y} \geqslant \sum_{t=x, m \in M}^{t=x+k} D_{m,t}, \forall x \in [1, 8760-k] \tag{3.19}$$

For Scenario 2a-A, the constraint for microgrid A does not change, as the first constraint below. But for microgrid B, it can buy electricity from the main grid during island mode. According to the transformers' sizes in microgrid B, the electricity supply from the main grid can be up to 36 MWh per hour. It makes the constraint for microgrid B looser, and same for the sum constraint, see the second and third constraint below.

**Island mode requirement constraint for Scenario 2a-A**

$$\sum_{i\in I} E^{is}_{m=A,i,x,y} + CC \times y \geqslant \sum_{t=x}^{t=x+y} D_{m=A,t} - \sum_{t=x}^{t=x+y} G_{m=A,t} \forall x \in [1, 8760-k], y \in [0,k] \tag{3.20}$$

$$\sum_{i\in I} E^{is}_{m=B,i,x,y} + CC \times y + 36000 \times y \geqslant \sum_{t=x}^{t=x+y} D_{m=B,t} - \sum_{t=x}^{t=x+y} G_{m=B,t} \forall x \in [1, 8760-k], y \in [0,k] \tag{3.21}$$

$$\sum_{i\in I} E^{is}_{m,i,x,y} + 36000 \times y \geqslant \sum_{t=x,m\in M}^{t=x+k} D_{m,t} - \sum_{t=x,m\in M}^{t=x+k} G_{m,t} \forall x \in [1, 8760-k] \tag{3.22}$$

For scenario 2a-B, things are similar with that in Scenario 2a-A. But this time the main grid input electricity through microgrid A. And the transformers' capacity is larger as 60 MW.

$$\sum_{i\in I} E^{is}_{m,i,x,y} + CC \times y + 60000 \times y \geqslant \sum_{t=x}^{t=x+y} D_{m=A,t} - \sum_{t=x}^{t=x+y} G_{m=A,t} \forall x \in [1, 8760-k], y \in [0,k] \tag{3.23}$$

$$\sum_{i\in I} E^{is}_{m=B,i,x,y} + CC \times y \geqslant \sum_{t=x}^{t=x+y} D_{m=B,t} - \sum_{t=x}^{t=x+y} G_{m=B,t} \forall x \in [1, 8760-k], y \in [0,k] \tag{3.24}$$

$$\sum_{i\in I} E^{is}_{m,i,x,y} + 60000 \times y \geqslant \sum_{t=x,m\in M}^{t=x+k} D_{m,t} - \sum_{t=x,m\in M}^{t=x+k} G_{m,t} \forall x \in [1, 8760-k] \tag{3.25}$$

### 3.2.2 Financial optimization

The standard of the optimization solution is from economic perspective. By minimizing the total cost, the cheapest solution is recognized as the optimal one. Therefore, the financial data collected for technical options and electricity trade are introduced as parameters in the model.

**Parameters**

| | |
|---|---|
| $C_i^{es}$ | Annualized energy storage capacity investment costs of energy storage technology $i$ [Euro/kWh, year] |
| $C_i^{in}$ | Annualized input capacity investment costs of energy storage technology $i$ [Euro/kW, year] |
| $C_i^{out}$ | Annualized output capacity investment costs of energy storage technology $i$ [Euro/kW, year] |
| $C_c^{inv}$ | Annualized investment costs of cable [Euro /(kW*km), year] |
| $C_{PCS}^{inv}$ | Annualized investment costs of PCS [Euro /kW, year] |
| $C_i^{v}$ | Variable O&M costs of each energy storage technology [Euro /kWh] |
| $P_t$ | price of electricity at time $t$ [euro/kWh] |
| $C_{m,t}^{net,trans}$ | Transfer fee to receiving electricity from the main grid to grid $m$ at time $t$ [Euro /kWh] |
| $C_{m,r}^{net,gen}$ | Capital compensation for generating in power plant $r$ in grid $m$[Euro /kWh] |
| $LC$ | Length of cable investment [km] |

To get the most cost-efficient solutions, the total cost $C^{tot}$ should be minimized. Therefore, the objective function is as follow.

**Objective function:**

Minimize $C^{tot}$

$$\begin{aligned} C^{tot} = & \sum_{i\in I, m\in M} C_i^{es} \times EC_{i,m} + \sum_{i\in I, m\in M} C_i^{in} \times IC_{i,m} + \sum_{i\in I, m\in M} C_i^{out} \times OC_{i,m} \\ & + \sum_{i\in I, m\in M, t\in T} C_i^{v} \times E_{m,i,t}^{out} + \sum_{m\in M, t\in T} E_{m,t}^{bought} \times P_t + C_c^{inv} \times (CC \times LC + C_{PCS}^{inv}) \\ & - \sum_{m\in M, t\in T} E_{m,t}^{sold} \times P_t + \sum_{m\in M, t\in T} E_{m,t}^{bought} \times C_t^{net,trans} - \sum_{m\in M, t\in T} E_{m,t}^{sold} \times C_r^{net,gen} \end{aligned} \tag{3.26}$$

**Cost saving effect verification:**

Sometimes to verify the running result is the most cost-efficient solution, some extra cases will be designed for comparison. For example, for Scenario 2b, a special case allowing investment in cable only is used, to show the investment in energy storage technology is effective indeed to cut the total cost. Following are some extra variables exclusively for the economic calculation about this case. The result is shown in Table 4.3.

The variables with subscript 'without storage' means these variables are in the scenario where no investment on energy storage technology is allowed, i.e., the only way to handle the requirements is to increasing the capacity of cable and PCS between the two microgrids.

Net profit from energy arbitrage $C_{net}^{ar}$:

$$C^{ar} = \sum_{m \in M, t \in T} E_{m,t}^{sell} \times (P_t + C_{m,t}^{net,trans}) - E_{m,t}^{bought} \times (P_t + C_{m,r}^{net,gen}) \tag{3.27}$$

$$C_{without\ storage}^{ar} = \sum_{m \in M, t \in T} E_{m,t,without\ storage}^{sell} \times (P_t + C_{m,t}^{net,trans}) - E_{m,t,without\ storage}^{bought} \times (P_t + C_{m,r}^{net,gen}) \tag{3.28}$$

$$C_{net}^{ar} = C^{ar} - C_{without\ storage}^{ar} \tag{3.29}$$

Extra cable cost if no energy storage $C^{cable,extra}$:

$$C^{cable} = C_c^{inv} \times (CC \times LC + C_{PCS}^{inv}) \tag{3.30}$$

$$C_{without\ storage}^{cable} = C_{c,without\ sotrage}^{inv} \times (CC \times LC + C_{PCS}^{inv}) \tag{3.31}$$

$$C^{cable,extra} = C_{wothout\ storage}^{cable} - C^{cable} \tag{3.32}$$

Cost of battery $C_{battery}^{cost}$:

$$\sum_{m \in M} C_{battery}^{es} \times EC_{battery,m} + C_{battery}^{in/out} \times OC_{battery,m} \tag{3.33}$$

Surplus from battery $C_{battery}^{surplus}$:

$$C_{battery}^{surplus} = C_{net}^{ar} + C^{cable,extra} - C_{battery}^{cost} \tag{3.34}$$

# 4

# Results

## 4.1 Optimization results for individual microgrids

### 4.1.1 Impact of island mode requirement to individual microgrids

For island mode requirement, results on installed energy storage capacity are analysed firstly because the island mode duration mainly impacts the energy capacity for backup power supply. The reason for installed charge/discharge power capacity to change may be partly explained by the change of installed energy storage capacity. Furthermore, the island mode requirement and N-1 constraint cause a stricter condition on installed discharge power capacity than on installed charge power capacity. Thus, the results about discharge power capacity will be shown before charge power capacity. The analysis on the total cost is discusses at the last because the cost constitution can be analysed based on change of capacities.

The energy storage capacity for scenario 1a is shown in Figure 4.1. For both microgrids in existing condition (without extra island capability requirements), there is no need for energy storage capacity, i.e., the benefit from arbitrage is not enough to offset the cost for new energy storage devices. In order to operate in island mode, investments in storage capacity is required. With island mode duration requirements shorter than 4 hours investments are made in battery storage only. The battery storage capacity is directly proportional to the duration for which island mode operation is required. Although hydrogen storage capacity is cheaper, the discharge power capacity in terms of fuel cell for hydrogen-electric generation is expensive. Therefore, the battery remains the most cost-efficient option to sustain the microgrid in island mode for short durations. However, after the duration requirement exceeds 4 hours, batteries are less cost-efficient in meeting the needs of the grid. The increasing island mode duration increases the energy storage requirement. Thus, the cost on energy storage capacity becomes the decisive factor on the choice of energy storage types. With cheaper energy storage capacity, hydrogen storage takes over the role as back up for island mode. The installed capacity of hydrogen storage grows faster at the beginning when it becomes a part of the optimization solution since it needs to not only catch up the extension of island mode requirement, but also cover the reduction of battery's storage capacity. After the island mode duration requirement increases for several hours, the value of battery capacity keeps at a relatively stable level ( around 3.4 MWh in microgrid A and 2.5 MWh in microgrid B) since battery storage capacity is arranged only to transfer load for

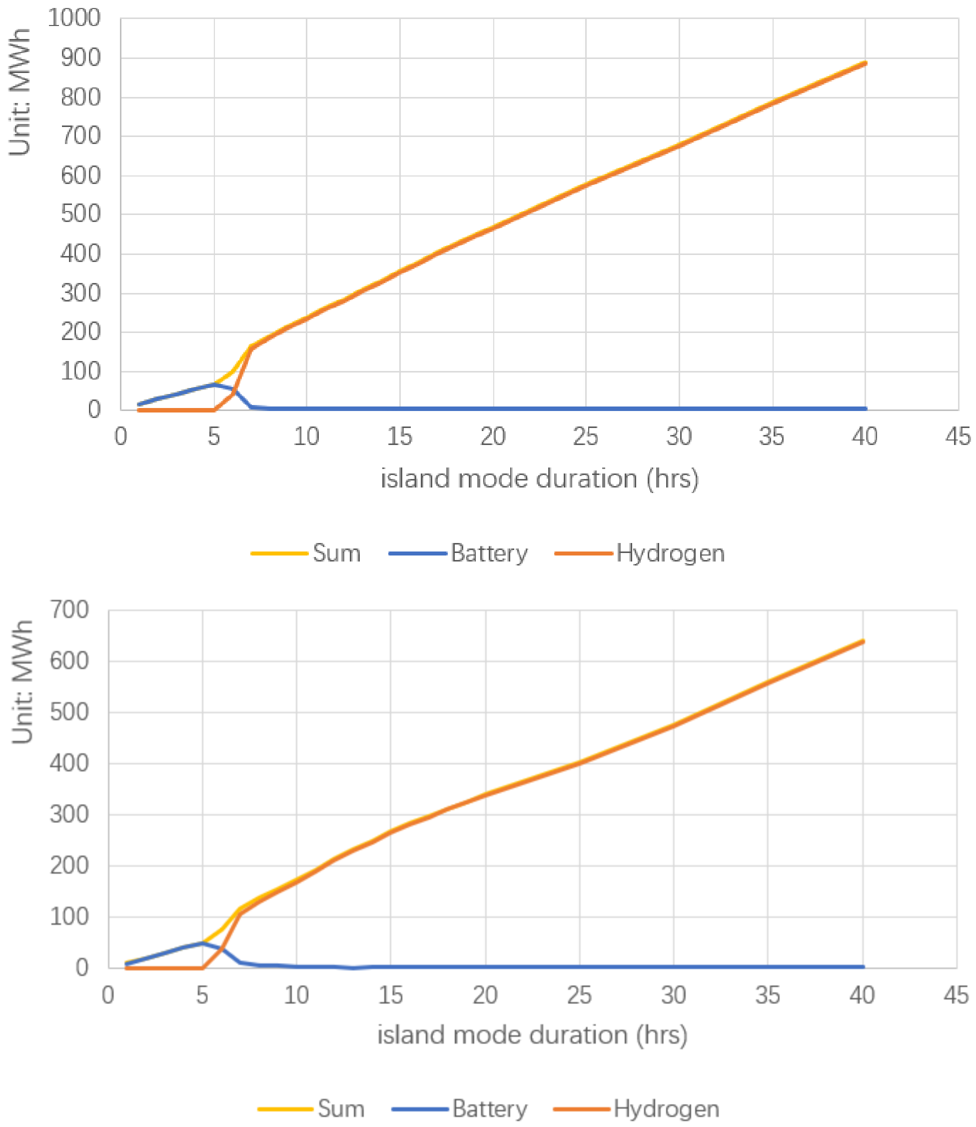


**Figure 4.1:** Sensitivity analysis on energy storage capacity (Scenario 1a,Microgrid A(Above), Microgrid B(below))

daily net load variation as a shifting strategy and satisfy the high power demand of the net load during island mode as a peak generation, which is little impacted by the longer island mode duration requirement. As a comparison, hydrogen storage capacity keeps growing because it serves as back-up storage to meet the island mode requirement.

Figure 4.2 shows results about discharge power capacity in Scenario 1a. For most of the time, the sum of discharge power capacity is a constant value. In microgrid A, the value is 14.273MW. In microgrid B, it is 10.245MW. Both values are the peak net loads in each microgrid. In this way, the battery and hydrogen storage device are designed to coordinate during island mode so that their discharge power capacities don't need to reach the peak net load individually. Since the island mode duration requirement doesn't impact the size of load, the total discharge power capacity is

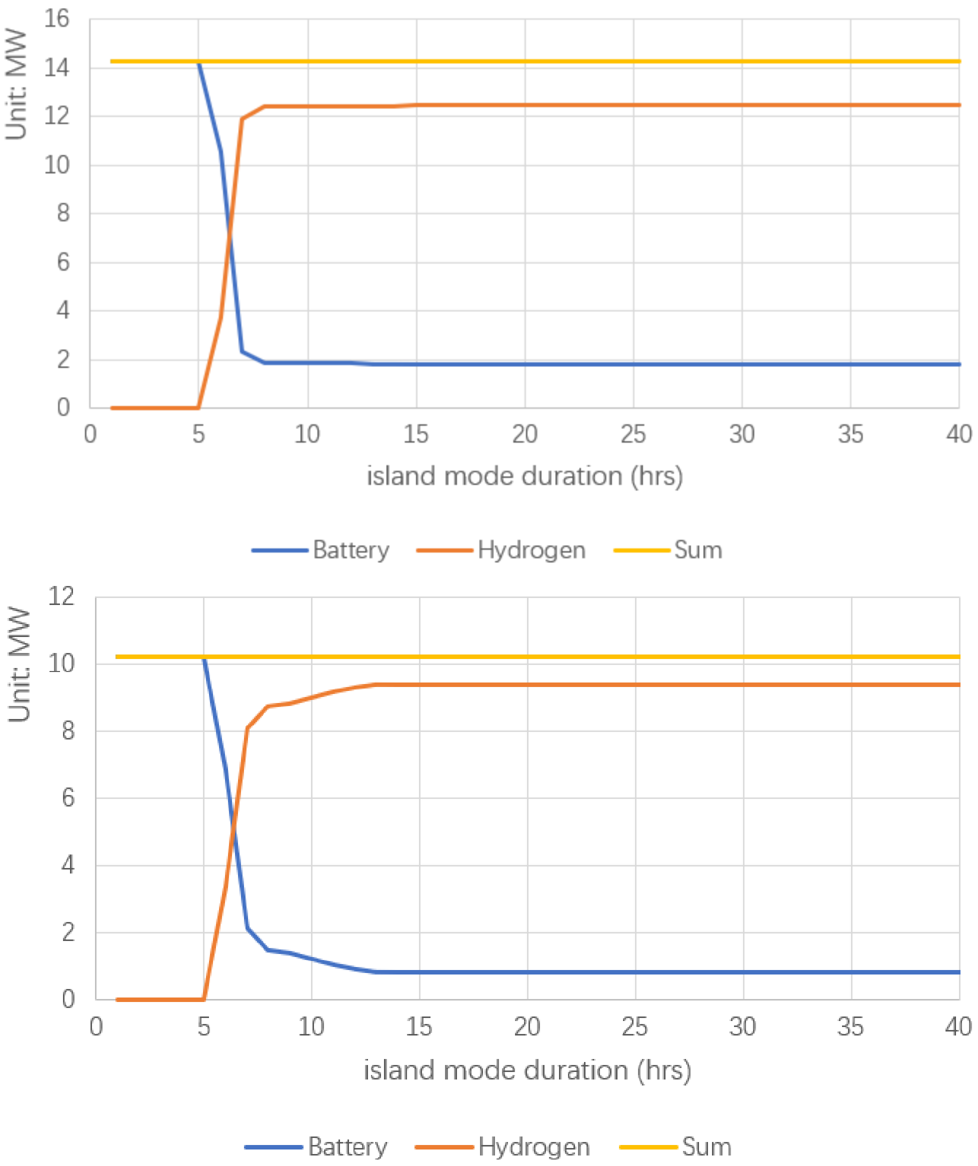


**Figure 4.2:** Sensitivity analysis on discharge power capacity (Scenario 1a,Microgrid A(Above), Microgrid B(below))

not sensitive to this requirement. The discharge power capacity of each technology is mainly decided by the cost of discharge power capacity and the cost-efficient size of the corresponding energy storage.

For the battery, the output capacity equals to the peak net load at the beginning because there is no other energy storage technology. It has to cover the whole net load during island mode. But after hydrogen storage technology appears in the solution, the output capacity of battery falls sharply down to a relatively low level. This level is mainly limited by the expensive energy storage capacity of the battery. Although the battery's output capacity is cheap, it is meaningless to increase it without matching energy storage capacity. Otherwise, the battery may be depleted before the end of island mode, leading the discharge power capacity of the fuel cell to rise until it equals to the peak net load, which is uneconomical.

For hydrogen storage system, it is not suitable for frequent cycling because of high investment cost on charge/discharge power capacity and relatively low energy roundtrip efficiency. However, the cost of energy storage is low, which makes it advantageous for long-term and large amount of energy. Figure 4.3 shows the energy storage of battery and hydrogen storage system over the year in the two microgrids while island mode duration requirement is 20 hours. According to the figure, the hydrogen storage system is hardly used for cycling in normal time, but more for a backup when island mode happens. To avoid frequent cycling, it is designed as the base generation i.e., to supply constant electricity output, during island mode. For this reason, the potential worst case of island mode for each duration in a year becomes the decisive case of hydrogen discharge power capacity. Table 4.1 is an example on cases when island mode duration requirements are 20 hours. To make a comparison, the serial 20 hours with highest accumulated netload, i.e., energy requirement, are found out. And their netload was changed to 0. With that, the discharge capacity of the hydrogen storage decreases. But battery's capacity even increases. The reason is that not only the worst case, but also the cases before and after the worst case are impacted. Their energy storage requirements decrease as well, causing lower threshold for battery to be more cost-efficient. Additionally, the total installed discharge power capacity in microgrid B also decreases after removing the worst case. The reason is that the peak net load in microgrid B is included in the worst case and removed as well. The requirement on total discharge power capacity is lower as the new peak net load is lower.

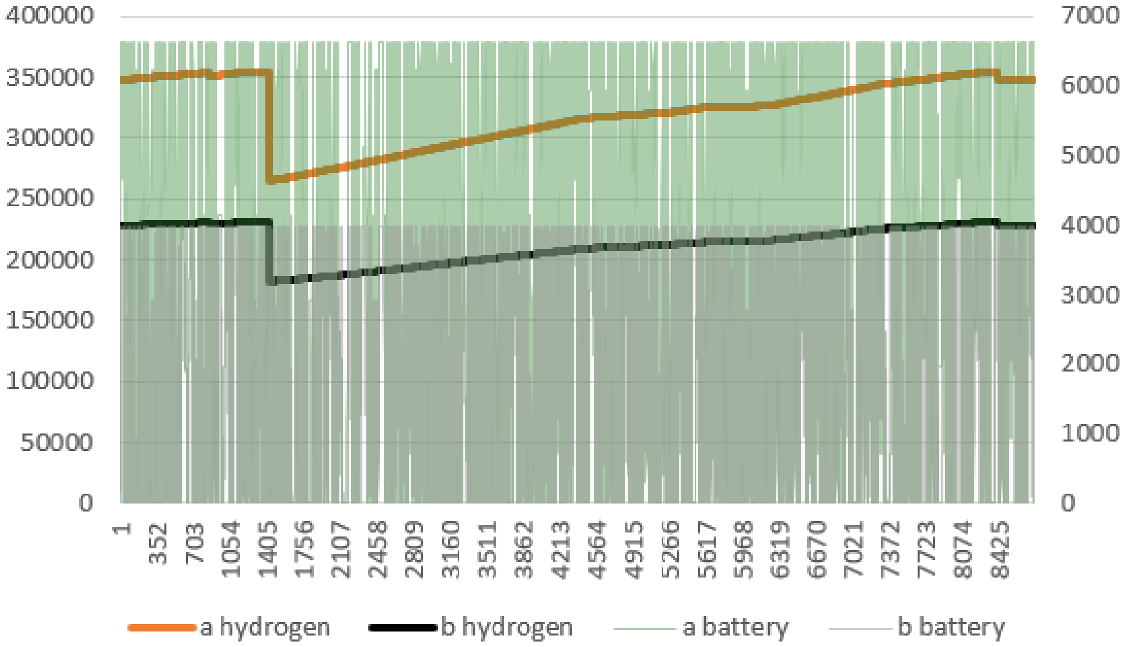


**Figure 4.3:** Change of storage level along the time (S 1a-20h)

As for the results about charge power capacity shown in Figure 4.4, battery's charge power capacity keeps the same with discharge power capacity. This is due to the characteristic of battery's power capacity cost. The cost is decided by the lager value of charge and discharge power capacity. In this way, no matter which one of

**Table 4.1:** Comparison of results before and after taking out the worst case

| | Installed Discharge capacity in Microgrid A (kW) | | | Installed Discharge capacity in Microgrid B (kW) | | |
|---|---|---|---|---|---|---|
| | Battery | Hydrogen | sum | Battery | Hydrogen | sum |
| S1a-20h | 1811.83 | 12461.16 | 14273 | 838.55 | 9406.44 | 10245 |
| S1a-20h without the worst case | 2554.58 | 11718.41 | 14273 | 961.66 | 8641.33 | 9603 |

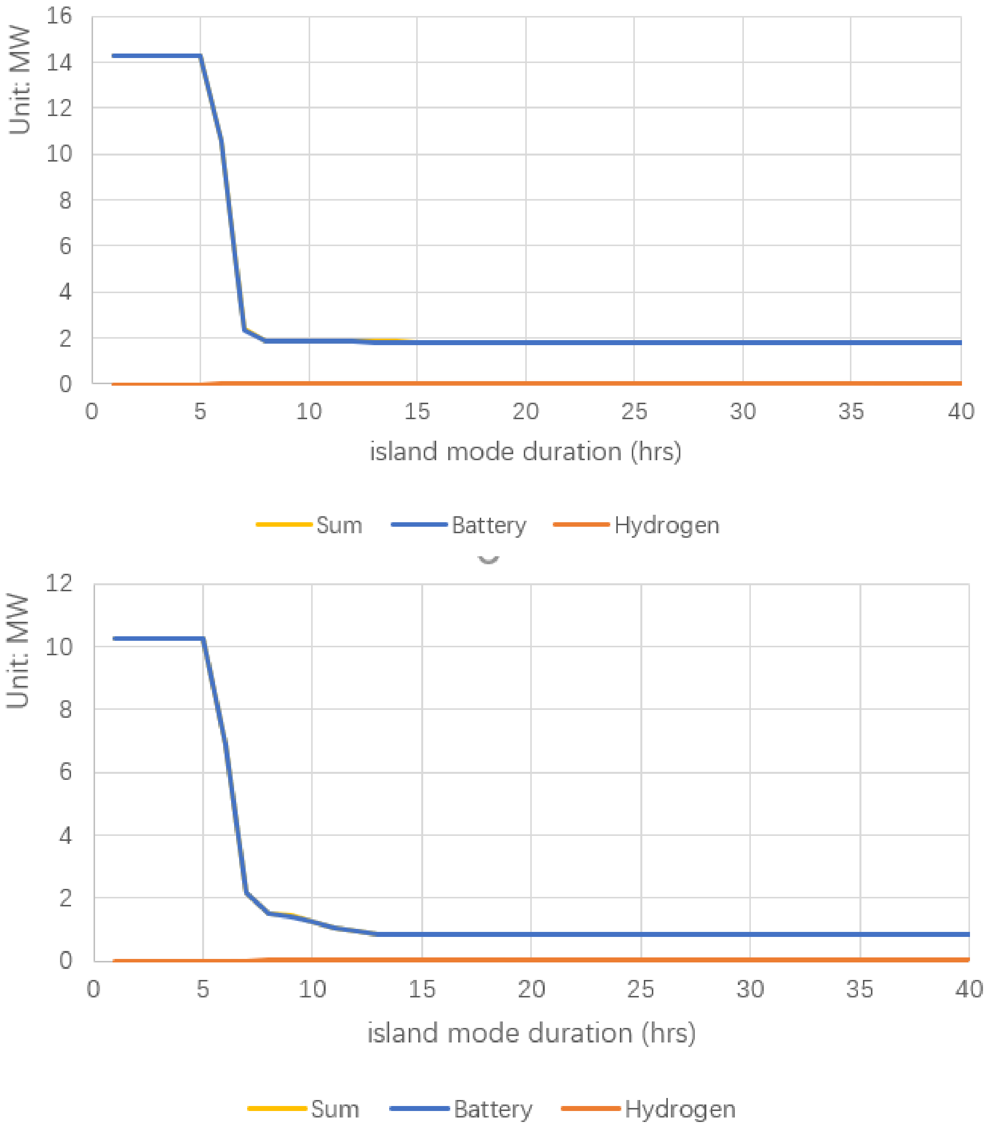


**Figure 4.4:** Sensitivity analysis on charge power capacity (Scenario 1a,Microgrid A(Above), Microgrid B(below))

them is the larger one, the other capacity can be regarded as free. Therefore, the charge power capacity is raised as long as it has no impact on total cost, to enhance battery's ability on absorbing energy. Comparing with battery, the charge power of hydrogen storage system is much smaller, which makes the curve of sum capacity nearly overlap the curve of battery's capacity. In microgrid B, there is even no charge power capacity for hydrogen storage before the island mode duration requirement is longer than 9 hours, i.e., hydrogen is a purely backup without cycling in these solutions. For other cases, the solutions contain charge power capacity for hydrogen storage system because the system discharges at least one time in a year, and the storage need to be refuelled. But as the duration curve shows in Figure 4.3, the discharge time occupies a tiny fraction of on a year, which means that all the time in the rest of the year is available for the system to charge. And only a small part of the hydrogen storage takes part in cycling. The storage level is more than 70% of the installed capacity all the time. As a result, the small charge power capacity is enough to keep the hydrogen storage system running.

Figure 4.5 A and Figure 4.5 B illustrate the constitution of total cost in each case. The stacked area analysis stops at the 20-hour-long island mode duration requirement. The reason is after that stimulation length steps change to 5 hours, instead of 1 hour. But the stable growth of total cost proves that results for omitted cases is likely to be similar with the cases that is showed.

The cost of energy storage technology is similar in the two microgrids. At the beginning, energy storage capacity investment cost causes the main cost as the battery is the dominating technology for energy storage. The cost declines while the hydrogen storage appears in the solution and competes with battery. Instead, the discharge power capacity investment cost for hydrogen storage grows rapidly until the function of the two technologies are clear in the solutions. As the island mode duration requirement increases continuously, the forementioned two type of investment costs occupy similar share in the total cost, which are also the critical factors enabling the two technologies as counterweights to each other. The O&M variable cost takes a relatively small share in total cost, especially after the introduction of hydrogen storage technology.

But there are also differences between the two microgrids. In microgrid A, income by selling electricity offsets a significant part of the total cost, since the renewable power in microgrid A (hydropower) is larger in size than that in microgrid B (wind power), there is more energy surplus that can be sold. But the power size does not grow with the island mode duration requirement. Thus, the benefit of selling electricity is smaller and smaller relative to the total cost. Furthermore, microgrid B needs to purchase more electricity from the main grid leading to a network cost around double of that in microgrid A. There is one more part named 'energy compensation'. It can be understood as 'negative network tariff', meaning that producers get paid for generating power, for helping with loss reduction in the network. The change of energy compensation is similar to the income of selling electricity in both microgrids. But the values are small, indicating that the main motivation for trade with the main grid is electricity price.

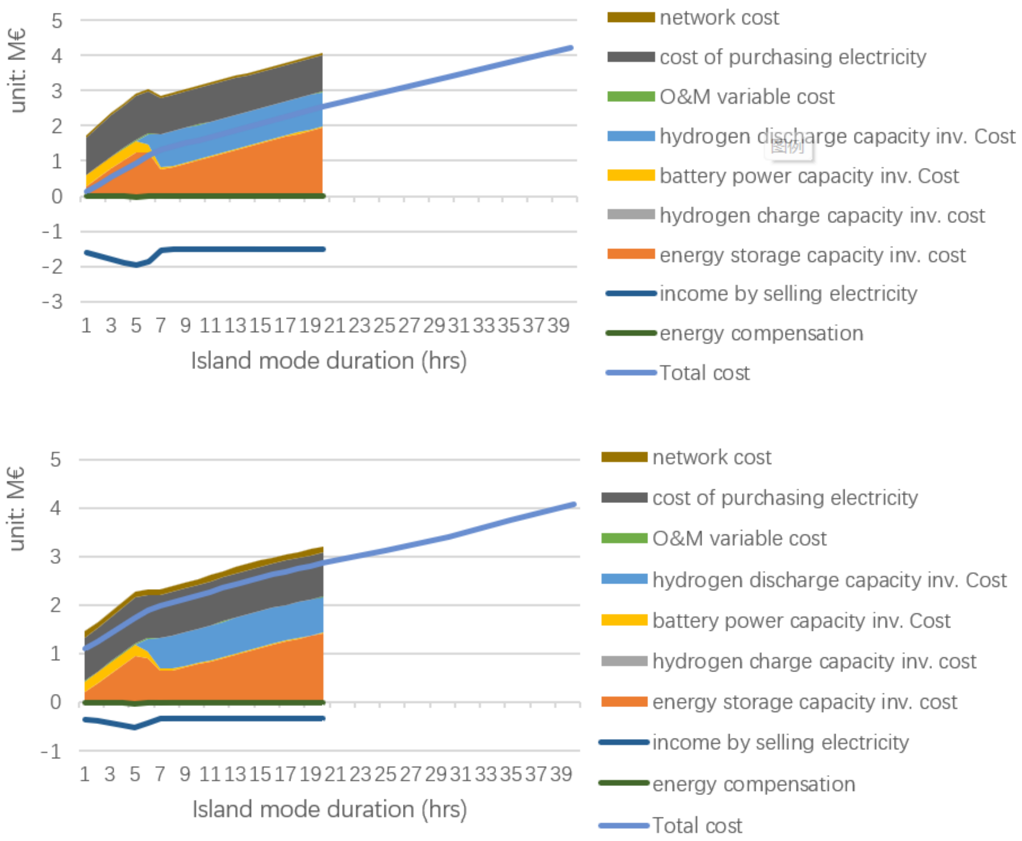


**Figure 4.5:** Stacked area of total cost (Scenario 1a,Microgrid A(Above), Microgrid B(below))

### 4.1.2 Impact of load increasing to individual microgrids

Comparing with scenario 1a, the optimization solution for scenario 1b seems relatively simple. As it is shown in Figure 4.6, there is no investment on energy storage technology until the load is raised to 150% of the existing size, taking N-1 constraint into consideration, i.e., the existing local grid is capable of satisfying 1.5 times of present load, even if it loses the largest transformer. If the load keeps increasing, the battery will be the only technology to manage the demand. In contrast to the island mode requirement, the scenario does not need long-term and large volume of energy storage anymore. Instead, the increasing load enhances the fluctuation of load, especially in short duration. Therefore, the main expectation of energy storage technology becomes the ability for frequent load shaving, i.e., transferring peak load from high net load hours to low net load hours. And the characteristics of battery match the expectation well. That is also why all the curves grow proportionately with the load size, or to say, with the net load variation size. The charge capacity equals the discharge capacity in all the solutions. The reason is mentioned before, as the cost is decided by the lager value of charge and discharge power capacities. The energy storage capacity is a bit larger but still close to the power capacity, indicating that hourly cycling is the main way of the battery to work. The battery is also arbitraging between high and low electricity price hours using the extra storage capacity. But the benefit from arbitraging is relatively low and does not incentivize more energy storage capacity. Thus the decisive factor of battery's installed discharge power capacity is N-1 constraint. As long as the capacity is enough for N-1 criteria, there is no more investment in it.

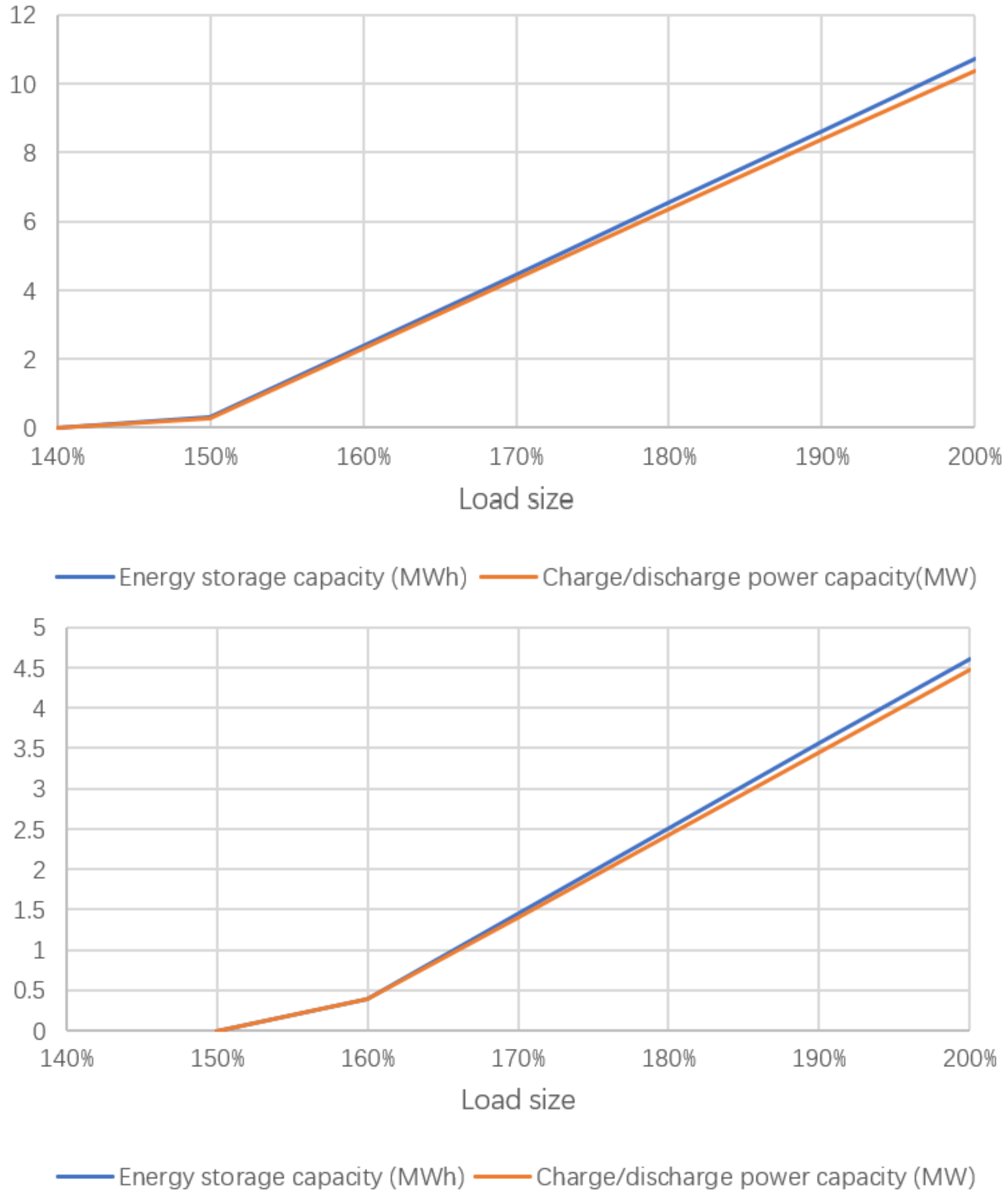


**Figure 4.6:** Sensitivity analysis on optimization solution (Scenario 1b,Microgrid A(Above), Microgrid B(below))

Figure 4.7A and 4.7B are stacked columns of total cost for microgrid A and B. The cost for battery is nearly negligible comparing with the cost to obtain electricity from the main grid. The two dominant components of total cost are cost of purchasing electricity and income by selling electricity, implying that in this scenario, direct interaction with the main grid is more cost-efficient than load transferring with energy storage technology. The network cost is higher in microgrid B because the electricity generation is less abundant than that in microgrid A. Thus, microgrid B has less possibilities for load management and more likely to purchase electricity while the network tariff or electricity price is high. With the proportional growth of the component costs, the curve for total cost is proportional to the load size as well.

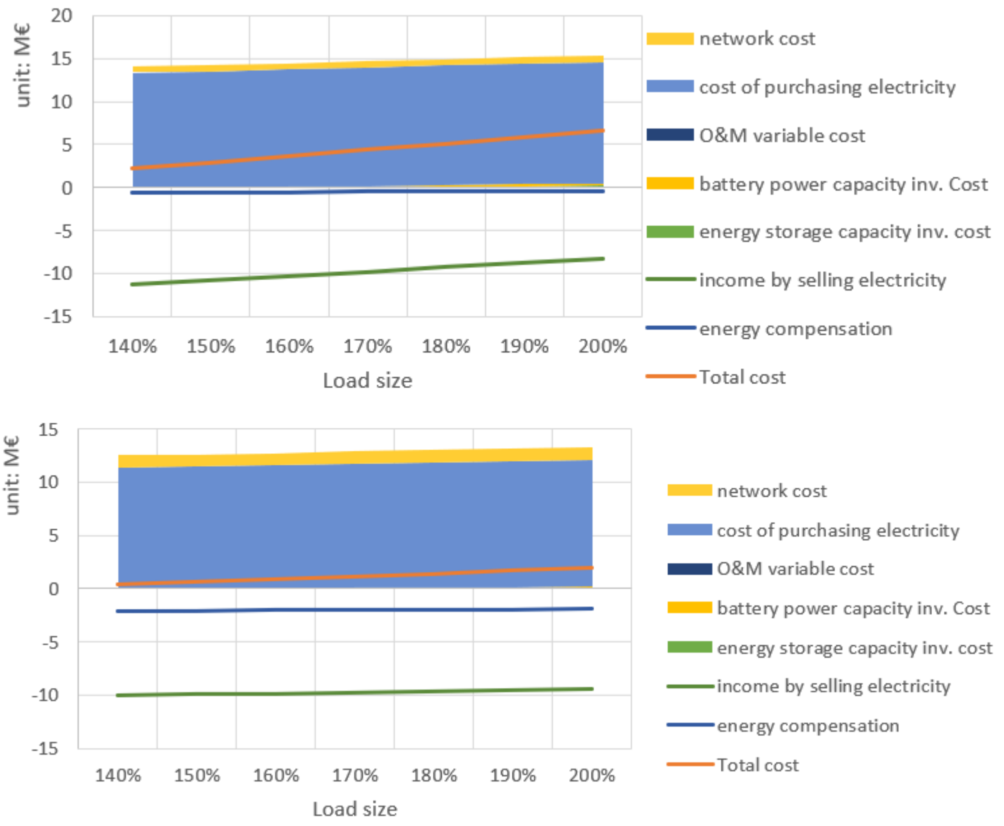


**Figure 4.7:** Stacked column of total cost (Scenario 1b,Microgrid A(Above), Microgrid B(below))

## 4.2 Optimization results for interconnected microgrids

When investigating the impact of an island mode duration requirement on microgrids with the possibility to interconnect by investing in cable capacity, two situations are considered: a situation when there is a grid disconnection at one of the microgrids ('single island mode') and a situation when there is are grid disconnections at both microgrids ('double island mode'). The 'single island mode' is more likely to happen in real life, than the 'double island mode' and is closer to the requirements on existing distribution grids.

### 4.2.1 Impact of ‘single’ island mode requirement to interconnected microgrids

Figure 4.8 and Figure 4.9 are results for interconnected microgrids with varying island mode duration requirement on microgrid A. It is worth noting that microgrid B does not lose connection with the main grid during island mode, which means microgrid B can interact with the main grid as normal. Therefore, there is no investment of energy storage capacity for microgrid B. Furthermore, there is only investment in battery capacity for energy storage. The reason is that the required amount for energy storage capacity in microgrid A is relatively small. As it is mentioned in Chapter 4.1, hydrogen storage is more suitable for long-term and large volume energy storage, such as back-up for long-duration island mode. While in this scenario the load during island mode can be satisfied by not only the electricity discharged from the energy storage system, but also the electricity transmitted from microgrid B through the power-conversion system (PCS) and the cable. The total transformer capacity between microgrid B and the main grid is 36MW, while the total peak net load of the two microgrids is 18.273MW. Thus, it is feasible to manage the total supply-demand balance by electricity trade with the main grid. Comparing with the cost to construct hydrogen storage system, it is cheaper to trade with the main grid to get large amount of electricity supply during island mode.

However, without energy storage technology, the investment on PCS & cable power capacity would be relatively large. Therefore, there is a competition between PCS & cable for interconnection and battery for island mode requirements of short duration, see Figure 4.8. As island mode duration requirements increase from 1 h to 2 h, both battery storage capacity and cable power capacity increase. The reason can be seen in Figure 4.10a. Every dot in the Figure represents the energy requirement and power requirement for an hour. Different color represents different island mode duration requirements. For island mode duration requirements of 1 h and 2 h, the ratio between energy requirement and power requirement is small. Even though the investment cost of the battery is higher than that of PCS & cable, battery is still more cost competitive for enabling short-duration island mode capability of the microgrid. This is because in this case, the requirement for storage capacity is low with respect to the power capacity (low energy time constant), and the additional benefits of using battery for energy arbitrage outweighs the extra investment cost of battery with respect to that of the PCS & cable. Accordingly, in Figure 4.9, the increase of income from supplying electricity to the main grid are relatively obvious when island mode duration increases from 1 hour to 3 hours. In these cases, one of the the motivations for investment in PCS & cable capacity is the network tariff. Since there is always extra cost to get electricity from the main grid, cable is used to enhance the microgrids’ self-sufficiency.The more important reason is that it cost more to use barely the battery to solve the energy requirements than to combine the battery and the interconnection technology.The installed capacity of the PCS & cable increases in these cases because the energy requirement grows rapidly with the respect to power requirement.

But the increasing island mode duration requirement increases the requirement on energy back up. Battery, with expensive energy storage capacity, is no longer suitable to deal with the large volume and long term energy storage. This is the reason that battery's power capacity falls as the island mode requirement exceeds 2 h. For requirements on island mode of 7 hours or longer, the interconnection technology becomes the main solution for island mode and the power capacity of the PCS & cable is no longer dependent on the duration of the island mode. The reason is that as the duration of the island mode requirement increases, more and more energy storage capacity is needed, which is not cost-efficient to be supplied with by using batteries. In contrast, the interconnection technology does not need to increase its capacity along with island mode duration requirement. Because it solves the requirement by load transferring through spatial dimension, instead of temporal dimension. In other words, during island mode, the maximum amount of electricity that can be supplied to microgrid A is equal to installed cable power capacity multiplied by island mode duration. This value increases along with the island mode duration requirement while the cable power capacity is fixed. Therefore, it is more cost-efficient to handle the large energy requirement with interconnection cable capacity. The size of the battery is dimensioned by the additional power requirement. Taking the 20-hour case in Figure 4.10a for example, the energy requirement is around 250 MWh, as the solution for it, the installed cable power capacity is 12.5MW, so that the cable can transmit 250 MWh electricity to microgrid A in 20 hours. Additionally, there are several hours when power requirement is up to 14.3MW but the energy requirement is not very large. Obviously, there is still 1.8 MW power requirement need to be supplied. The dots representing high power requirement distribute discretely, indicating the energy requirement changes a lot for different hours. If the energy requirement is falling, there is possibility for battery to make benefits with the overmuch electricity in storage. In this way, battery enhances its competitiveness to handle the last 1.8MW power requirement.

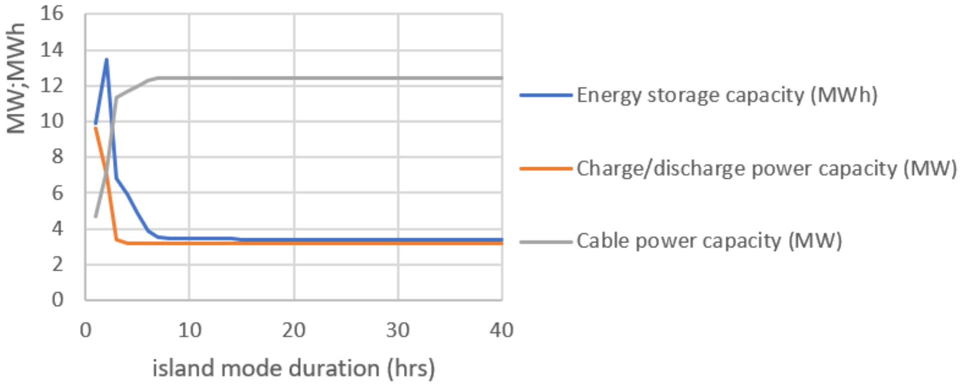


**Figure 4.8:** Sensitivity analysis on optimization solution (Scenario 2a-A, Microgrid A)

Table 4.2 is used to prove the explanation above. In Table 4.2, the three hours with the highest power requirement over the year are located. To get rid of the

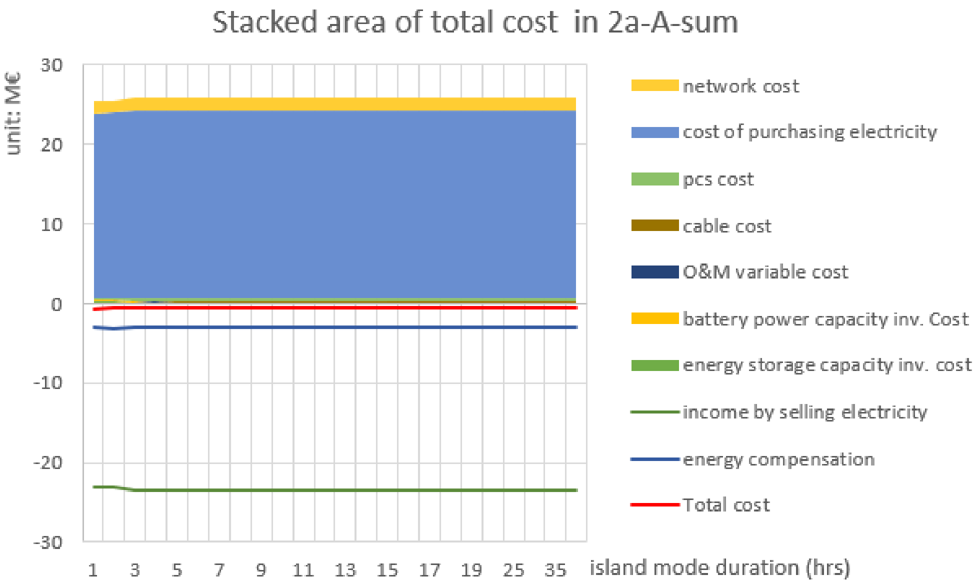
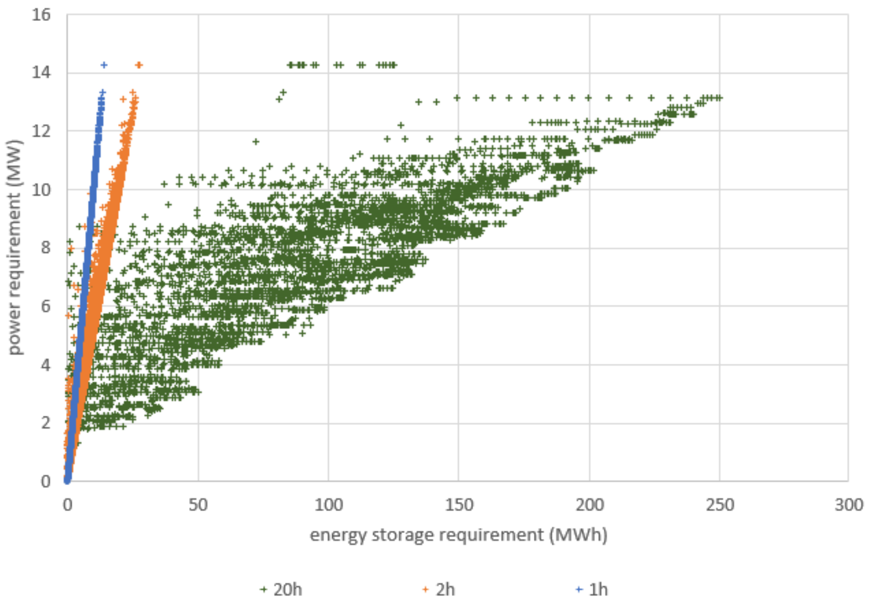


**Figure 4.9:** Stacked area of total cost for Scenario 2a-A

impact from the extremely high power requirement, the power requirements in these hours are replaced by the average power requirement of the neighbouring hours (two hours before and two hours after). The results are for 20-hour-island capability in microgrid A. According to the result, the size of BESS falls significantly while the investment in microgrid interconnection rises. This implies that the battery is losing its competitiveness rapidly. Additionally, battery makes itself more cost-efficient by arbitrage. To verify it, one more model for a scenario prohibiting investment in energy storage system is run. While the island mode duration requirement for microgrid A is 20 hours, the result is shown in Table 4.3. The calculation of items in Table 4.3 is detailed by the equations (3.27) - (3.34). By comparing the optimization solution and the solution with interconnection cable & PCS only, the benefits of arbitrage by battery can not only cover the extra cost for investment in BESS over cable & PCS but also reduce the total cost.



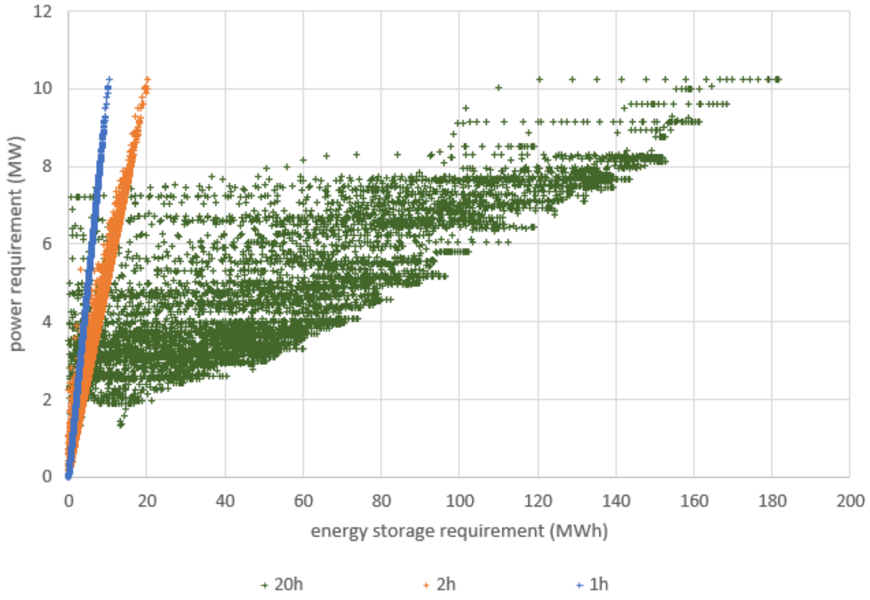


**Figure 4.10:** Energy and power requirement (Microgrid A(Above), Microgrid B(below))

In single island mode, it is possible to result in a negative total cost, as it can be seen in Figure 4.9. Negative total cost is a result of the fact that the annual renewable power generation exceeds the annual load. Since there is no need for large amount of energy back up, the electricity surplus can bring large income by the trade with the main grid. As mentioned before, the increasing island mode duration requirement does not enhance the energy storage requirement when cable capacity is used to meet the energy requirement. Thus, the optimization solutions are similar after the island mode requirement exceeds 7 h. The trade between grids under normal operation is similar as well. The total cost even remains the same for several cases although island mode duration requirement is increasing. About results for microgrid B in island mode, there is no investment on energy storage capacity regardless

of island mode duration. And the interconnection cable power capacity is 10.245 MW, equal to the peak net load in microgrid B. From technical option perspective, interconnection cable totally defeats energy storage technologies, which is different from the results for microgrid A in island mode.
The reason can be explained by the aid of Figure 4.10b. Comparing with microgrid A (Figure 4.10a), there is no dots with extremely high power requirement but low energy requirement in microgrid B, i.e., the high load hours always appear together with large energy requirement. As a result, the battery can provide little flexibility as a peak generation technology. The benefits brought by the energy storage is not enough to cover the investment cost and variable cost of it, making the temporal flexibility costly in Scenario 2a-B. Therefore, it is more economic to purely choose spatial flexibility for maintaining the energy balance during island mode, i.e., the interconnection between the two microgrids.

**Table 4.2:** Comparison of results before and after taking out the cases with extremely high power requirement

| | battery energy capacity(kWh) | battery power capacity(kW) | cable power capacity(kW) |
|---|---|---|---|
| S2a-A-20h | 3398.45 | 3167 | 12461.17 |
| S2a-A-20h without extremely high power requirement | 616.49 | 598 | 12831.5 |

**Table 4.3:** Comparison of cost for solutions with and without battery investment (S2a-A-20h)

| | Cost or Profit(Euro) |
|---|---|
| net profit from energy arbitrage | 18362.49 |
| extra cable cost if no energy storage | 14274.21 |
| cost of battery | 24754.73 |
| cost saving of the optimization solution over the solution without investment in storage technology | 7881.96 |

### 4.2.2 Impact of 'double' island mode requirement to interconnected microgrids

Figure 4.11 shows the change of energy storage capacity with respect to the island mode duration requirement. Results about values in sum are shown in Figure 4.12, together with those in Scenario 1a. The substitution of battery by hydrogen storage device is similar to what happens in scenario 1a. Therefore, the explanation can be the same as function division in scenario 1a, i.e., the battery as the daily storage technology to keep demand-supply balance and hydrogen storage as back up in case island mode happens. At the beginning since the energy storage requirement is relatively small, investment in battery capacity only is the most cost-efficient solution. While with 5-to-10-hour island mode requirement there is a competition between the two technologies and there is a sudden ramp up of total energy storage capacity within these hours. One reason is hydrogen storage capacity need to not only catch up with the increasing energy storage capacity need due to the increasing island mode duration, but also supply the missing capacity due to declining battery capacity. Furthermore, the round-trip efficiency of hydrogen storage system is lower than that of battery. Thus, more storage capacity is needed for hydrogen storage than battery to reach the same discharge power.

In Figure 4.12, there is a comparison between Scenario 1a and 2a-AB. The total energy storage capacity of Scenario 2a-AB is smaller than that in Scenario 1a because the decisive value is not the worst case with peak energy requirement in each individual microgrid. Instead, the total installed energy storage capacity is decided by the worst case regarding the total energy requirement in the two microgrids, i.e., the total energy storage demand. For each microgrid, it is possible to get electricity from the other microgrid by the interconnection cable because the net load of the two microgrids are complementary to each other to a certain extent. Unless the worst cases for the two individual microgrids appear at the same period, the peak energy requirement in Scenario 2a-AB is always lower than that in Scenario 1a.

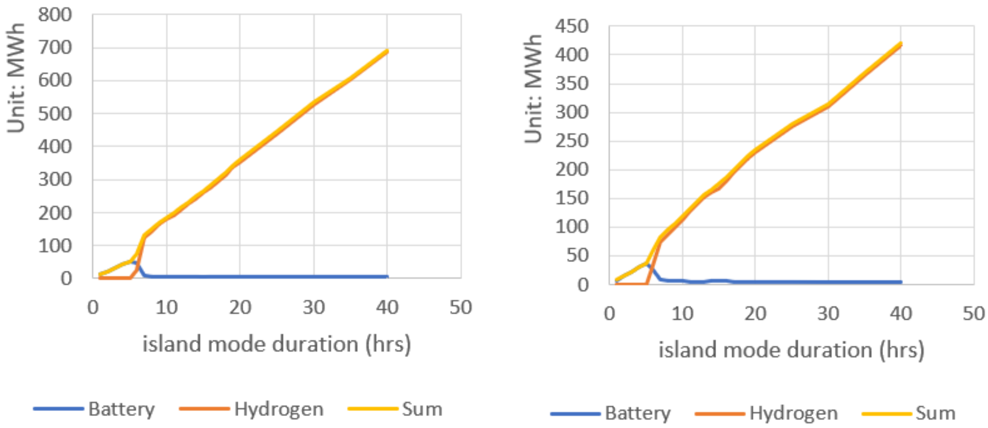


**Figure 4.11:** Sensitivity analysis on energy storage capacity (Scenario 2a-AB, Microgrid A(left) and B(right))

In addition, the share of battery storage capacity in Scenario 2a-AB is higher than that in Scenario 1a since the interconnection cable provides more flexibility to trade with the main grid when not in island mode. For example, while the storage system in microgrid A is full charged, the energy surplus of hydro power can only be sold to the main grid or curtailed in Scenario 1a. But with interconnection cable, it can also be transmitted to cover the load in microgrid B or stored in microgrid B until the electricity price is high enough for selling. In this way, the interconnected microgrids offers more benefits of the battery.

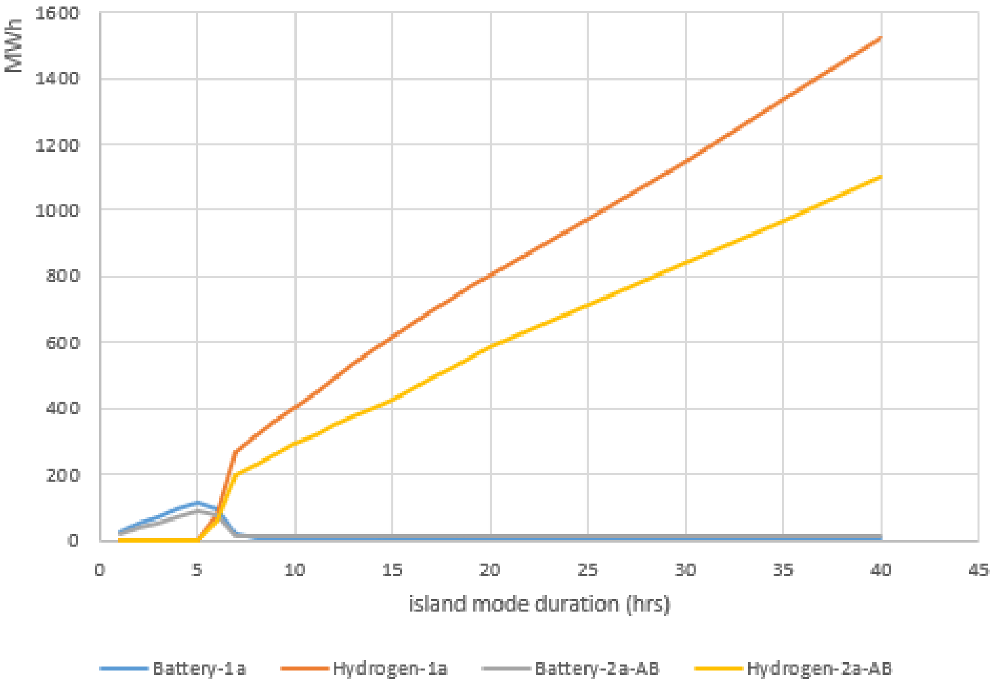


**Figure 4.12:** Comparison on energy storage capacity between Scenario 1a and Scenario 2a-AB

It is also notable that for both scenarios, the ratio of the installed energy storage capacity in microgrid A and that in microgrid B fluctuated between 1.37 to 1.7. This ratio is decided by different factors in different cases. For most of the cases, the distribution of energy storage capacity is designed for better variation management, taking the peak net load in microgrid A (14.273 MW) and microgrid B (10.245 MW) as reference. Additionally, in some cases the decisive constraint is energy requirement for island mode. Even though the total installed energy storage capacity is enough, the energy requirement in individual microgrid may be stricter. During the worst island mode case, the microgrid in island not only need large volume of energy storage, but also large amount of electricity transmitted from the other microgrid, which may become a decisive factor of the installed cable power capacity. Therefore, sometimes installed energy capacity will be distributed more in one microgrid, to avoid too much cable power capacity expansion. These cases will be detailed later, combining with analysis on cable power capacity and discharge power capacity.

Figure 4.13 illustrates how island mode duration requirements impact the discharge power capacity in optimization solutions. There is also a substitution process from battery to hydrogen storage system in both microgrids. The dominating energy storage technology is in accordance with the result for installed energy storage capacity. According to Figure 4.14, the difference in the sum of discharge power capacity does not change drastically in both microgrids. Combining with the values of interconnection cable power capacity, the results can be divided into 3 types,according to the power capacity of the interconnection technology: 1) equal to 2.8975 MW; 2) smaller than 2.8975 MW; 3) larger than 2.8975 MW.

For the first type of results, the installed cable power capacity equals to 2.8975 MW, which is ubiquitous in the optimization solutions, see Figure 4.15. In this type of cases, the sum of cable power capacity and discharge power capacity in microgrid A is kept to 14.273 MW, which is the peak net load in microgrid A. And the same rule can be found for interconnection cable and microgrid B. Therefore, the cable is fully used in both directions to satisfy the peak net load in each microgrid. This is an effective way to save the investment on discharge power capacity, which can be proved through the comparison with Scenario 1a in Figure 4.14. As it is shown, the total discharge power capacity of the two microgrids in Scenario 1a is 24.518 MW, equal to the peak net load in microgrid A (14.273 MW) added by the peak net load in microgrid B (10.245 MW). So that the two individual microgrids can depend on their own energy storage system to cover the peak net load during island mode. While for scenario 2a-AB, the total discharge power capacity keeps as 18.723 MW for most of the cases. 18.723MW is the peak value regarding the total net load regarding the two microgrids. And the total discharge power capacity must reach this value. Accordingly, the discharge power capacity in microgrid A and microgrid B are 11.3755MW and 7.3475MW for these cases in Figure 4.12. This distribution enables the interconnection capacity to reach a lower limitation. The limitation is for interconnection cable to cover the peak net load in each microgrid together with the 18.723MW total discharge power capacity of energy storage system. Because in this condition, the requirements on interconnection capacity to meet the peak load for both directions are the same, i.e., microgrid A needs 2.8975 MW electricity power from microgrid B to satisfy its peak net load, and vice versa. The way to get installed PCS & cable capacity is also shown in Equation 4.1. In this type of cases, both the installed cable power capacity and installed discharge power capacity is decided by the power requirement during island mode.

$$CC = (D_A^{peak} + D_B^{peak} - D_{total}^{peak})/2 \tag{4.1}$$

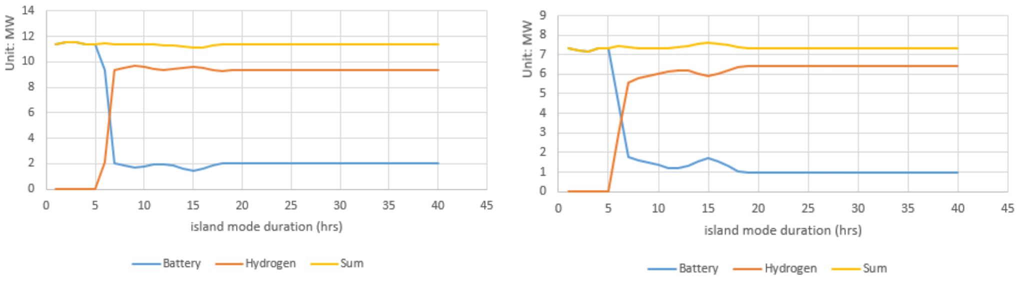


**Figure 4.13:** Sensitivity analysis on discharge power capacity (Scenario 2a-AB, Microgrid A(left) and B(right))

For the second type of cases, the installed cable power capacity is smaller than 2.8975 MW. This type of result appears when island mode duration requirement is 6 hours and 7 hours. In these two cases, the size of battery and hydrogen storage system are the closest, indicating the two technical options are both competitive and advantageous. Furthermore, the two energy storage technologies coordinate well on demand side management. The effect of load shaving and arbitrage is so ideal that it is even worthwhile to replace a part of interconnection cable to energy storage device. As a result, the total installed discharge power capacity is larger than 18.273 MW, leading the installed cable power capacity to decrease. To prove the explanation, an extra scenario named '2a-same' is simulated. In Scenario 2a-same, the average electricity price and average network tariff are set as the electricity price and network tariff for all the hours. In other words, the cost or income to trade with the main grid remains the same between hours and there is no benefit to arbitrage. Figure 4.16 compares the installed cable power capacity in the two scenarios. As it shows, the increase of installed discharge power capacity and decrease of installed cable power capacity disappear in Scenario 2a-same. Therefore, for the second type of cases in Scenario 2a-AB, the installed cable power capacity is still decided by the power requirement during island mode, while the investment on discharge capacity is decided by the objective function considering the cost-benefit analysis.

For the third type of cases, the installed cable power capacity is larger than 2.8975 MW. According to Figure 4.16, the increase of installed cable power capacity remains after taking out the impact of electricity price and network tariff. Therefore, this phenomenon is not due to pursuit on benefits by arbitrage. The reason was mentioned in analysis on energy storage capacity, i.e., stricter peak energy requirement. Take the case when island mode duration requirement is 15 hours for example. Table 4.4 shows some data in optimization solutions. Among them, the 'sum of available energy storage capacity' is calculated regarding the electricity output to the system and multiplied by output efficiency before adding up. As it is shown in the table, to handle the worst case regarding peak energy requirement in each microgrid, not only the energy storage need to be fully charged, but also the interconnection cable must be fully used during the worst case to transmit electricity from the other microgrid. Since the peak energy requirement in both microgrid is exactly satisfied, this installed cable power capacity reaches the lower limitation. Otherwise, the total installed energy storage capacity would exceed the peak total energy requirement. This explanation can also be expressed by Equation 4.2. Since the total installed discharge power capacity can not be lower than 18.723 MW, the sum of installed cable power capacity and discharge power capacity will surpass the peak net load somewhere, i.e., microgrid A or B.

$$CC = (ER_A^{peak} + ER_B^{peak} - ER_{total}^{peak})/k/2 \tag{4.2}$$

As for the distribution of installed discharge power capacity between microgrid A and B, the motivation is different. When island mode requirement is 2 hours and 3 hours, the distribution is impacted by the electricity price and network tariff, see Figure 4.17, more investment on discharge power is arranged in microgrid A for more opportunity to shave load and arbitrage. When the island mode requirement extends to 12-18 hours, microgrid B would get the extra discharge power investment no matter the electricity price and network tariff fluctuate or not. Thus, for the third type of cases in Scenario 2a-AB, the installed interconnection power capacity is still decided by energy requirement during island mode in each microgrid, while the total installed discharge power capacity is decided by power requirement during island mode. The distribution of discharge power investment firstly handles the peak net load in each microgrid, then is decided by objective function considering the cost-benefit analysis.

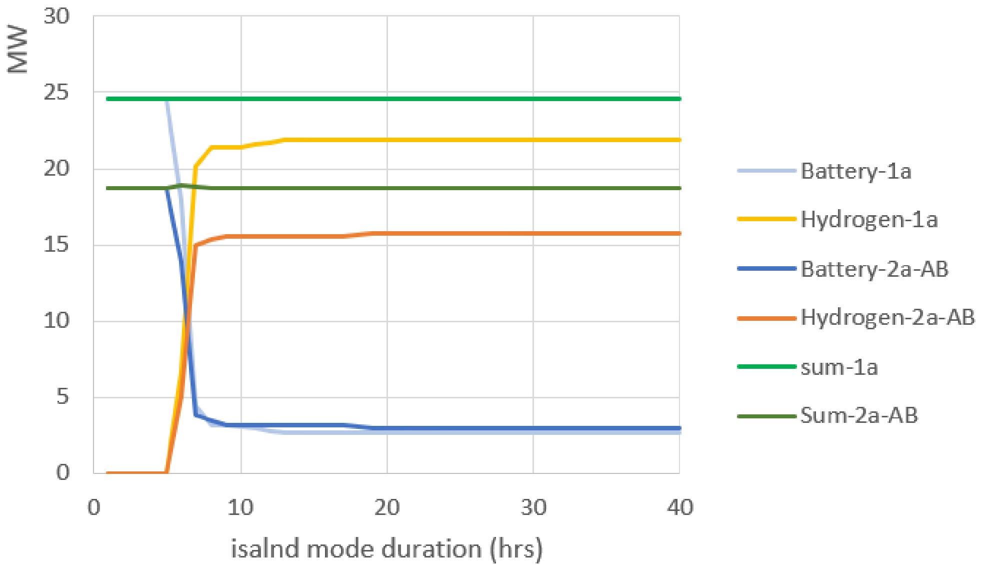


**Figure 4.14:** Comparison on discharge power capacity between Scenario 1a and Scenario 2a-AB

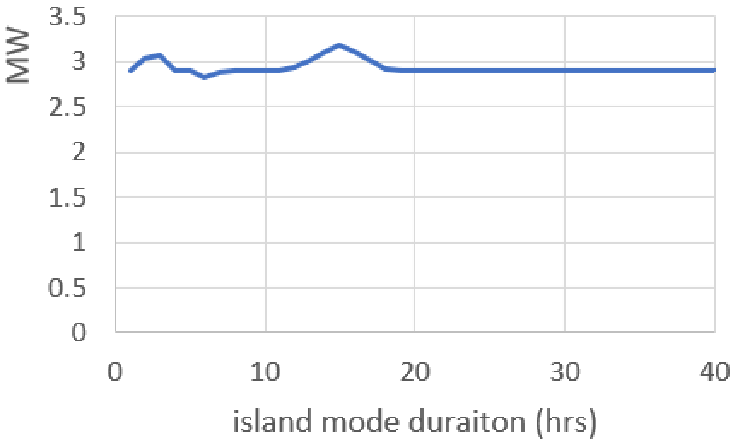


**Figure 4.15:** Sensitivity analysis on cable power capacity (S 2a-AB)

Through Figure 4.14, it can also be found that the availability of interconnection cable mainly cuts the discharge power capacity for hydrogen storage. For battery, the installed discharge power capacity is even larger in scenario 2a-AB than that in Scenario 1a after the island mode duration is longer than 10 hours. Because the interconnection cable improves the total flexibility for the two microgrids to interact with the main grid. And battery, which is suitable for frequent cycling, is the best technical option to make use of the extra flexibility, i.e., produce more benefits through more reasonable interaction with main grid.

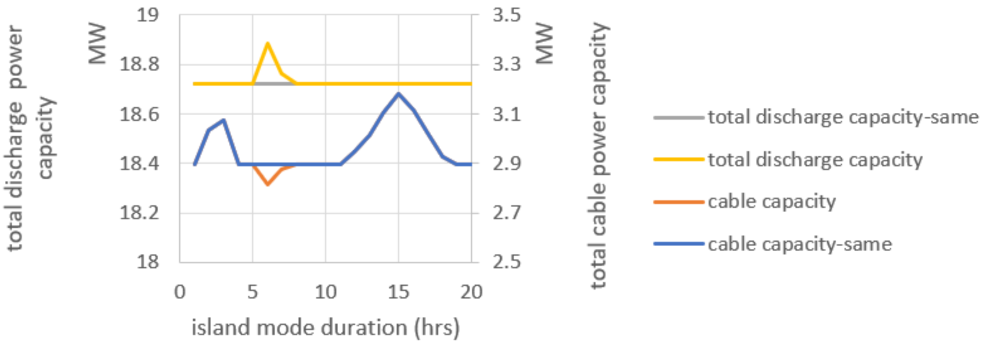


**Figure 4.16:** Comparison of installed power capacity with and without impact from electricity price and network tariff

**Table 4.4:** Example of connection between installed energy storage capacity and cable power capacity (S 2a-AB, 15 h)

| | microgrid A | microgrid B |
|---|---|---|
| peak energy requirement (kWh) | 190214 | 143412 |
| installed battery energy storage capacity (kWh) | 5037 | 7020 |
| installed hydrogen storage energy capacity (kWh) | 259688 | 167754 |
| sum of available energy storage capacity (kWh) | 142520.5 | 95718.5 |
| installed cable power capacity (kW) | 3179.56 | |
| storage +cable*20 hour (kWh) | 190214 | 143412 |

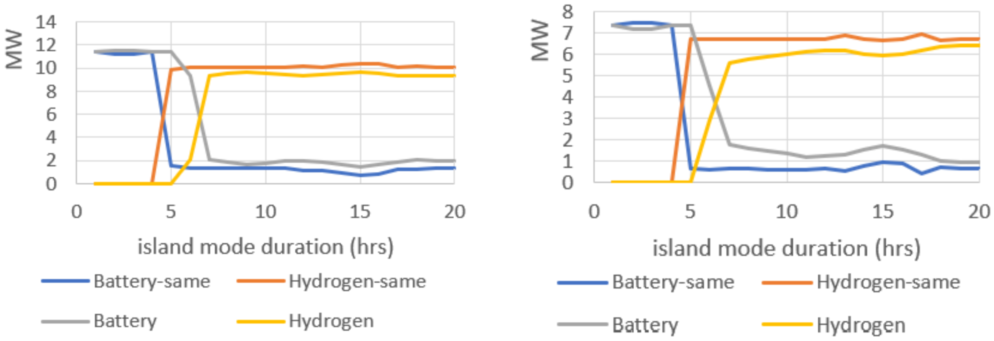


**Figure 4.17:** Comparison of discharge power capacity between S2a-AB and S2a-same in Microgrid A(left) and B(right)

Figure 4.18 shows the installed capacities of charge power for optimization solutions considering 'double' island mode. For battery, the curves of charge power capacity are exactly the same as that of discharge power capacity in Figure 4.13. The reason is the cost for battery's power capacity is decided by the larger value between installed charge power capacity and installed discharge power capacity, which is

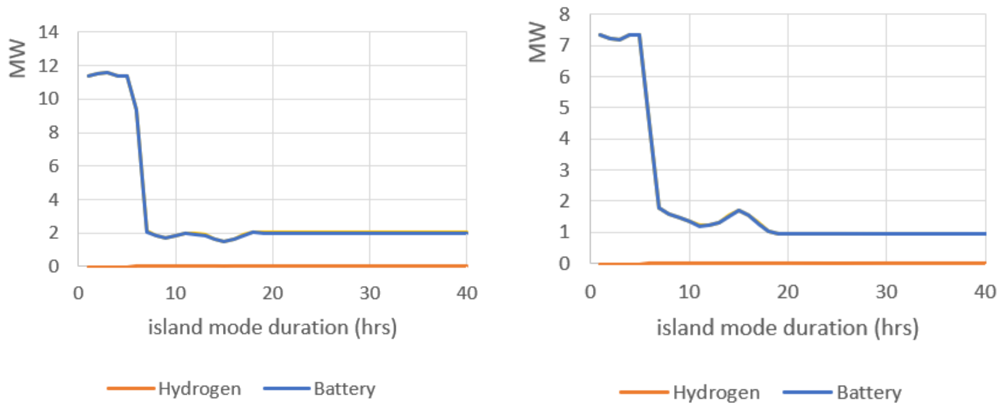


**Figure 4.18:** Sensitivity analysis on charge power capacity (Scenario 2a-AB, Microgrid A(left) and B(right))

mentioned in Chapter 4.1. For hydrogen storage system, the charge power capacity is very small as several kW. Because the hydrogen storage is mainly used as back up storage for island mode. It hardly cycles for demand-supply balance in daily life. The detailed explanation can also be found in Chapter 4.1.

Figure 4.19 illustrates how different parts of the total cost change with the island mode duration requirement. The main cost items for different technical options are the same as those in Scenarios 1a, i.e., investment cost on energy storage capacity and investment cost on hydrogen discharge power capacity, which are the limitation of battery and hydrogen storage system to defeat other technical options. Other cost constitutions as well as their performances can be well connected with the substitution and function division between battery and hydrogen storage system, similar to what happens in Scenario 1a. One difference with Scenario 1a is the additional cost on interconnection cable and power conversion system, but they only occupy a small share of the total cost. The low cost keeps interconnection cable capacity a competitive technical option, in comparision with the energy storage technologies.

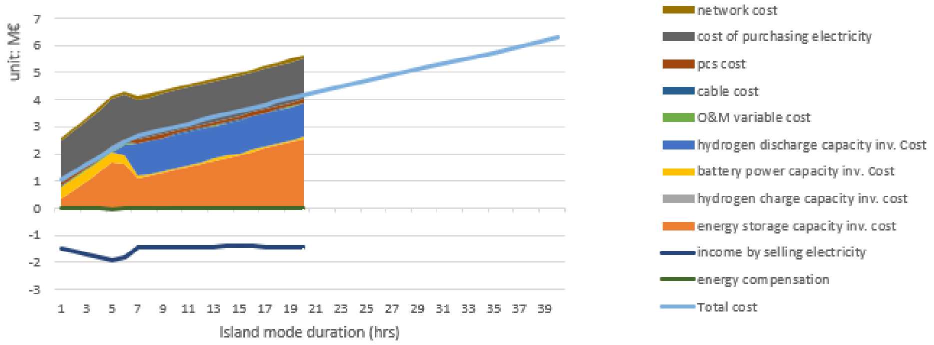


**Figure 4.19:** Stacked area of total cost (Scenario 2a-AB, sum)

Figure 4.20 compares the total cost composition between Scenario 1a and Scenario

2a-AB, regarding the cases before, during and after the substitution between battery and hydrogen storage system. The construction of interconnection cable results in a reduction especially in the cost for energy storage capacity and discharge power capacity. The cost for purchasing electricity does not change a lot while the income by selling electricity is even more in Scenario 1a. But the optimization solution with interconnection cable keeps cutting the total cost as the island mode duration requirement increases, as Figure 4.21 shows. This result implies that if there is energy surplus in the microgrids, it is always cost competitive to connect the microgrids if they need to meet an island mode constraint.

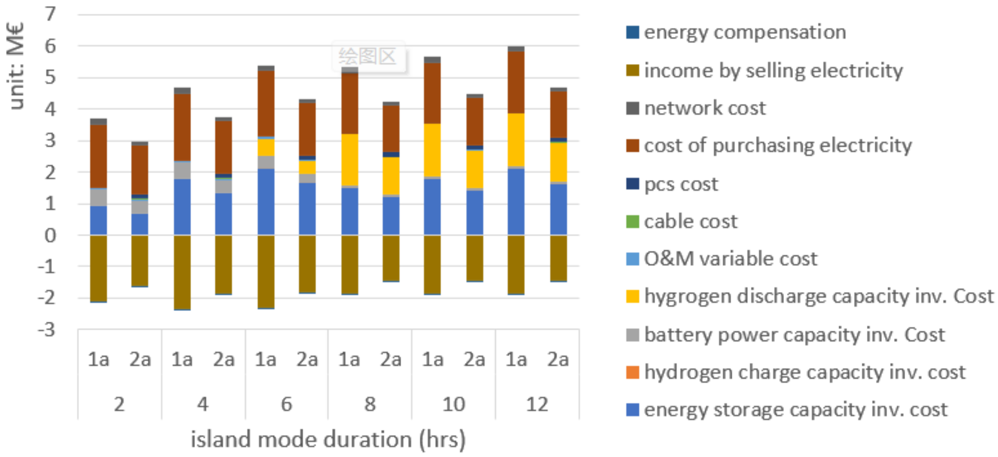


**Figure 4.20:** Comparison of cost constitution between S1a and S2a-AB

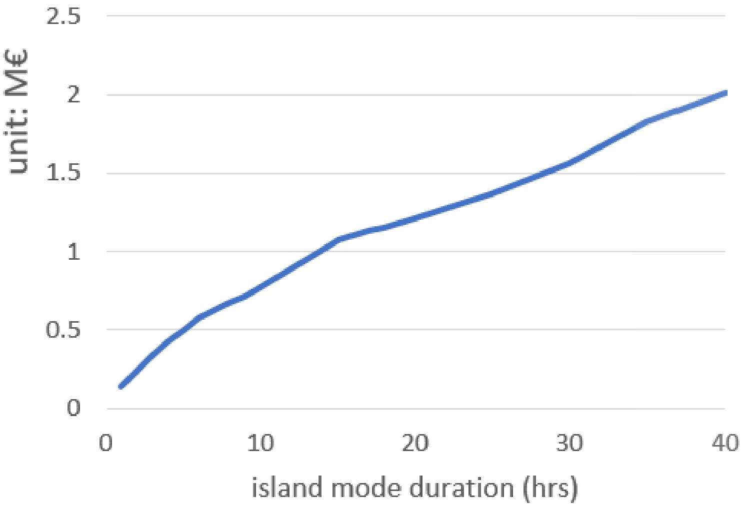


**Figure 4.21:** Cost saving of S2a-AB over S1a

### 4.2.3 Impact of load increasing to interconnected microgrids

Figure 4.22 shows the optimization solutions for cases in Scenario 2b, when the loads in both microgrids are expanding and the interconnection between the microgrids is allowed. There is no investment on energy storage technology and interconnection cable becomes the only solution for increasing load. In contrast to Scenario 2a, there is no large energy requirement. The load expansion mainly raises the power requirement. The result indicates that interconnection cable is more economic than any other energy storage technology to handle the high power requirement while there is no extra energy requirements in addition to daily supply-demand balance. Along with the increasing load, more and more transformer capacity is occupied for supplying electricity to load from generation. Thus there is not enough transformer capacity for battery to arbitrage, which makes the battery less competitive in this scenario. The dimension of installed cable power capacity is decided by the N-1 constraint, i.e., if microgrid A loses one of the 30-MVA transformers (which is the transformer to test N-1 criteria while the two microgrids are interconnected), the microgrid A will need the full power capacity of the cable to handle its peak net load.

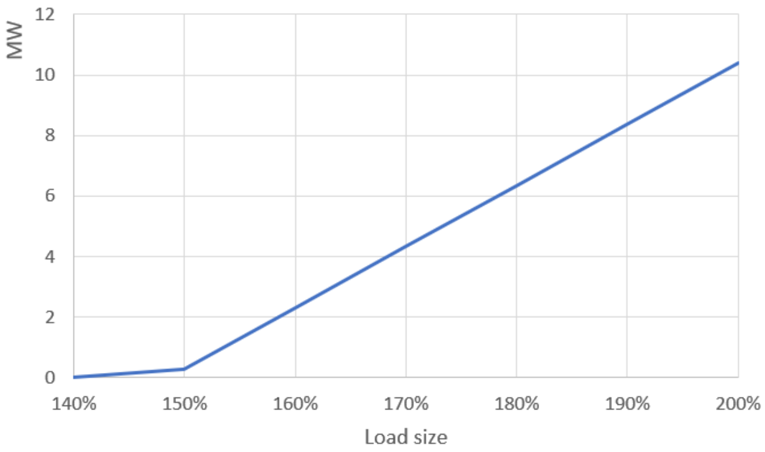


**Figure 4.22:** Installed cable power capacity in S2b

Figure 4.23 are the results about the total cost in Scenario 2b. The cost of purchasing electricity has very small increase, indicating that the microgrids are better at self-sufficiency while the installed cable power capacity is greater. In this way, the microgrids need similar amount of electricity from the main grid even though the loads are increasing. Furthermore, since more and more generated electricity is consumed by the load directly, there is less and less electricity that can be sold to the main grid. Thus, the income by selling electricity keeps declining and becomes the main factor impacting the total cost. The cost to interconnect the two microgrids increases along with load expansion but is very small compared to the total cost.

Figure 4.24 compares total cost in Scenario 1b and Scenario 2b regarding different parts. The interconnection increases the interaction between the two microgrids thus reduce their trade with the main grid. Although the income by selling electricity

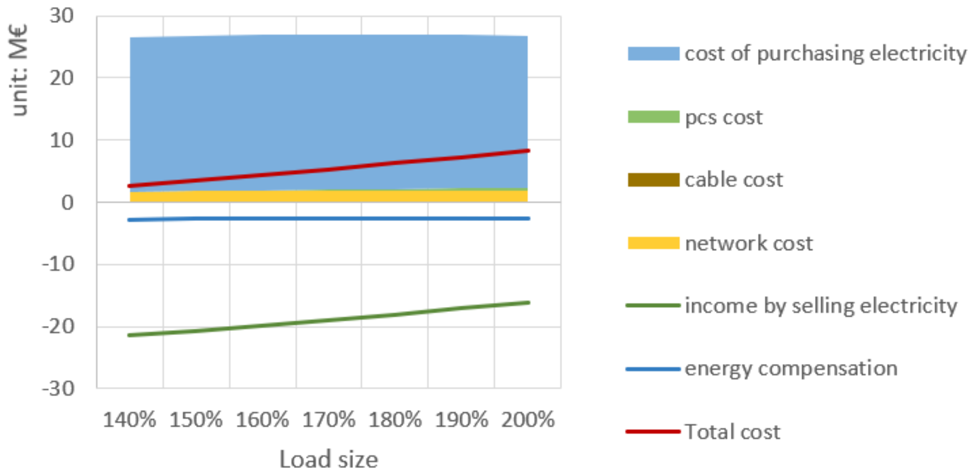


**Figure 4.23:** Stacked area of total cost (Scenario 2b, sum)

decreases in scenario 2b, the total cost is cut in Scenario 2b, which can be seen in Figure 4.25, due to reduction on cost of purchasing electricity. The cost on battery (for S1b) and interconnection cable (for S2b) is almost negligible according to Figure 4.24. Therefore, it is not the cost on technical options themselves that leads to different solutions resulting in different total costs. Instead, cable and battery represent different ways for microgrids to keep capacity adequacy for power balance. Figure 4.25 proves that to handle the increasing load, it is more economic to solve the problem by interconnecting the two microgrids than to install BESS. And this rule is more obvious while the load is larger.

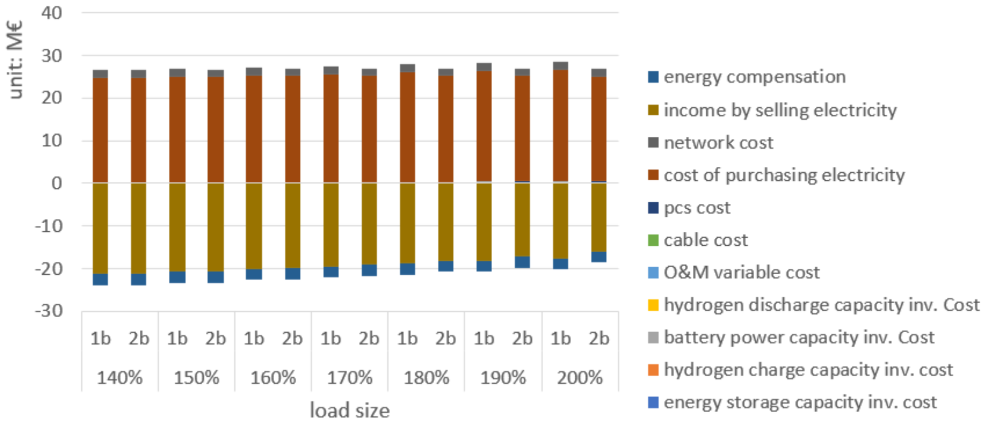


**Figure 4.24:** Stacked area of total cost (Scenario 2b, sum)

Considering the distance between the two microgrids is 2km, which is relatively short for cable construction, it is worthwhile to explore if longer distances will reduce the competitiveness of the interconnection cable & PCS. Additionally, the investment cost of cable may be higher for different land conditions. Thus, following is a sensitivity analysis on the cable length and cable cost. The cable length varies from

2 km to 50 km. Usually the length of cable does not exceed 50 km in real life in medium voltage distribution system. And the investment cost of cable is set from 60 k€/MW, which is the data for the standard products and used in the previous simulation, to 140 k€/MW, which is the highest level of cable investment cost. To make the results more obvious, the condition is evaluated with 200% of present load.

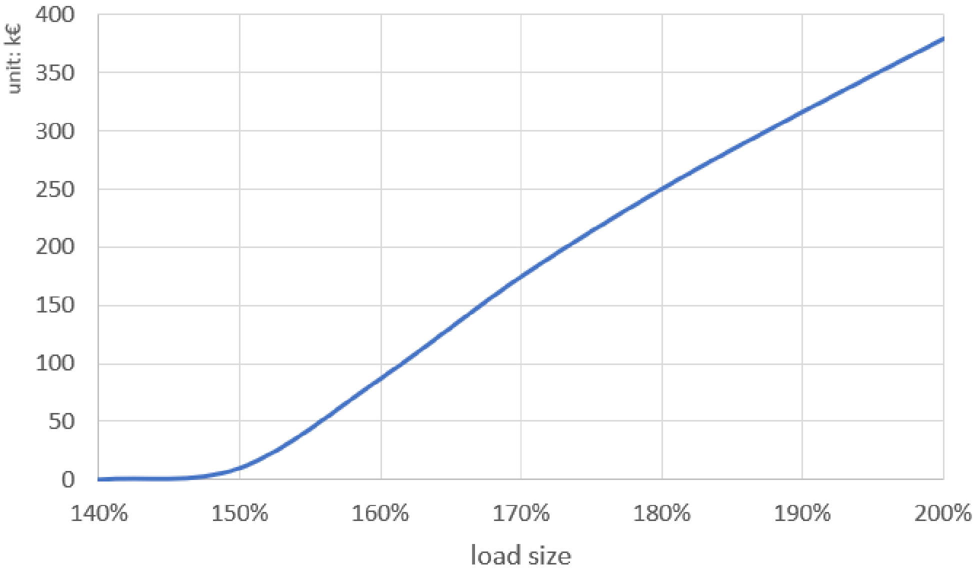


**Figure 4.25:** Cost saving of S2b over S1b

Figure 4.26 is analysis about cable power capacity. The impact of cable cost is shown at the beginning. Except for the cheapest cable, the cables are replaced by battery more or less, while their length is still 2 km. After the distance is longer than 5 km, cables in all price levels begin to lose competitiveness, i.e., battery would complement the power capacity reduction of cable, as shown in Figure 4.27. For the requirement on cable length longer than and including 20 km, the two most expensive cables are totally defeated. The two microgrids act as individual microgrids and solely depend on the battery to handle the power requirement. But for the cheapest cable, it is still competitive with battery when the distance reaches 50 km.

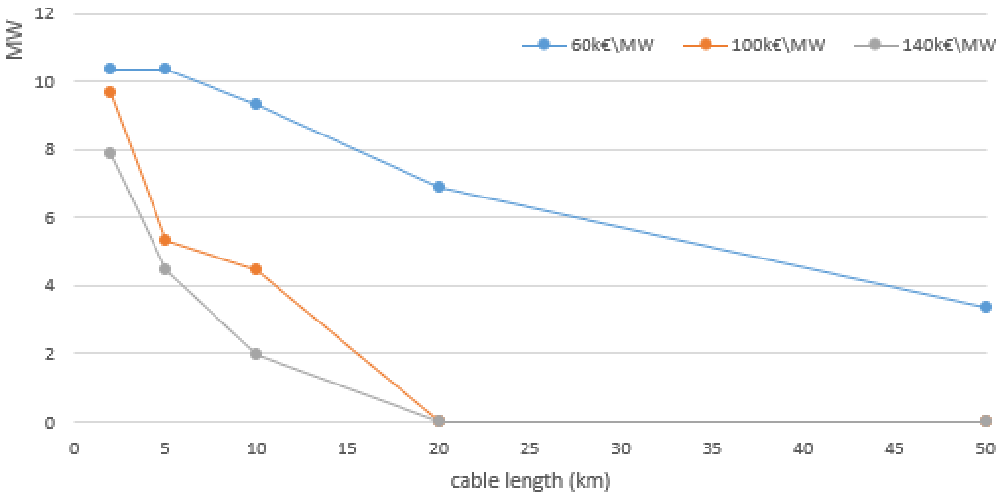


**Figure 4.26:** Sensitivity analysis on cable length and cable cost to cable power capacity (200% load)

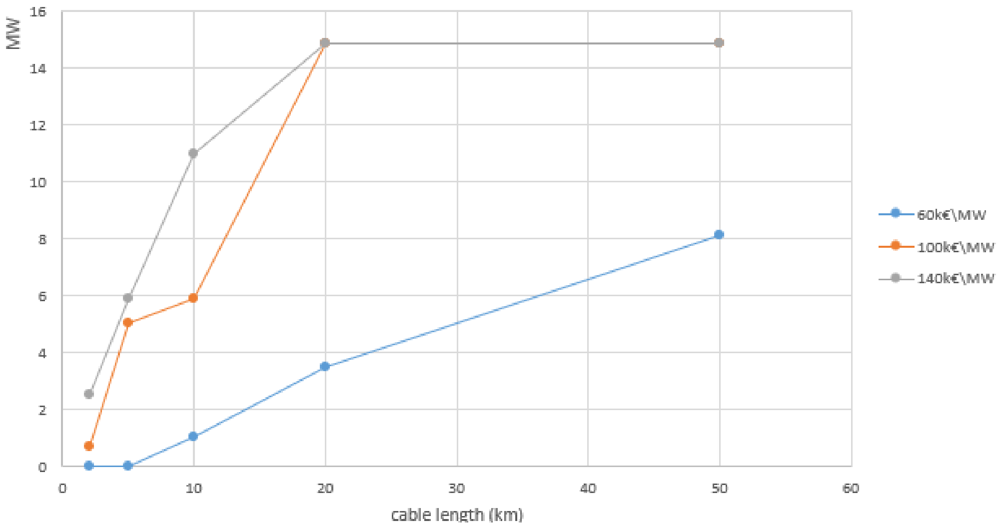


**Figure 4.27:** Sensitivity analysis on cable length and cable cost to battery power capacity (200% load)

# 5

# Conclusion

The thesis has found out the optimum design of the microgrids in different scenarios through energy system modelling for mitigating the local grid capacity shortage and improving the supply reliability for the consumers. The result analysis mainly focuses on the driving factors that affect the dimension of the optimization solution for each scenario, including the investment in the energy storage technologies and the interconnection technology.

For an individual microgrid, it is more cost efficient to enhance the island operation capability and handle potential long-duration island mode requirement with coordination between a battery and a hydrogen storage system compared to enhancing the island mode using a single storage technology. With high round trip efficiency, the battery provides temporal flexibility to the electricity system effectively. Thus,the function of battery is to manage the net load variation during normal time and increases the benefit from interaction with the main grid by frequent cycling. For this reason, the installed size of the battery is not sensitive to the island mode duration requirement. As a complementary technology, the size of hydrogen storage capacity increases with island mode duration requirement. The cheap hydrogen storage capacity is suitable to supply back-up energy for potential long-duration island mode. However, the charge and discharge power capacity of the hydrogen storage is expensive so the discharge capacity, i.e., the capacity of fuel cell, is dimensioned to meet the base load (i.e. the constant part of the load) during island mode. Since the amplitude of the base load does not depend on the duration of the island mode constraint, the discharge capacity is not sensitive to the island mode duration. And the hydrogen storage system hardly cycles diurnal net load variation because the low round-trip efficiency would make it consume more electricity to satisfy the same demand. Due to the high cost of discharge capacity, hydrogen storage is not competitive to handle load expansion. Since there is no demand for large volume and long-duration energy storage, the main cost on energy storage technologies becomes the cost for charge/discharge power capacity, which makes the hydrogen storage system cost more than battery to deal with load expansion. Additionally, as it is mentioned before, the low round-trip efficiency would lead hydrogen storage system to be more energy-consuming. Therefore, it is more cost efficient to manage the higher amplitude of the variation with battery.

The microgrid interconnection can effectively enhance the self-sufficiency of each microgrid, and thus cut the investment cost of energy storage system. The interconnection of the two microgrids is enabled by a power-electronic converter and a local cable. The interconnection reduces the total net load of the two microgrids due to their complementary net load profile. As a consequence, the demand for hydrogen storage as a back-up to handle long-duration island mode decreases. On the other hand, the interconnection technology can transfer load between the two microgrids, which is cheaper than load shifting on time scale by battery. Therefore, the interconnection reduce the interaction between the microgrids and the main grid. In particular, more electricity is self-used instead of being sold to the main grid. The cost saving on energy storage system because of microgrid interconnection results in a reduction in the total cost of the 'double island mode', and the effect is greater with longer island mode requirement. For 'single island mode', the interconnection cable is the main solution for large energy requirements because it can transmit electricity from the main grid to the island, which is more economic than investing in an energy storage system. In the case of a high power requirement and a varying energy requirement the battery is competitive by complementing the peak power and arbitraging with the available energy in the energy storage. The self-sufficiency of interconnected microgrids is much improved to manage double of the present load. The interconnection cable and PCS is much more cost-efficient than the energy storage option, which also indicates that the spare capacity in substation transformer for energy arbitrage is significantly reduced due to the load increase. But if the distance between the two microgrids are long the cable cost is high and it is possible for the battery to be a competitive option.

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# A

# Appendix A

**Table A.1:** Parameter data for Battery [31, 32]

| | |
|---|---|
| **Annualized energy storage capacity investment cost(€/kWh/year)** | 18.61628023 |
| energy component (M€/MWh) | 0.132 |
| - other project costs (M€/MWh) | 0.1 |
| Technical lifetime (years) | 20 |
| discount rate for all units | 0.05 |
| CRF | 0.080242587 |
| **Annualized charge/discharge power capacity investment cost(€/kW/year)** | 22.20549854 |
| Fixed O&M (k€2015/MW/year) | 0.54 |
| Annualized capacity component (€/kW) PCS | 21.66549854 |
| capacity component (M€/MW) PCS | 0.27 |
| Technical lifetime (years) | 20 |
| discount rate for all units | 0.05 |
| CRF | 0.080242587 |
| **O&M variable cost(€/kWh)** | 0.002 |
| Variable O&M (€2015/MWh) | 2 |
| **Charge efficiency (%)** | 98 |
| **Discharge efficiency (%)** | 97 |

The calculation of CRF (capital recovery factor) is shown below.

$$CRF = r/1 - (1 + r)^{-T} \tag{A.1}$$

| | |
|---|---|
| $r$ | discount rate |
| $T$ | life time |

**Table A.3:** Parameter data for Hydrogen [31, 32]

| | |
|---|---|
| **Annualized energy storage capacity investment cost(€/kWh/year)** | 4.044290066 |
| Specific investment (M€2015 per MWh) | 0.057 |
| Technical lifetime (years) | 25 |
| discount rate for all units | 0.05 |
| CRF | 0.070952457 |
| **Annualized charge power capacity investment cost(€/kW/year)** | 55.87506012 |
| Specific investment (€/ kW of total input$_e$) | 750 |
| Fixed O&M (% of specific investment / year) | 5 |
| Variable O&M (€/ kWh of total input) | - |
| Startup cost (€/ kW of total input per startup) | - |
| Technical lifetime (years) | 25 |
| discount rate for all units | 0.05 |
| CRF | 0.070952457 |
| **Annualized discharge power capacity investment cost(€/kW/year)** | 78.08936805 |
| Specific investment ($/kWe) | 1320 |
| exchange rate($ to €) | 0.87 |
| Technical lifetime (years) | 30 |
| discount rate for all units | 0.05 |
| CRF | 0.065051435 |
| Fixed O&M ($/kW/year) | 3.89 |
| output Fixed O&M (€/kW/year) | 3.3843 |
| **O&M variable cost(€/kWh)** | 0 |
| Variable O&M (€2015/MWh) | - |
| **Charge efficiency (%)** | 66.00 |
| **Discharge efficiency (%)** | 53 |

**Table A.4:** Parameter data for Heat [32, 33]

| | |
|---|---|
| **Annualized energy storage capacity investment cost(€/kWh/year)** | 4.079980358 |
| Specific investment (€per kWh) | 62.71929825 |
| investment cost for one unit (€) | 65000 |
| energy storage capacity for one unit (kWh) | 600 |
| Technical lifetime (years) | 30 |
| discount rate for all units | 0.05 |
| CRF | 0.065051435 |
| **Annualized charge power capacity investment cost(€/kWh/year)** | 0 |
| **Annualized discharge power capacity investment cost(€/kW/year)** | 119.146839 |
| Specific investment ($/kWe) | 2105.263158 |
| exchange rate($ to €) | 0.87 |
| Technical lifetime (years) | 30 |
| discount rate for all units | 0.05 |
| CRF | 0.065051435 |
| **Charge efficiency (%)** | 100.00 |
| **Discharge efficiency (%)** | 27.5 |

**Table A.5:** Parameter data for Cable [34]

| | |
|---|---|
| **Annualized cable power capacity investment cost(€/(kW*km)/year)** | 0.328660413 |
| Specific investment (€/MVA*km) | 6000 |
| Technical lifetime (years) | 50 |
| discount rate for all units | 0.05 |
| CRF | 0.054776735 |
| **Annualized converter investment cost(€/kW/year)** | 43.33099708 |
| - capacity component (M€/MW) PCS | 0.27 |
| Technical lifetime (years) | 20 |
| discount rate for all units | 0.05 |
| CRF | 0.080242587 |

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