UNIVERSITETET I AGDER

Planning of Residential Microgrid Community with Technical and Economic Analysis

DANIEL JORDSKAR

INDUSTRY PARTNER
Magnus Johansen, Nettpartner AS

SUPERVISOR
Professor Mohan Lal Kolhe

University of Agder, 2018
Faculty of Engineering and Science
Department of Engineering Science

Abstract

Establishment of microgrid communities in Norway can contribute to solve many upgrading challenges of the existing grid. Today's grid are in many areas not suited to handle both bidirectional power flow and the increasing consumption from the consumers. With great progress in the development of PV systems, wind turbines and other DG units, is it necessary to establish sustainable solutions to handle the impact this components has on the grid. Since its easier to integrate DG units in microgrids, than in traditional distribution networks, can microgrid be a sustainable solution that is beneficial for both consumers and distribution system operator.

The thesis consists of both a literature study involving microgrid technologies and barriers for microgrids to develop in Norway, and a sustainable plan for a residential microgrid in Linnheia in Aust-Agder. Block Watne AS has a local agreement to develop area regulations of Linnheia Nord, and its desirable to investigate, in cooperation with Nettpartner AS, the opportunity of a residential microgrid in one part of the area that is $4000m^2$ and will consist of 40 family houses. The microgrid planning is based on the planning book of power grids from Sintef, and guidelines for planning of microgrids developed by International Electrotechnical Commission.

Three different grid-connected microgrid scenarios are simulated and optimized in the software Homer Energy. Every scenario consists of building integrated PV systems on the house roofs, and the microgrid is optimized with and without wind turbines with a minimum of three turbines. One scenario has a district heating system with a CHP micro-gas turbine, the second scenario has geothermal energy storage, while the last scenario do not have any heating system.

The simulations showed that it might be advantageous to plan a microgrid based on a heating system to cover space heat and/or hot water. This will be an adjustable component that is very suitable for a microgrid that consists of several DG units. The heating system covers the heating demand, which decreases the total consumption in the microgrid. This makes both wind turbines and battery ESS superfluous in Linnheia Microgrid.

Further investigation on cost expands of the heating system, and also clarifications with the DSO is necessary to develop the microgrid plan further. The software Homer Energy also makes some simplifications in the simulations and a detailed load forecast must be created.

Preface

This master thesis has been submitted in partial fulfillment of the degree of Master of Science in Renewable Energy at the University of Agder, and has been written during the spring 2018. The thesis' main intention has been to plan and simulate a microgrid scenario in Linnheia, outside of Arendal. Magnus Johansen, Nettpartner AS, was the initiator of the problem statement, and together with Lars Magne Jensen in Block Watne AS did we come up with the idea of *Linnheia Microgrid*.

A special thanks goes to Magnus Johansen in Nettpartner AS. Magnus has helped me during the whole semester with relevant suggestions and inputs, which has been really inspiring. Together, we have been on excursion to Fredrikstad Energi to learn about the project *Smart Energi Hvaler*, and how they are implementing smart technology into people's home. He has also introduced me to Lars Magne Jensen and other business contacts that have helped me with issues like prices, information of products and similar work.

I would also like to express my sincere gratitude to my supervisor, Professor Mohan Lal Kolhe, for his time, guidance and encouragement throughout the whole semester. His comments and suggestions have greatly helped me to improve the thesis, and his guidance has been crucial for my work.

Daniel Jordskar
University of Agder
Grimstad, Norway
May 2018

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List of Abbreviations

AC Alternating current

BESS Battery energy storage system

BIPV Building integrated photovoltaic

CAES Compressed air energy storage

CHP Combined heat and power

DC Direct current

DG Distributed generators

DoD Depth of discharge

DSO Distribution system operator

EMS Energy management system

ESS Energy storage system

EU European Union

EV Electrical vehicle

FESS Flywheel energy storage system

HESS Hydrogen energy storage system

HV High voltage

IEC International Electrotechnical Commission

IRENA International Renewable Energy Agency

KILE Kvalitetsjusterte inntektsrammer ved ikke levert energi

LV Low voltage

MASL Meter above sea level

MPPT Maximum power point tracking

MV Medium voltage

NDES Non-dispatchable energy sources

NOK Norwegian kroner

NPC Net present cost

NVE The Norwegian Water Resources and Energy Directorate

nZEB Near-zero energy building

O&M Operation and maintenance cost

PCC Connection point for microgrid and main grid

PHS Pump hydro storage

RES Renewable energy source

SoC State of charge

SST Solid state transformer

STES Seasonal thermal energy storage

THD Total harmonic distortion

TLC Thermal load controller

VOLL Value of lost load

ZEB Zero energy building

1 Introduction

1.1 Background and Motivation

The aging Norwegian grid infrastructure has to be changed, due to new smart grid technologies and modern lifestyles. The Norwegian power system consists of large and controllable energy sources, which supplies distributed loads and has one directional power flow. In the modern power system will the power flow be bi-directional with different consumption pattern than earlier, and with limited capacity. Reinvestments of the existing grid will be costly, and its important that the new upgrades is suitable for the future needs.

The upgraded distribution networks must be able to integrate distributed generator (DG) units, renewable energy source (RES) and energy storage system (ESS), while the power flow to the end consumers are maintained effective. In the new smart grid is customized measuring systems, voltage control and protection schemes essential in the distribution network. New smart grid technologies can play a major part in solving the upgrade issues in an effective way.

Establishment of microgrid communities in Norway can contribute to solve many upgrading challenges of the existing grid, based on control opportunities and sustainable implementation of DG units. Microgrids has the opportunity to operate isolated from the distribution network, grid-connected, and also switch between these modes. Both thermal energy and electricity can be delivered by the microgrid, and also increase the local delivering security and voltage quality by reducing voltage drops and support the voltage level. Also, if the microgrid is given attractive benefits can it offer supplementary services to support the grid.

In this thesis is a potential grid-connected combined heat and power (CHP) microgrid in Southern-Norway planned and analyzed in cooperation with Nettpartner AS who wants to establish a proposal to Block Watne who has the local agreement with *Grimstad Kommune* to develop area regulation over the area *Linnheia Nord*. The thesis will present a suitable microgrid proposal for the area with relevant considerations and discussions. Agder Energi is the grid owner in Aust-Agder and will be referred to in the thesis.

1.1.1 Energy Strategy for the European Union

The European Commission presented a new package proposal in 30th of November 2016 that gives clear directions for how the European Union (EU) could enabling the targets in the *Paris Agreement* [1]. The proposals in the package are intended to help the EU energy sector to become more stable, more competitive and more sustainable. To enabling this development has the package three main goals:

- Putting energy efficiency first.
- Achieving global leadership in renewable energies.
- Providing a fair deal for consumers.

The European Commission will encourage cross-border cooperation and mobilizing public and private investments in the clean energy sector. Potentially can the proposal be good for the economy and could generate an estimate of 900 000 jobs in Europe, which will develop technologies that are positive for the environment and makes it possible to reach the emissions targets for 2030 [2].

Local Energy Communities
The package proposal from the European Commission stated that the member states shall facilitate for local energy communities, where consumers can buy a small part of the grid and build their own local energy community [3]. The proposal implies that neighborhoods, island communities or industrial areas could take over the distribution network in their own area.

The commission sees local energy communities as an efficient way of managing energy at community level by consuming the electricity they generate either directly for power or for heating/district heating and cooling, with or without a connection to distribution network. Norway, as a EEA country (European Economic Area), will be subjected to this directive. Although, to ensure this initiative to develop must each Member States of EU/EEA create an appropriate legal framework for the market design. This is further described in Section 3.

1.2 Problem Statement

The problem statement is created in cooperation with Nettpartner AS and UiA. Its desirable to investigate the opportunity to establish microgrids in Norway, and create a realistic proposal. Following sub-goals are used to further investigation.

- Studying the different microgrid technologies and control methods.
- Studying barriers by establishing microgrids in Norway.
- Studying the relevant components in microgrids.
- Plan a practical CHP-microgrid with an optimized system.

1.3 Thesis Outline

The thesis has two parts; a literature search and a practical section. The literature search presents the theoretical items from the problem statement in the section above, and illustrates the different scopes of a microgrid. In the practical part is the software Homer Energy used to plan a grid-connected microgrid in Southern-Norway.

Chapter 1 gives the introduction to the thesis work.

Chapter 2 briefly describe the operation and the different architectures of microgrid. During the chapter will grid-connected and isolated microgrids be discussed, the same will different control methods be.

Chapter 3 explains the package proposal from the European Commission that facilitates local energy communities for European countries, included the consultation responses in Norway. Further are regulations and demands of microgrids in Norway described, and other relevant elements of establishing microgrids in Norway are also mentioned.

Chapter 4 describes some DG units that are relevant for Norwegian microgrids.

Chapter 5 describes energy storage solutions for microgrids.

Chapter 6 describes how a microgrid can be planned, and is based on the planning book of power grids from Sintef, and guidelines for planning of microgrids developed by IEC. The four planning stages are; advance studies, DG and microgrid planning, technical requirements, and evaluations.

Chapter 7 describes the planning of Linnheia Microgrid. The planning will follow the stages given in Chapter 6, and consists of print-screens from the simulations in the Homer Energy software.

Chapter 8 is the thesis conclusion, and chapter 9 is recommendations of further research.

2 Microgrid

Microgrids are considered to be a key component in smart grid, in order to improve system energy efficiency and reliability. Microgrids can be designed to support both AC and DC, which has different advantages and disadvantages that need to be evaluated [4]. For example can AC microgrids prevent different distribution types like single phase, three phase and three phase with neutral. When DC microgrids has no reactive power will DC distribution present several advantages such as reduction of power losses and voltage drop, and increase of capacity of the electrical lines. For the main grid can microgrids be beneficial by reducing congestion and other threats to the system, also the number of unpredictable loads in the distribution network can be reduced. Furthermore, the power electronics in microgrids could also be designed to behave like e.g. a constant impedance load, a modulated load, or a dispatchable load [5]. The Microgrid Exchange Group (an *ad hoc* group of experts) defines the microgrid system as:

> *"A microgrid is 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* [6]."

By this conclusion, microgrid is a platform for integration of DG, ESS and control systems in a local distribution network. In a microgrid concept is the focus on local energy distribution within local loads. Therefore is a microgrid often placed in the distribution network. The main differences between a microgrid and a passive grid with DG units is the control and coordination of available resources. The operation of microgrid involves more than operation of small DG units, it is also the control of loads and distribution of electricity. The microgrid executes all this functions, according to governmental environmental and technical targets. According to the Microgrid Exchange Group, the benefits of microgrids include:

- Enabling grid modernization and integration of multiple smart grid technologies.
- Improve the integration of DG and RES that help to reduce the peak loads and reduce losses by locating generation near demand.
- Meeting end-users needs by ensuring energy supply for critical loads, controlling power quality and reliability at the local level and promoting customer participation through DMS and community involvement in electricity supply.
- Supporting the main grid by handling sensitive loads and the variation of local RES.

2.1 Why Do We Need Microgrids?

The increasing focus on environmental friendly solutions, like RES in the grid, has also increased the microgrid market in the energy sector. Several places in Norway is the grid capacity close to the limit in periods with high consumption, and improvements will be expensive. Although, without improvements in these areas is the grid not suitable for the future. Microgrid could be a possible solution in these areas, and also be economic and environmental friendly solution with high delivering security. In island communities has local production been a natural energy solution, in particular to isolated island or in industry areas. Microgrid could be a very suitable solution to this communities.

Microgrid is beneficial in several contexts and situations, in particular to local communities. In some areas would it be the most suitable solution, either economical or because its most energy efficient. At a local level will a microgrid be effective and an economic way to integrate the end consumers and buildings with distributed and produced electricity. It could also be necessary to reach local environmental targets like delivering security, carbon emission reduction and diversification of energy sources [7]. The purpose of microgrid is to focus on planning and delivery design of local energy to match the demand from the area, which could be a city, university, neighborhood, industry area or other similar locations.

2.2 Microgrid Categories

Microgrids are usually divided into two main categories; grid-connected microgrid and isolated microgrid, where the microgrid is a group of interconnected loads and DG units within defined electrical boundaries that acts as a single controllable unit with respect to the grid.

Grid-Connected Microgrid
Grid-connected microgrid is connected to the grid through a circuit breaker called *point of common coupling* (PCC) [8]. In normal operation is the microgrid connected to the main grid, and in error-situations can the microgrid disconnect from the power system into island mode. The microgrid should guaranty grid stability to every load in the system, even if the microgrid is switching from one operation mode to another.

In a microgrid should the time of isolated operation be settled to dimension DG units and ESSs, combined with the overall energy consumption. Beside this will the economic profitability decide the dimension of the energy resources and the rest of the components. To optimize the operation cost should the microgrid also have the ability to monitor the operation costs related to local energy production and import of energy from the main grid [8].

Isolated Microgrid
Isolated microgrids are not connected to the main grid, and it is always operating in island mode. To guaranty grid stability does the microgrid consist of adjustable DG units that can cover the daily consumption, without being independent of the weather conditions and other uncontrollable situations [8].

An isolated microgrid is often build to provide electricity to rural areas or in developing countries without a stable power grid. Historically has isolated microgrid had a huge amount of fossil power sources, although with new technology and reduced material cost for RES will future microgrids consist of a much larger amount of renewable energy [8].

2.3 Operation of Microgrid

There is a wide range of loads that can be connected to a microgrid, and this is illustrated in Fig. 1 that is a general scheme of a microgrid infrastructure. The blue elements in the figure differs in the AC microgrid, while the green elements differs in the DC microgrid. The illustrated microgrid system is separated into different main categories, shown with red numbers. As illustrated is the *PCC* constituting the gateway between the microgrid and main grid, while the main elements of a microgrid are interconnected with *distribution lines*. Meanwhile AC microgrids use single or three phase lines, the distribution in DC microgrids are monopolar, homopolar or bipolar [4].

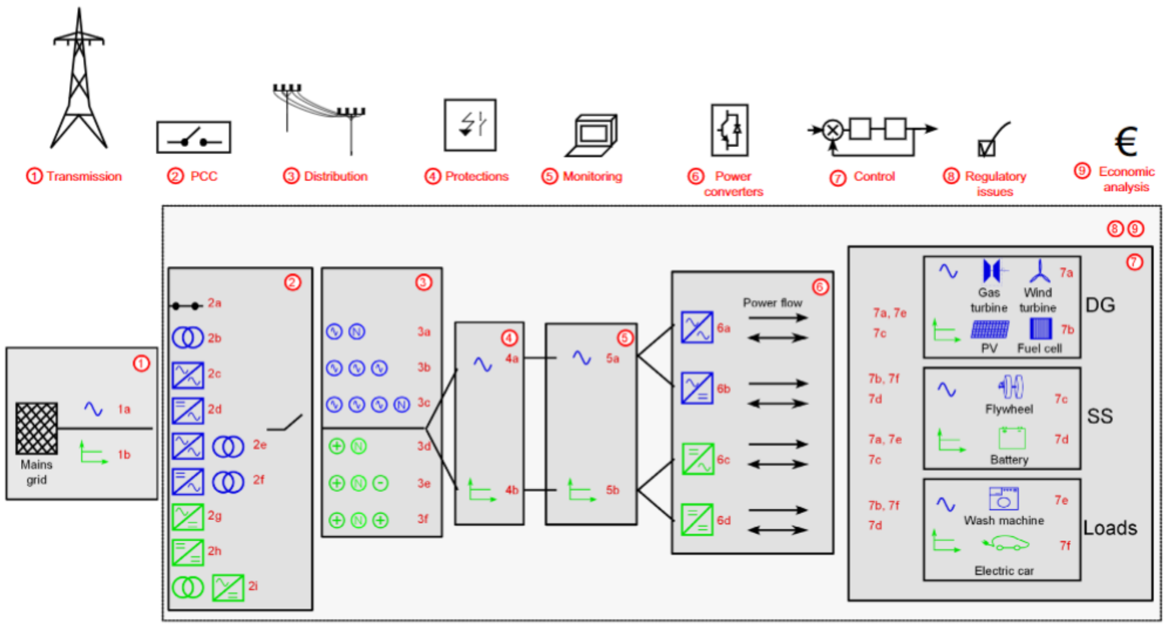

Figure 1: A general scheme of a microgrid [4]

To guarantee safe operation, microgrids need to have *protection mechanisms* that must be designed following different principles and parameters. Therefore is it important to have a *monitoring system* to measure all the parameters for voltage, frequency and power quality that must be continuously supervised. DG units and loads are generally connected to the distribution lines of the microgrid through *power converters*, which adapt the currents and voltages levels of the microgrid to the connected units.

An *economic analysis* of the cost and benefits of a microgrid requires to consider multiple factors and variables. To keep this system stable, the measured parameters and information throughout the system must be gathered. After that can certain tasks be performed and coordinated, such as load sharing, voltage level control, and electric generation. Both AC and DC have a hierarchical *control system* to complete this tasks. Although, microgrids needs a regulatory framework in order to provide a successful development and implementation, and prevent *regulatory issues*.

Monitoring And Measuring System

The monitoring system for microgrids needs to perform several tasks and must fulfill certain requirements; distributed structure to monitor each unit simultaneously, online definition and modification of system configuration and remote control, and monitoring of the whole system, among others [4]. Microgrids could be monitored and controlled by different commercial solutions from vendors, although it is also possible to monitor microgrids through phasor measurement units. The phasor measurement units are systems which offer more accurate data about the power system, which allow to manage the system more efficiently and with a higher level of response.

The main difference between AC and DC microgrids is that DC microgrids only require to monitor and control a reduced number of variables, while AC microgrids also require to monitor the frequency and the reactive power. This makes DC microgrids easier to measure and monitor [4].

2.4 Control Methods for Microgrid

In microgrids can power electronics provide the control and flexibility that the system needs. Microgrids should seamlessly connect and isolate itself from the grid, reactive and active power can be independently controlled, voltage sag and system unbalances can be corrected, and microgrids can meet the dynamic requirements from the grid [5]. AC and DC microgrids require different control tasks in order to guarantee a correct operation of the system, and often is hierarchical control used to carried out these tasks. An example is illustrated in Fig. 2.

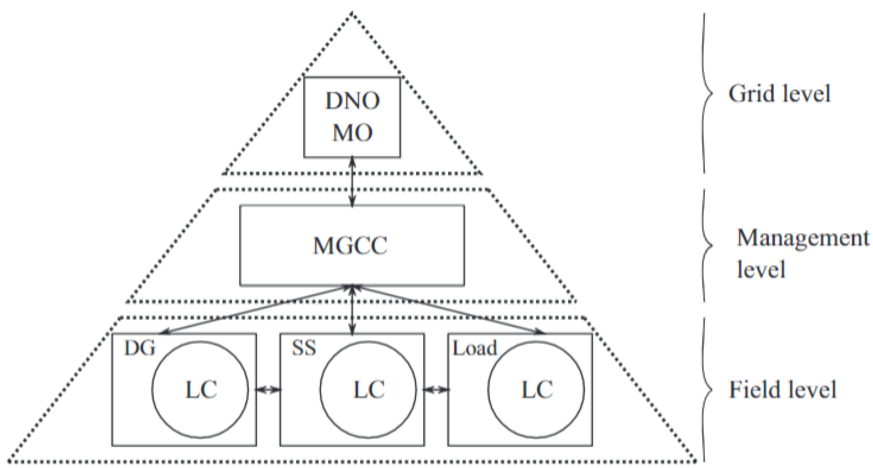

Figure 2: Hierarchical control of microgrid [4]

Grid Level
At this level a distribution system operator (DSO) and a market operator are found. Active management techniques in microgrids allow the DSO to take advantage of several control variables, to control active and reactive power flow between the microgrid and distribution network. The market operators is in charge of the participation of the microgrid in energy markets, and it can follow different market policies.

Management Level
A control centre can perform those tasks related to the management of the microgrid. The main functions is to maintain:

- Frequency (only for AC microgrid).
- Voltage.

- Synchronizing between microgrid and distribution network (only for AC microgrid).
- Load control.
- Optimization of the production in the microgrid.

The microgrid controller also controls the connect/disconnect of microgrid from the distribution network.

Field Level
Local controllers are placed in every element of the microgrid, such as DG units, ESS and loads. The load controller is executing the necessary tasks for every type of element:

- The best alternative to control DG units (gas turbine, diesel generators, etc.) is the droop control. This control method gives high reliability and there is no need for communication between the generators. For uncontrollable DG units, like wind and PV, can nonlinear droop control and hybrid droop control with MPPT be used.
- The ESS needs specific charge/discharge control strategies to optimize the operation.
- Local controller for loads controls the load and reduces the need of a microgrid controller.

Droop Control
DG units are connected to the microgrid through an interfacing inverter, that has a large role in the operating performance of microgrid. Droop control of an inverter is a control strategy commonly applied to generators for primary frequency control and also voltage control, to allow parallel generator operation [9]. The droop control controls the frequency of a generator based on the generator load, so each generator can operate at rated power. Figure 3 illustrates the frequency droop characteristic, while Fig. 4 illustrates voltage droop. When the frequency falls from f_0 to f, the power output of the generating unit is allowed to increase from P_0 to P. A falling frequency indicates an increase in loading and a requirement of more active power. The droop control allows multiple units to share load without the units fighting each other to control the load.

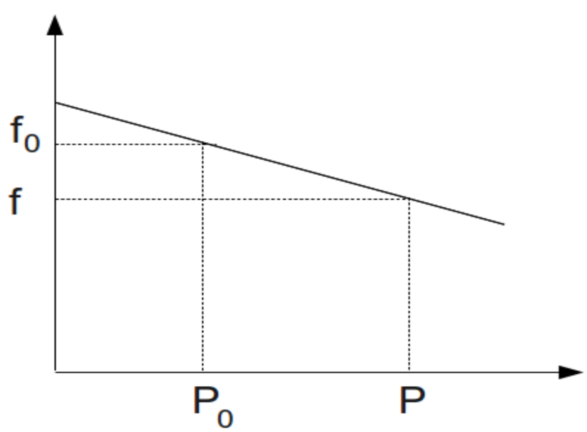

Figure 3: Frequency droop characteristic [9]

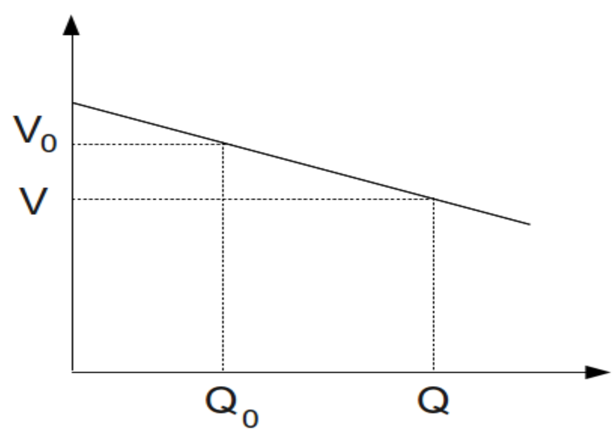

Figure 4: Voltage droop characteristic [9]

2.5 Stability

Stability of the microgrid becomes an issue if the sources in the microgrid are controlled of local measurements. The stability is mainly affected by frequency droop, and its usually improved by solid design and droop control with adjustable dynamic behavior [4]. Microgrids in island mode needs at least one controllable DG to guarantee stable operation.

Figure 5 illustrates the criteria and different methods for stability improvements on AC microgrids. The stability in AC microgrids are especially depending on the operation mode (grid-connected or island), control strategy, DG-type and network parameters [4]. In DC microgrids are the stability related to the behaviour of the power electronic interface to integrate DG units and ESS.

Issues	Reasons	Improvement methods
Small signal stability	Feedback controller Small load change System damping Power limit for DGs	Supplementary control loops Coordinated control of DGs Stabilizers for DGs Energy management system (EMS)
Transient stability	Islanding Loss of DG Large load step Fault	Control of storage Load shedding methods Protection device setting Control of power electronics
Voltage stability	Reactive power limit/current limiters Load dynamics (induction motors) Under voltage load shedding Tap changers and voltage regulations	Reactive compensation Load shedding Modified current limiter for microsources Voltage regulations with DGs

Figure 5: Main stability issues and reasons, with corresponding possible improvement method in AC microgrid [4]

Quality of delivery voltage

In Norway, the definition of voltage quality is given in *Forskrift om leveringskvalitet i kraftsystemet* (FoL) [10], which includes frequency, slow variations in voltage values, short overvoltages, short undervoltages and voltage drops, flicker intensity, asymmetric voltage, as well as harmonic voltages. The voltage quality demands in low voltage networks is illustrated in Tab. 1 from Sintef.

Category	Phenomenon	Demand	Time Scale
Frequency	Harmonic frequency	49.5-50.1Hz	Measured over 10 sec.
Power value	Slow voltage variations	U=230V ±10% of the time	Measured over 1 min.
	Voltage drop	$\Delta U_{max} \geq 5\%$ max 24 times a day $\Delta U_{stationary} \geq 3\%$ max 24 times a day	Changes over 0.5% over 1 sec.
	Short over- and undervoltages	The same as voltage drop	Measured between 10 ms and 1 min.
	Flicker	$P_{st} \leq 1.2$ 95% of the time $P_{lt} \leq 1$ 100% of the time	Measured over 10 min. Measured over 2 hours
	Asymmetry	$U_{-}/U_{+} \leq 2\%$	Measured over 10 min.
Voltage symmetry	Transient overvoltage	No demands	Less than 10 ms
	THD	THD $\leq$ 8% THD $\leq$ 5%	Measured over 10 min Measured over one week
	Individual harmonics	Different demands for each harmonic	Measured over 10 min.
	Interharmonic	No demand	Measured over 10 min.

Table 1: Voltage quality criteria, FoL [10]

2.6 Architecture of Microgrids

The selection of a proper microgrid architecture is a critical issue, which must be done correctly, or else it can seriously affect the economic viability of the project. Its necessary to consider the loads, the existing and planned DG units, possibility of ESS, the difficulty to place new electrical lines, and existing communications, among other relevant issues [11].

The microgrid architectures are based on either AC or DC buses, or a combination of both, to find the highest reliability and efficient of the microgrid. It is six main microgrid categories, depending on how the AC and DC buses are connected. The technology in AC microgrids are more developed than DC microgrids, although DC microgrids has several advantages, since there is no reactive power, like reduction of electric losses and lower voltage drops. That is why preparations, implementations and operation of DC microgrids is easier and less expensive than AC microgrid, illustrated in Tab. 2 [4]. Nevertheless, based on the established infrastructure and loads is it usually more economic to select AC microgrid.

Device	Location	AC	DC	Reasons
Protections in PCC	Fig. 1 ②	Lower	Higher	Technology more mature and lower power ratings in AC systems
Distribution	Fig. 1 ③	Higher	Lower	Due to skin effects, reactive power etc. higher losses in AC systems
LV protections	Fig. 1 ④	Lower	Higher	Lower power ratings and more mature technology in AC systems
Metering	Fig. 1 ⑤	Higher	Lower	More variables to be monitored in AC systems
Communication	Fig. 1 ⑤	Similar	Similar	Depending to the control technique used
Power converts	Fig. 1 ⑥	Higher	Lower	Lower efficiencies and more components in AC systems
Local controller	Fig. 1 ⑦	Higher	Lower	More tasks (synchronism, reactive power control etc.) in AC systems
Load controller	Fig. 1 ⑦	Similar	Similar	Similar tasks in AC and DC systems

Table 2: Development costs in AC and DC microgrids [4]

2.6.1 AC Microgrid

AC microgrids consists of one or more AC buses, and any device connected to the microgrid has to be AC-components, or connected through a DC/AC converter. The microgrid is connected to the grid through the PCC. Figure 6 illustrates an example of the architecture of an AC microgrid. which is composed by three AC feeders, where *Feeder 1* and *2* contains of DG units and critical loads, while non-critical loads are connected to *Feeder 3*. Each feeder consists of loads, DG units and ESS. The static switch manages the connection of the microgrid to the distribution network, and if the quality of the electrical distribution grid is poor, will the static switch disconnect from the microgrid, leaving the microgrid in islanded operation mode.

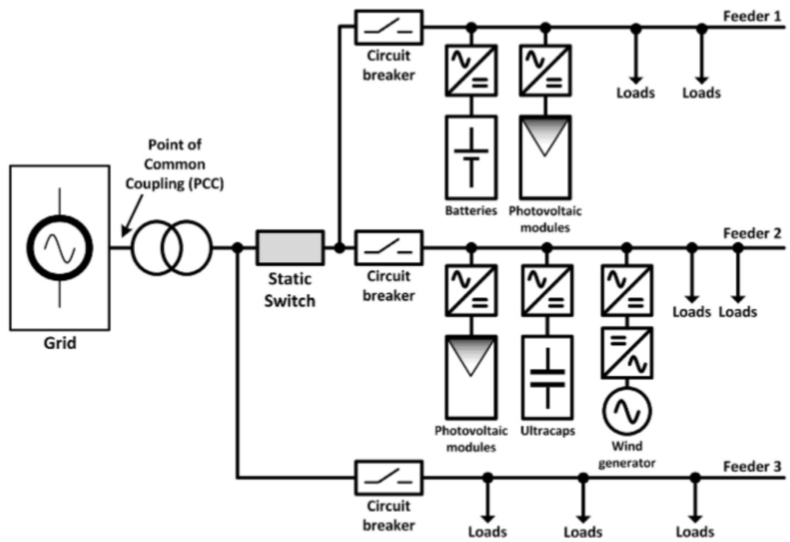

Figure 6: Architecture of AC microgrid [11]

In the AC microgrid architecture operated in grid-connected mode, the power flows directly from the grid, and does not need any series-connected converter. This provides a high reliability of the microgrid. When AC microgrids are grid connected are the voltage and frequency in all feeders the same as the distribution network, while in island mode are this parameters independent of the distribution network. Existing electrical grids can be easily reconfigured to an AC microgrid scheme, although the main drawback of this architecture is the large amount of complex power electronics interfaces required (inverters and back-to back converters) to reduce the efficiency and reliability of the overall microgrid. However, the microgrid concept is especially suitable for integration of AC microgrid in existing installations, and will probably be the most common microgrid architecture in the near future [11].

2.6.2 DC Microgrid

DC microgrids are connected to the distribution network through a bidirectional AC/DC converter. It is bidirectional to export excess energy from DG units to the distribution network. The DC microgrid presents a DC-bus with a regulated voltage since most DG units needs DC/DC or DC/AC power electronic interfaces to be connected to the DC-bus. Depending on the voltage level, the DC-loads might in some cases be directly connected, and since the voltage of the DC-bus is regulated by the main AC/DC converter is the quality of the voltage to the DC-bus very high. When the distribution network fails must the microgrid regulate the DC-bus voltage itself without the main AC/DC converter. The power flow control from DG units and ESS must take into account the available stored energy to obtain better reliability. Figure 7 illustrates an example of the architecture of an DC microgrid.

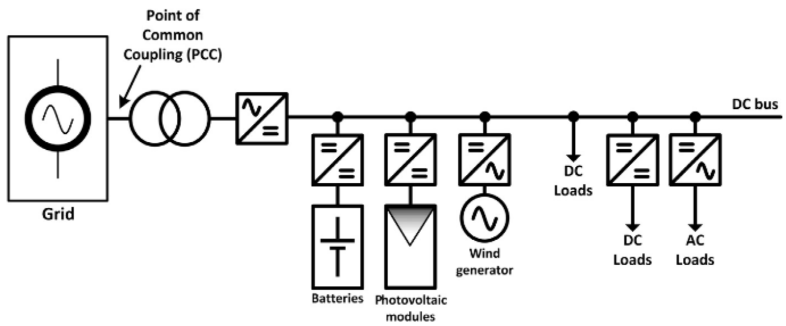

Figure 7: Architecture of DC microgrid [11]

DC microgrids architecture has both advantages and disadvantages compared with AC microgrids:

+ Reduced number of power converters.
+ The possibility to adapt the DC-bus voltage, so that some DC loads can be connected directly to the DC-bus.
- The power flow to/from the distribution network goes through the AC/DC converter, which reduces the reliability.
- Existing AC installations (cables etc.) can not be used.
- AC loads can not be directly connected to the microgrid.

2.6.3 Hybrid AC/DC Microgrid

The architecture of a hybrid AC/DC microgrid consists of an AC microgrid with a DC sub-grid, connected with a bidirectional AC/DC converter, shown in Fig. 8. DG units can be connected to AC or DC feeders. AC loads are connected to AC-feeders, while DC loads are connected to the DC-feeder by using a power converter to adapt the voltage level if necessary. DC sub-grid can act like a generator or a load of the AC microgrid, depending on the power balance in the DC feeder. This architecture combines the advantages from both AC and DC microgrids. It is two direct connections to the grid that presents high reliability; the AC feeder allows using the existing equipment, and the DC feeder allows the use of a reduced number of simpler converters. However, some DC loads can be connected directly to the DC feeder, without the need of any power converter, which makes this architecture suitable for installations with critical loads (at the DC feeder) in combination with more robust loads (at the AC feeder). An example of an hybrid AC/DC microgrid is illustrated in Fig. 8.

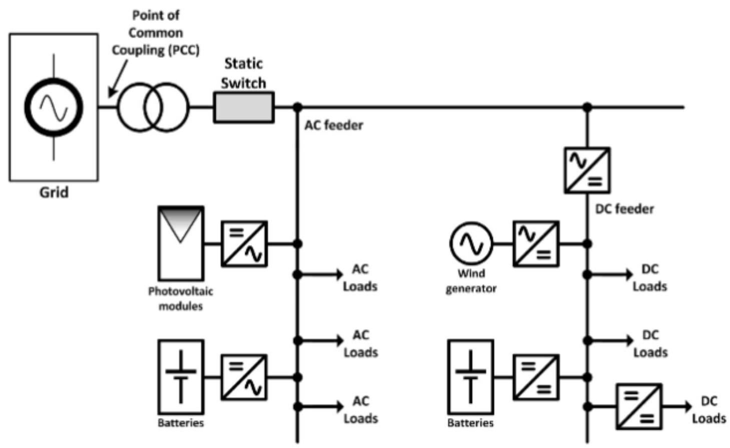

Figure 8: Hybrid AC/DC microgrid architecture [11]

2.6.4 AC Microgrid with DC Storage

Its possible to improve the flexibility of the AC microgrid by placing the ESS at a separate DC bus, while the DG units and the AC loads are placed at the AC bus. The interconnection with the grid is done by a static switch, which manages the transition from islanded to grid-connected operating modes and vice verse. DG units and loads can be grouped at a single feeder or distributed at different ones. The ESS is placed in a separate DC-bus, and if its several ESS at the DC-bus is an AC/DC bidirectional power electronic interface used to connect them. The architecture is illustrated in Fig. 9. The architecture is similar to the hybrid AC-DC with easier management of the ESS.

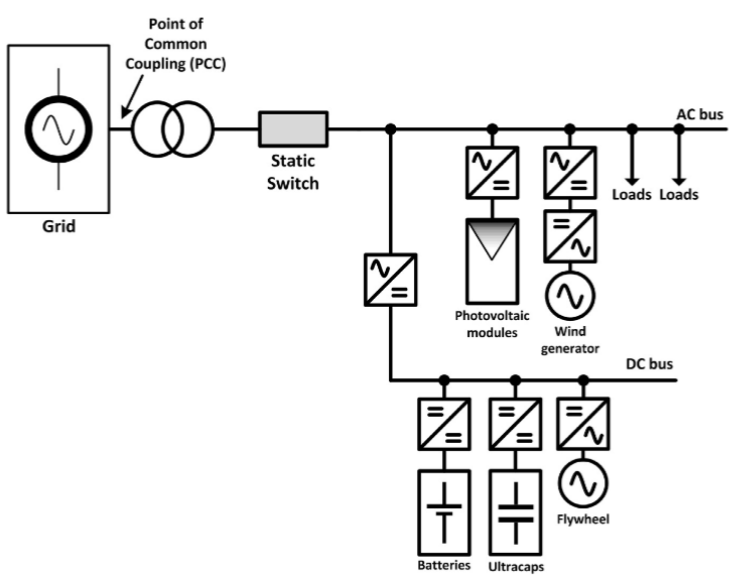

Figure 9: AC microgrid with DC storage architecture [11]

2.6.5 DC-Zonal Microgrid

In this architecture is several DC feeders connected to the main AC bus through centralized bidirectional AC/DC converters. DG units and loads are connected to the DC feeders with suitable power electronic interfaces, and the architecture is illustrated in Fig. 10. This architecture consists of the same advantages and disadvantages as the DC microgrid, although DC-zonal microgrid allows different DC-bus voltages and management techniques at each feeder. However, the main disadvantages of the architecture is the increased complexity, due to the interconnection between feeders. This architecture can be suitable for facilities that require very high voltage quality and and reliability.

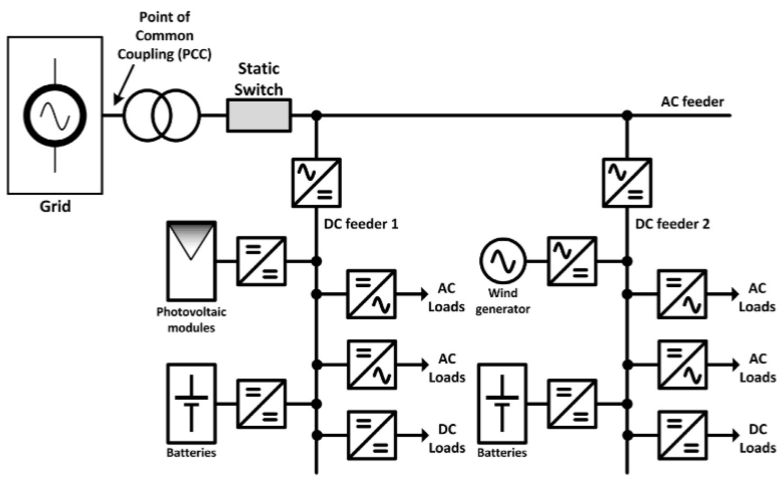

Figure 10: DC-zonal microgrid architecture [11]

2.6.6 Solid State Transformer Based Microgrid

The grid frequency transformer is replaced by a solid state transformer (SST) in this architecture, since SST can use high frequencies, has reduced size and weight compared to regular transformers. The SST can also manage the power flow between the feeders and the grid. AC loads are connected directly to the AC feeder, and DC loads are connected to the DC feeder. In Fig. 11 is a SST based microgrid illustrated. The SST is a single input dual-output power converter that converts AC to DC, back to AC again. The advantages of the architecture are very high quality energy, simple electronic interfaces, simple connection of DC loads, compatibility with AC grid loads and robust management of ESS. Main disadvantage is reduces reliability and efficiency of the system, due to series-connected power converter.

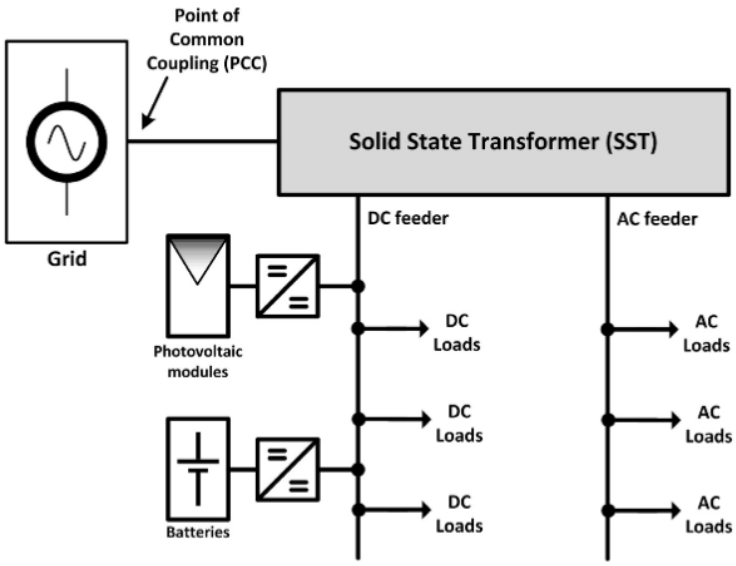

Figure 11: Solid state transformer based microgrid architecture [11]

2.7 Protection Schemes

The design of protection schemes of AC and DC microgrids are challenging, since it is several parameters involved, such as the dynamic structure of the microgrid and different levels of current of the devices. The design of protection should be based on following parameters; sensitivity, selectivity, speed of response and security level [4]. Among all these parameters and issues is the protection scheme basically derived from two; the number of the installed DG units, and the availability of a sufficient level of short circuit current in an islanded operating mode.

It is developed several protection schemes for AC microgrids, which can be classified as centralized or decentralized schemes. In the decentralized schemes are each DG protected by their own relay, which is an efficient technique against line-to-ground and line-to-line faults, although it has limited effect to faults with low impedance. The centralized schemes are based on voltage protection and require a central protection unit [4].

Protection schemes of DC microgrids has different challenges, mainly the immaturity of standards and guidelines, and almost no practical experiences. A common objection against the application of DC in power systems is that the current in DC system does not have any natural zero crossing, thus short-circuit current interruption is more difficult to obtain than in an AC system. Protection schemes also has to include ground fault detection and isolation mechanisms to ensure system safety [4].

Type	Protection strategy	Operation	Communication link
AC	Adaptive	Both	Yes
	Based on communication-assisted digital relays	Both	Yes
	Voltage	Islanded	Yes
	Harmonic content	Islanded	Yes
	Current travelling waves	Grid-connected	No
	Distance	Both	No
DC	Based on commercial DC protections	Both	No
	Optimal unit and non-unit protection	Both	Yes

Table 3: Examples of protection schemes for AC and DC microgrids [4]

3 Establishing Microgrid in Norway

Today, there is not any standardized manner to planning or operate microgrids in Norway. Although, the European Commission has established a proposal called "Clean Energy for All European" where *local energy communities* was defined, and registered for consultations for relevant actors. In Norway will microgrids be an effective opportunity to integrate DG units and further develop the smart grid technology. Nevertheless, regulations and demands must be statutory, both national and regionally, before microgrid can be common in Norway.

Even though the delivery quality in the Norwegian grid can be considered as good, does the LV grid need significantly upgrades and reinforcements. 40-50% of the LV grid is considered as weak [12]. Microgrids can be an alternative of expensive LV grid upgrades. This can be beneficial for the environment, costs and electrification, as well as reliable and secure power supply in Norway.

3.1 The Norwegian Power Grid

The Norwegian power grid can be divided into three networks:

- Main grid
- Regional grid
- Distribution network

The main grid connects the larger generators all over the country to the rest of the grid. It also connects the transmission lines to neighbouring countries. The distribution network is the local network that distributes power to the consumers, and the regional grid connects the main grid and the distribution network. In decades has the distribution network been disregarded in the development of new analysis and operational techniques compared to the main and regional grid [13]. This has result in an oversized distribution network, where it most of the time is mismatch between consumption and available electricity. Although, the electricity consumption has continuous expanded and especially for the last 10-15 years, with the entry of electric vehicle (EV) and modern technology in most homes. This has lead to operation on the distribution network close to its maximum capacity [14]. With the expansion of RES from end consumers to the distribution network, a restructuring of the distribution network is necessary to maintain an acceptable voltage quality [13].

3.2 *Clean Energy for All European*

The European Commission presented in November 2016 a package of measures to keep the European Union competitive as the clean energy transition changes global energy markets [3]. The Commission wants the EU to lead the clean energy transition, not only adapt to it. The three main goals for the package are putting energy efficiency first, achieving global leadership in renewable energies and providing a fair deal for consumers. Local energy communities, like microgrids, was described in the package as follow:

> *"Local energy communities can be an efficient way of managing energy at community level by consuming the electricity they generate either directly for power or for (district) heating and cooling, with or without a connection to distribution systems. To ensure that such initiatives can freely develop, the new market design requires Member States to put in place appropriate legal frameworks to enable their activities."*

Article 16 in [3] sets the local energy community requirements for EU member states, where its established that local energy communities are:

- Entitled to be owned and established in the member states.
- Can access all organized markets.
- Subjects to fair, proportionate and transparent procedures and cost reflective charges.

The member states shall provide and enabling regulatory framework to ensure that:

- Participation in a local energy community is voluntary.
- Shareholders or members of a local energy community shall not lose their rights as household costumers or active costumers.
- Applies to generate capacity installed by local energy communities, as long as such capacity can be considered small decentralized or distributed generation.
- Local energy communities shall perform activities of a DSO.
- Local energy communities may conclude an agreement with a DSO to which their network is connected on the operation of the local energy community's network.

3.2.1 Consultation Responses in Norway

The response in Norway after the the European Commission published the package proposal has been divided. NVE is positive to develop regulations for local energy communities [15]. Furthermore, they claims its critical to evaluate how this system will affect rights of the costumers connected to the system, and what kind of consequences the establishment can give to the remaining grid costumers. Skagerak Energi claims that the statement from the European Commission is a bit unclear, although the development of local energy communities will engage several positive activities like; production, distribution, aggregation, storage etc. [16]. Especially in outlying areas where its difficult to maintain a sustainable grid connection could local energy community be a suitable solution, according to Skagerak Energi. Hafslund is skeptical to the proposal, since grid companies has to sell grid areas to private organizations that want to establish local energy communities in the area [17]. This proposal does not match the Norwegian legislation, where it requires trading license, individual measuring of each housing unit, technical concessions for operations of LV grid etc. Hafslund does not see how this proposal can be sustainable and fair to the Norwegian population, and want further research on the subject.

3.3 Regulations and Demands

A grid-connected microgrid has to follow different obligations and requirement given by the related power company of the distribution network. Since the microgrid will have sellable excess electricity and in periods produce much more electricity then consumed, can the microgrid be defined by the *plus costumer agreement* developed by NVE. A plus costumer is defined by NVE as end consumers of electricity which also generates electricity for own consumption [18]. In January 2017 was the end consumer agreement regulated to only involve costumers that does not feed the grid with more than 100 kW at any time. In this definition will the end consumer be exempt from the second tariff section for feeding electricity to the grid.

3.3.1 Electricity Tariffs

Grid-connected microgrids needs suitable tariffs for sale and consumption of power from the distribution network. End costumers of electrical power without power settlement pays grid rental, which consists of a permanent section and an energy section. For end costumers with power settlement are also a power section included in the grid tariff. The second tariff section consists of permanent- and power section, where the permanent section is a fixed sum, while the power section depends on the costumers electricity consumption in a given time period [19]. Plus costumers are equally tariffed as regular end costumers, although plus costumers are exempt for the second tariff section and the grid rental will also be simplified compared to other power producers.

Prices Agder Energi

The current grid rental prices of Agder Energi are shown in Table 4, and has been applicable since 1st of January 2018. The prices includes the governmental energy fund fee (Enova) of 1.25øre/kWh, and the consumption tax of 20.73øre/kWh. The plus costumers gets a sale price of spot price + 4.00øre/kWh [20].

Description	Permanent section NOK/mo	Energy section øre/kWh	Power section Summer NOK/kW/mo	Power section Winter NOK/kW/mo
Grid rental	162.50	50.10		
Grid rental season differentiated Summer (May-Oct) Winter (Nov-Apr)	162.50	38.55 56.35		
Power grid rental season differentiated Summer (May-Oct) Winter (Nov-Apr)	62.50	25.06 26.71	44.58	133.75

Table 4: Grid tariffs Agder Energi [20]

3.3.2 Demands of Distributed Generators

Before installing DG units and deliver power to the grid, is it necessary to considered the guidelines regarding engineering, exportation, operation and maintenance (O&M) of system. Also, how the DG affects the grid and how to maintain the grid security and quality [21]. An agreement between the plus costumer and the power company is mandatory to comply the national regulations.

The main technical challenge regarding DG units connected to the distribution network is related to voltage quality and surge protectors [22]. Both slow and rapid voltage variations has to be limited. For a grid-connected microgrid is it important to estimate the impact of the DG on the distribution network. When the microgrid is feeding power to the grid, both large changes in normal operation and errors in the grid may occur. The power will be bidirectional, stationary voltage and voltage quality will be affected, and island mode will be possible. DSOs has to consider if the proposed size and limits in the guidelines are suitable for the their grid.

3.4 Benefits

Microgrids with smart micro-production is environmental friendly, and will be beneficial for the consumers and the grid. The micro-production makes it possible to utilize the renewable resources like wind, PV and biomass from the industry [23]. There will be lower transmission losses since the production is close to the end consumer, which contribute to increased voltage quality, which leads to reduced expenses and further investments in the grid can be exposed.

Microgrids are better prepared for both the known and unknown future needs, compared to today's centralized grid. Local energy communities will have the opportunity to effectively increase the total power supply through relatively small DG units, instead of waiting for the power company to build expensive centralized power plants, which would take a long time to complete. Microgrid technology would also motivate the consumers to future innovations and activities in electrical contexts.

Isolated communities with unreliable power supply, or isolated grids only supplied by aggregates, might have great benefits of using microgrid for renewable production. The delivering quality will increase significantly and fossil fuel consumption will be reduced [23]. From the distribution network point of view will the microgrid be a controllable load that could be disconnected if needed.

Since the microgrid structure is customized for the operation, is the system very effective. The planning and operation of production and supply are based on the needs from the microgrid, which would be different for each microgrid. This need would be based on the size of the community and if its any industry in the area. In a local energy community will the microgrid integrate the consumption and buildings with electrical distribution and production in an economic and environmental friendly way.

3.5 Challenges and Disadvantages

Is the construction of the microgrid not suitable for the use, could this lead to weakening in the supplying security, reliability and voltage quality. With increasing number of DG units in the power system could the voltage exceed the thermal limit, and the stability and supplying security will not be satisfactory. A partial solution at this challenges could be smart solutions for monitoring, control and protection which would reduce the demand of new wires, cables or transformers [24].

Today's Norwegian power grid is design for one direction power flow, from large power plants connected to the main- and regional grid. Large integration of prosumers (*consumer which also produce energy to the grid* [18]) will be a challenge for the existing power grid, since production close to the end consumers will lead the current in the opposite way, which could lead to errors at short circuit protections [23]. Several power producers has experiences that the grid disconnects more often then it should, since the protection system is reacting on small interruptions in the grid. Stable and secure operation is necessary to avoid this, which is achieved by accurate settings for the protection system [23].

A significant challenge is also to establish a supplier- and service market for microgrids. Together with the challenges regarding expertise will this be one of the main focus areas in the future.

Skepticism regarding local energy communities
Norwegian DSOs has expressed skepticism regarding the European Commissions package proposal regarding local energy communities [25]. This proposal implies that DSOs has to sell their grid to anyone that wants to establish a local energy community. This is against Norwegian legislation that requires a trading license, individual metering of each residential unit, and technical concessions and requirements for low-voltage grid, among other things. The grid tariff for the remaining consumers will also probably exceed. Although, the DSOs are positive to the concept of local energy communities, if the legal requirements of selling/renting the grid is rational for both DSOs and consumers.

4 Distributed Generators In Microgrid

DG is a term that refers to the production of electricity near the consumption place, and is connected to the electricity distribution system on medium and low voltage levels (MV=11kV and LV=230/400V). The DG units are typically RESs and co-generation (simultaneous production of heat and electricity) [26]. DG units are increasing all over the world, and in Norway is the integration of PV systems in many homes making both opportunities and potential issues for the electric power system [27].

Integration and utilization of DG is an important aspect within the concept of microgrid, since microgrid will require extensive interaction between various actors in the electric energy system. Although, DG can provide benefits for producers, customers and DSOs. From the DSOs point of view can integration of DG replace or postpone investments in the MV and LV distribution network or HV transmission levels. This provides new opportunities for DSOs, like solving capacity problems, voltage support and reliability improvements [27].

4.1 Distributed Generator Technologies

The DG units in microgrids can be either renewable and non-renewable sources. In Tab. 5 and Tab. 6 is the different relevant technologies for microgrids summarized. These tables highlights that non-renewable based technologies provide higher efficiencies, and that wind and small hydropower based systems has highest efficiencies of the renewable based technologies. The electricity production of fossil energy sources has typically lower capital costs and higher operation- and maintenance costs than renewable energy. The energy cost is also extremely independent of the fuel price. The fossil energy sources will not be further described in this thesis.

Energy based technology type	**Primary energy**	**Output type**	**Module power [kW]**	**Electrical efficiency [%]**	**Overall efficiency [%]**	**Advantages**	**Disadvantages**
Reciprocating engines	Diesel or gas	AC	3-6000	30-43	~ 80-85	Low cost	Environmentally unfriendly emissions
						High efficiency	
Gas turbine	Diesel or gas	AC	0.5-30000	21-40	~ 80-90	Ability to use various inputs High efficiencies when using with CHP Environmentally friendly	Too big for small consumers
Micro-turbine	Bio-gas, propane or natural gas	AC	30-1000	14-30	~ 80-85	Cost effective Small size and light weight	Expensive technology
						Easy start-up and shutdown	Cost-effectiveness; sensitive to the price of fuel
						Low maintenance costs	Environmentally unfriendly emissions
Fuel cell	Ethanol, H_2, N_2, natural gas, PEM, phosphoric acid or propane	DC	1.20000	5-55	~ 80-90	One of the most environmentally friendly generator	Extracting hydrogen is expensive
						Extremely quiet	Expensive infrastructure for hydrogen
						Useful for combined heat and electricity applications	

Table 5: Main technologies for non-renewable DG units [4]

Energy based technology type	Primary energy	Output energy	Output type	Module power [kW]	Electrical efficiency [%]	Advantages	Disadvantages
Wind	Wind	AC	0.2-3000	-	~ 50-80	Day and night power generation	Still expensive
						One of the most developed renewable energy technology	Storage mechanisms required
Photovoltaic systems	Sun	DC	0.02-3000	-	~ 40-45	Emission free	Storage mechanisms required
						Useful in a variety of applications	High up-front cost
Biomass gasification	Biomass	AC	100-20000	15-25	~ 60-75	Minimal environmental impact	Still expensive
						Available throughout the world	A net loss of energy in small scale
						Alcohols and other fuels, produced by biomass are efficient, viable, and relatively clean burning	
Small hydro power	Water	AC	5-100000	-	~ 90-98	Economic and environmentally friendly	Suitable site characteristics required
						Relatively low up-front investment costs and maintenance	Difficult energy expansion
						Useful for providing peak power and spinning	Environmental impact
Geothermal	Hot water	AC	5000-100000	10-32	~ 35-50	Extremely environmentally friendly	Non-availability of geothermal spots in the land of interest
						Low running costs	
Ocean energy	Ocean wave	AC	10-1000	-	-	More predictable than solar and wind	Lack of commercial projects
						High power density	Unknown operations and maintenance costs
Solar thermal	Sun and water	AC	1000-80000	30-40	~ 50-75	Simple, low maintenance	Unknown operations and maintenance costs
						Operating costs nearly zero	Low energy density
						Mature technology	Limited scalability

Table 6: Main technologies for renewable DG units [4]

4.1.1 Solar Energy

Globally has solar energy the potential to be the most important RES, and at the end of 2016 was the total amount of installed solar energy 303GW [28]. The most important method to utilize solar energy in Norway is passive utilizing of solar heat, active utilizing of solar heat by using solar collectors, and electricity production. The average solar potential in Northern-Norway is $700kWh/m^2$ and in southern $1000kWh/m^2$, compared to $2500kWh/m^2$ across equator [29]. Figure 12 compares the solar radiation in seven different cities in Northern-Europe, and illustrates that the solar resources in Oslo is the same as in the other European cities.

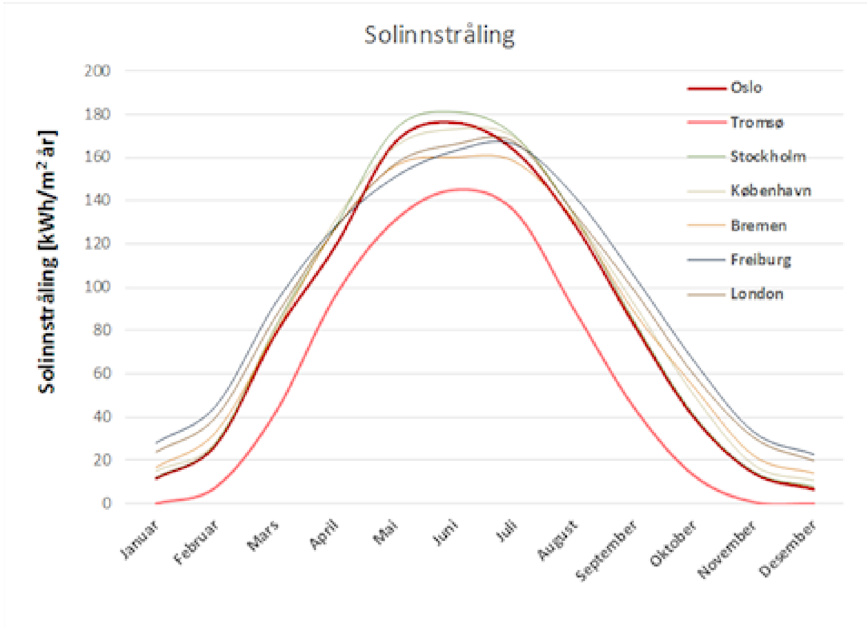

Figure 12: Solar radiation in seven European cities [29]

Its normally the latitude that decides the solar radiation, although other factors like the season of the year and local weather conditions (e.g. temperature, wind, snow, clouds etc.) can also make an impact. Plant specific variations like tilt angle, orientation of the plant and shielding from buildings, vegetation and mountain also affect the amount of produced energy [29].

The marked for solar energy in Europe has changed significantly for the last years, due to reduced price and increased amount of installation. This has lead to increased interest for solar energy in Norway. Combined with reduced costs has also other factors like environmental focus, stricter TEK-demands [30] and increased demands for zero energy building (ZEB) contributed to the development [29].

PV cells are an electronic unit created to convert solar energy into electricity. Its several types of PV cells, although multicrystalline silicon cells are mostly used. A PV system produced approximately 700-950$kWh/kWp/yr$, which is equivalent to 14-150kWh/m^2 is Southern-Norway and 90-110kWh/m^2 in Northern-Norway [29]. The cold climate in Norway has excellent impact on the efficiency, that is between 12-18%. Depends on the material of the cells, production method and outside temperature has also an impact on the efficiency. Furthermore, the efficiency decreases after a few years operation.

4.1.2 Wind Energy

Norway has a great wind power potential with a high amount of wind spread over larger areas. The potential is greatest in the winter half of the year, which corresponds well with the Norwegian power consumption. Since wind power is a non-dispatchable Energy Sources (NDES) can it only cover some of the power supply in a microgrid, or be combined with an ESS. Table 7 illustrates data of wind power in Norway from 2017.

Wind Power in Norway 2017	
Installed power [MW]	1 188
Total production [GWh]	2 849
Number of turbines [-]	468
Average size of turbine [MW]	2.5
Hours of operation [h/yr]	2 856
Capacity factor [%]	32.3

Table 7: Wind power in Norway 2017 [31]

The wind resources at the coast of Norway are very suitable for wind power production, and NVE has calculated that 800TWh/yr can be build at ocean depths down to 50 meters. Offshore constructions are normally more expensive than onshore, and are often facing environmental conflicts [32]. This will naturally vary after construction methods, scope of the project, as well as the vulnerability of the affected nature. The wind resources in Norway are illustrated in Fig. 13.

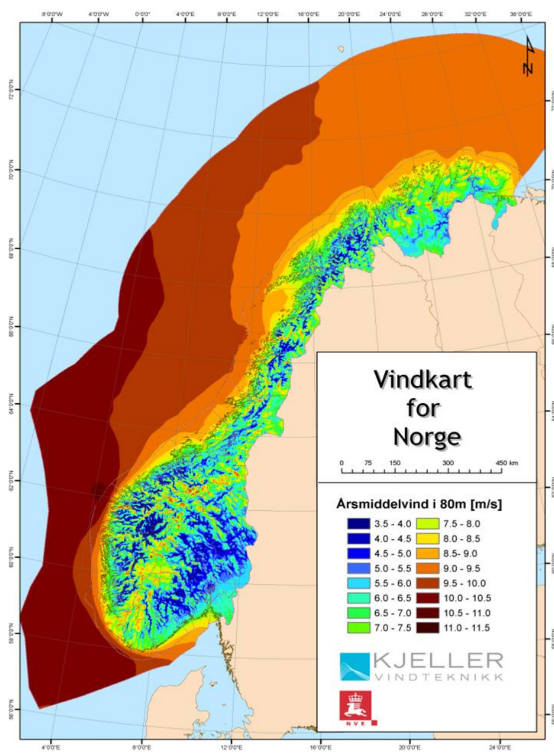

Figure 13: Wind map for Norway [31]

Small wind turbines can be in the range of 0.2 to 100kW, and can be suitable for small energy societies and individual buildings/companies, although the cost of small wind turbines are significantly higher than larger wind turbines. The height of small wind turbines are usually lower than the large ones, and the wind speed is normally lower closer to the ground. So, in many cases will one large wind turbine be more efficient the several small wind turbines [32].

Legal therms of constructing a wind power plant
Construction and operation of a wind power plant is covered by *Energiloven* [33], and specifies voltage or power level that trigger the licensing obligation for electrical plants of production and distribution electrical energy [34]. Onshore wind power plants has licensing obligation on installed power over 1MW, or more than five wind turbines. Other legal therms a wind power plant has to clarify are *kulturminneloven*, *forurensningsloven*, *naturmangfoldloven*, among others. This thesis will not investigate further the legal therms, due to limited time.

4.1.3 Hydro Power

Almost 95% of the power production in Norway comes from hydro power. At the start of 2018 was annual energy production from Norwegian hydro power stations estimated to be 133.9TWh, while 10.3TWh represents small hydro power stations [35]. The remaining potential for new hydro power stations are mostly for relatively small scale hydro power stations, and to increase the interest for new developers has the government simplified licensing obligation for power stations lower than 10 MW [36].

Small scale hydro power stations (≤10MW) are most relevant for residential microgrids, and is therefore further discussed. The stations can be constructed in brooks and smaller rivers without regulation magazines, and since the water stream is not adjusted is the environmental consequences lower. However, without the ability to control the water stream will the power station only produce power when the streams are big enough. The life cycle costs for small scale hydro power stations are typically between 30 and 50 øre/kWh, depending on the initial cost and total energy production [36].

4.1.4 District Heating System

District heating systems produce, transmits and distributes hot water or other heating mediums to external consumers. The system mainly consists of one or several heating plants and a district heating network, which distribute waterborne heat to the costumers. The district heating system can utilize different heat sources as waste heat, wastes, heat pumps and bio fuel [37]. Its most commonly to use one of the heat sources to cover the main load in the system. Historically has the backup power been covered by oil, gas and electricity. Although, for the last years has it become more common to use renewable energy products like bio oil and powder burners for this purpose. Figure 14 illustrates the development of the different energy carriers since year 1990.

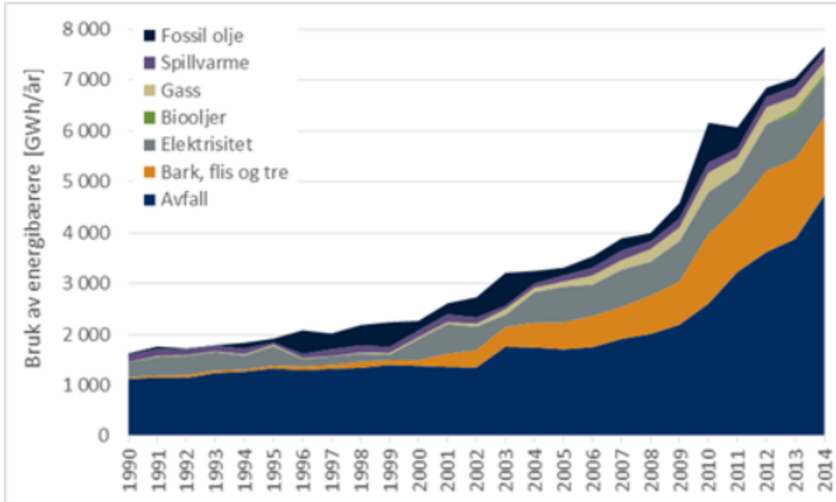

Figure 14: Use of energy carriers in district heating systems in Norway [37]

District heating concession
Norwegian district heating plants encompassed of *energiloven* [33], and the licensing requirements are triggered if the plant supplies external costumers and has an output over 10MW. NVE gives permission in a district heat concession to build and operate heat plants and main pipe networks within a limited geographical area. Remaining pipe grid can the concessionaire establish in consultation with the county, road owner and other parts that is affected of the expansion. With municipal approval is it also possible to establish district heating plants in areas with other plants [37].

4.1.5 Bioenergy

Bioenergy is energy released by conversion of organic materials (biomass). In Norway, bioenergy resources primarily comes from forestry, agriculture and waste, although it also includes green marine botanicals. Bioenergy contributes to energy flexibility and reduction of environmental gas emission [38]. Use of biomass in an energy perspective is CO_2-neutral in that sense that under combustion of trees is the released CO_2 equivalent with the CO_2-amount the trees has collected from the surroundings during the growing phase. For bioenergy to be sustainable is it important that the withdraw exceeds the growth [39].

Biofuels can be separated into hard and liquid fuel. Example of hard biofuels could be wood, bark and pellets. Liquid fuels are basically produced from different raw materials and has different combustion techniques. The main types are alcohols, produced vegetable/animal manure, pyrolysis oils and different synthetic fuels produced from gasification biomass [39].

Bioenergy are traditionally often used for heating, and the heat efficiency is significantly high since most of the biomass can be combusted and converted into direct heat. Bioenergy could also be used to power production, either separate or combined heat and power (CHP). In a CHP is the released heat energy used to produce high pressure steam, which produce electricity by a conventional steam turbine.

5 Energy Storage in Microgrid

In microgrids are ESS an important component to solve the challenges regarding improving of stability, power quality, reliability of supply and the overall performance of the microgrid. Microgrids with NDES relies on an suitable ESS to store excess energy to periods with lower energy production. Especially for isolated microgrids is it important to compensate for the lack of grid connection. ESS are also useful for microgrids with weak transmission capacity to the grid, and it can give economic advantages for microgrids with high energy production. ESS varies in size, costs and the impact it will have in the microgrid. Correct dimension of ESS is important to microgrids in island mode, and grid-connected microgrids are more independent of ESS. Although, grid-connected microgrids has to consider the maximum time period for island mode occasions to optimize the dimension of ESS.

It is different types of technologies for storing energy, which can be separated into the main categories illustrated in Fig. 15.

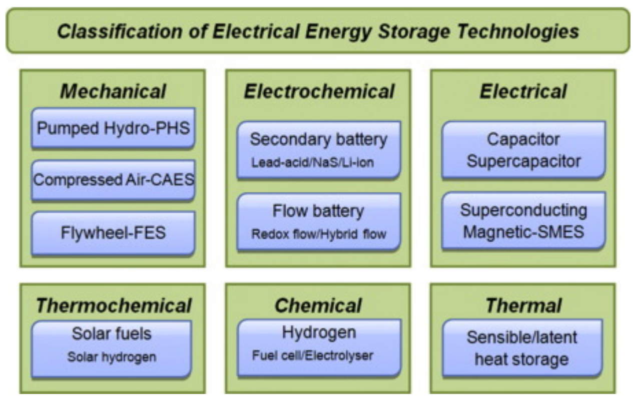

Figure 15: Electrical energy storage technologies [40]

The most suitable technology depends on required amount of stored energy, the storing time period, losses and costs related to the storage method, including evaluation of how secure the method is [40]. In Fig. 16 is the actual storage opportunities in different time scales. The figure shows that pumped hydro storage (PHS) is a suitable alternative to long time storage of large amount of energy, while battery energy storage (BESS) and flywheels are suitable alternatives for variations over short periods. Furthermore, several of the technologies has not been tested in different surroundings and the expectations of lifetime, efficiency and maintenance is hard to predict.

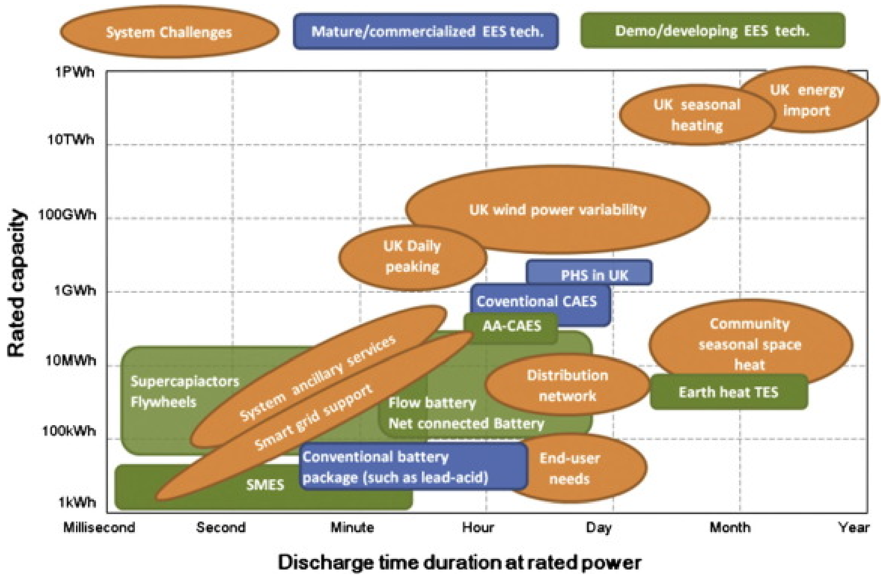

Figure 16: Energy storage technologies with challenges to the UK energy systems [40]

5.1 Requirements for Energy Storage in Microgrids

The International Electrotechnical Commission (IEC) is an ideal, non-governmental international standards organization which designs and publish international standards for all types of electric, electronics and relevant technologies collectively known as *electrotechnology* [41]. In this section is relevant IEC requirements regarding microgrids described.

Requirements in grid connected microgrids

- The storage unit needs P/Q regulation/control. The pre-determinable active power (P) should be the difference between local produced power and real power. This will give sustainable power flow in the microgrid.
- The storage unit should absorb active/reactive power to/from the distribution network depending on the demand from the system or EMS-instructions to secure stable power flow in the microgrid and POC.
- When the microgrid is connected to the distribution network will the voltage and frequency be supported by the distribution network, and energy storage units in the microgrid does not need to be in operations.

Requirements for energy storage in island microgrids

- The largest converter in the storage units should adopt the control mode for V/f and establish and maintain the system voltage and frequency, if there is no stable DG units like micro-turbines.
- The storage unit should compensate if the output power from the local DG units in the microgrid is not adequate.

- The storage unit should receive the excess power when the output power from the DG units are higher then the demand.

Requirements for energy storage in isolated microgrids

- The capacity of the storage units must be larger in an isolated microgrid than in grid connected and isolated microgrids.
- The storage units must have enough capacity to prevent load shedding.

Requirements for energy storage in transmission mode

- When the microgrid is switching from connected to disconnected mode should the storage inverters operate immediately to secure the stability of the system.
- When the microgrid is switching from connected to disconnected mode should the storage inverters detect the voltage amplitude and phase in the distribution network, and then modify the amplitude and phase in voltage and frequency in the microgrid.
- Quick and accurate detection of errors in the microgrid can reduce the impact an error might have on sensitive loads and local DG units.

5.2 Mechanical Storage

Mechanical energy storage systems have been recognized as attractive short term utility load leveling and peak shaving technologies that could be implemented to achieve substantial savings in premium fuel together with some economic advantages. The main technologies are PHS, compressed air energy storage (CAES) and flywheel energy storage (FES), as illustrated in Fig. 15.

5.2.1 Pumped Hydro Storage

PHS has large energy capacity with efficiency over 80%. A typical PHS plant uses two water reservoir at different heights, and during off-peak electricity demand hours can water be pumped into the highest level reservoir. A bidirectional turbine is placed at the lower level reservoir, eventually a combined pump and turbine at the same generator, shown in Fig. 17. The amount of energy stored depends on the height difference between the two reservoirs and the total volume of water stored. The rated power of PHS plants depends on the water pressure and flow rate through the turbines and rated power of the pump/turbine and generator units [40]. An example of the PHS is illustrated in Fig. 17.

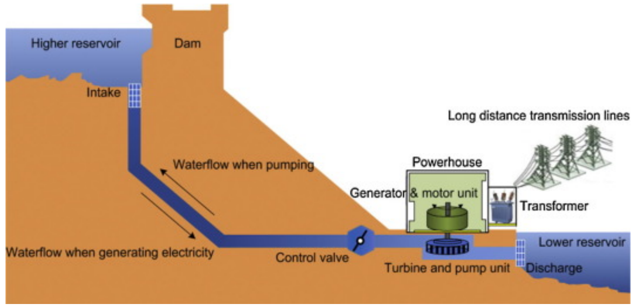

Figure 17: Pumped hydroelectric storage plant layout [40]

5.2.2 Compressed Air Energy Storage

CAES can provide power output over 100MW with a single unit. During off-peak power demand periods, the surplus electricity drives a reversible motor/generator unit in turn to run a chain of compressors for injecting air into a storage vessel, which can be either an underground cavern or over ground tank. The energy is stored in the form of high pressure air. When the power generation cannot meet the load demand is the stored compressed air released and heated by a heat source which can come from biomass or heat recovered from the compression process. The compressed air energy is finally captured by the turbines, and the waste heat from the exhaust can be recycled by a recuperator unit [40].

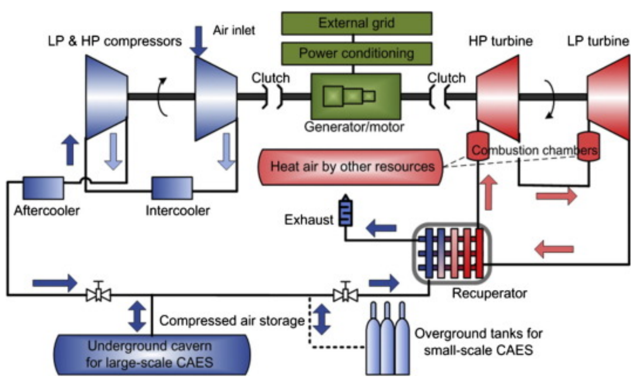

Figure 18: CAES plant layout [40]

5.2.3 Flywheel Energy Storage

The main components in a flywheel energy storage system (FESS) is a flywheel, a group of bearings, a reversible electrical motor/generator, a power electronic unit and a vacuum chamber, illustrated in Fig. 19. FESS uses electricity to accelerate or decelerate the flywheel, and the stored energy is transferred to or from the flywheel through an integrated motor/generator. The amount of energy stored is depending on the rotating speed of flywheel and its inertia. The lifetime of FESS is approximately 20 years with an efficiency of 90% [40].

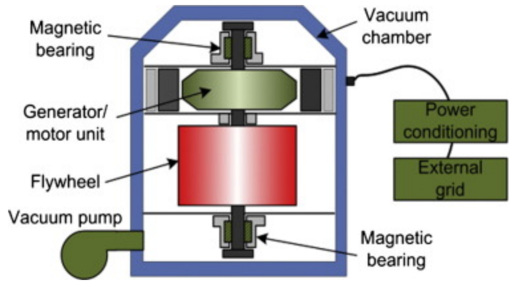

Figure 19: Flywheel energy storage layout [40]

5.3 Capacitor and Supercapacitor

A capacitor is composed of at least two electrical conductors separated by a thin layer of insulator. When a capacitor is charged, energy is stored in the dielectric material in an electrostatic field. Capacitors are appropriate for storing small quantities of electrical energy and conducting a varying voltage, so compared to batteries does capacitors have a higher power density and shorter charging time. Although, capacitors have limited capacity, relatively low energy density and high energy dissipation, due to high self-discharge losses, compared to batteries. Based on these characteristics can capacitors be suitable for power quality applications, such as high voltage power correction, smoothing the output of power supplies, bridging and energy recovery in mass transit systems [40].

Supercapacitors contains of two conductor electrodes, an electrolyte and a porous membrane separator. According to these characteristics, supercapacitors can have both the structure of traditional capacitors and electrochemical batteries. The energy is stored in the form of static charge on the surfaces between the electrolyte and the two conductor electrodes. The benefits of supercapacitors are long cycling times, more than $1 \cdot 10^5$ cycles, and high cycle efficiency of $\sim 84 - 97\%$. However, the daily self-discharge rate of supercapacitors is high, $\sim 5 - 40\%$, and the capital cost is also high, in excess of 6000\$/kWh. Therefore is supercapacitors suitable for short-term storage applications, although not for large scale and long-term ESS. Typical applications in power quality consist of pulse power, hold-up bridging power to equipment, solenoid and valve actuation in factories, UPS devices etc. [40].

5.4 Hydrogen Storage and Fuel Cell

Hydrogen energy storage systems (HESS) use two separate processes for storing energy and producing electricity. HESS consists of three major components; electrolyzer, hydrogen tank and fuel cell [42]. The electrolyzer converts electrical energy into chemical energy by decompose the water into hydrogen and oxygen. The produced hydrogen is compressed and fed into the hydrogen tank for storage. Unlike the electrolyzer does the fuel cell use hydrogen and oxygen to generate electrical power.

Fuel cell is adopted when using the stored hydrogen for electricity generation, which is a key technology in a HESS. Fuel cells can convert chemical energy in hydrogen and oxygen to electricity, where electrical and heat energy are released during the process. Using fuel cells are quieter, produces less pollution and is more efficient than the fossil fuel combustion. Fuel cells are also easy to scale with a potential from 1kW to hundreds of MW, and has a compact design. Fuel cell systems combined with hydrogen production and storage can provide stationary or distributed power, like primary electrical power, heating/cooling or backup power. HESS with fuel cell can offer capacity and power independence in energy production, storage and usage, due to separated processes [40].

Figure 20 illustrates how hydrogen storage can be grid-connected, where hydrogen also can be reproduced.

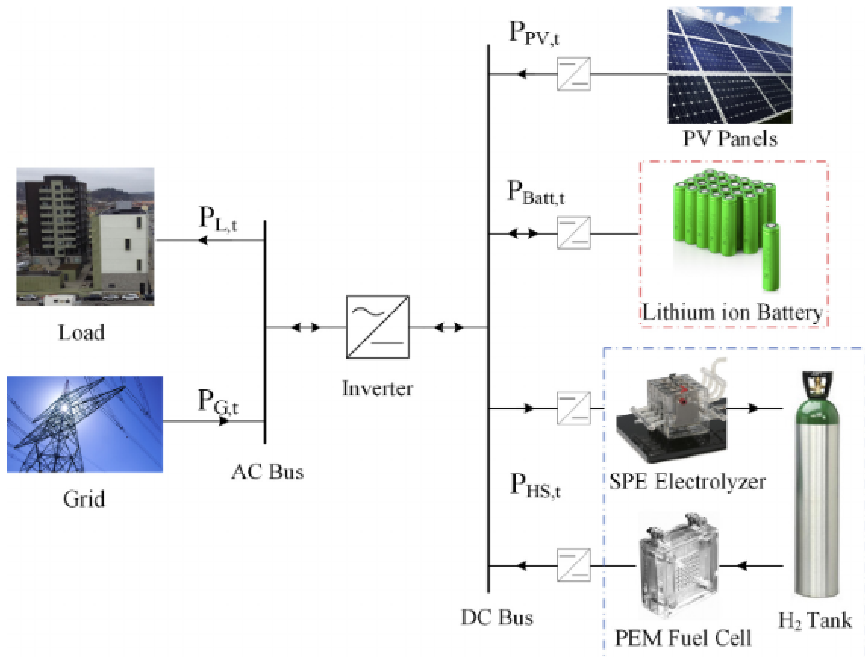

Figure 20: Grid-connected hydrogen storage [42]

The technology of HESS with fuel cell is currently in a development stage. Cost reduction and durability verification/improvement are essential to distribute this technology in large-scale applications. In late 2004 was the worlds first utility-scale test of a stand-alone renewable energy system integrated with hydrogen storage and fuel cells, which was installed at the island Utsira outside of Haugesund. Utsira delivered power with required quality and high reliability [43], and the HESS is illustrated in Fig. 21. The excess wind power in the system are used to produce hydrogen, which is stored and used as power source in windless periods. The experiences from Utsira has not been satisfying, where system efficiency is low and technical problems regarding integration of the fuel cell in the system [44]. Although, the Utsira project proves that the combination of RES and HESS is possible.

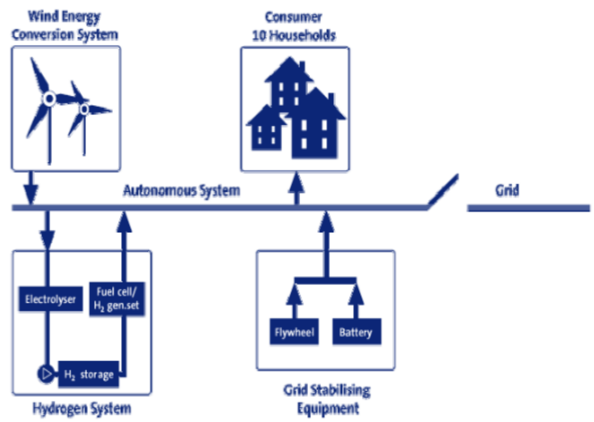

Figure 21: Illustration of the Utsira stand-alone wind-hydrogen energy system [43]

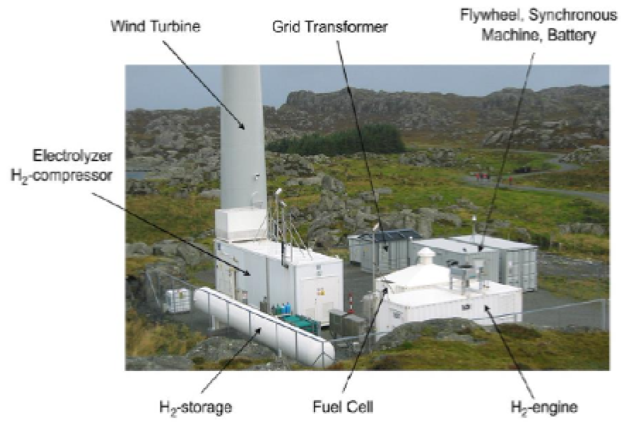

Figure 22: Utsira stand-alone wind-hydrogen energy system [44]

5.5 Seasonal Thermal Energy Storage

Seasonal thermal energy storage (STES) can store either heat or cold for periods of several months. The thermal energy can be collected whenever it is available and utilized when needed. STES can provide energy to district heating systems, and also single buildings or complexes. The design peak temperature for STES used for heating is between 27 and 80°C, and the temperature difference occurring in the storage over a year can be several tens of degrees. There are several types of STES technologies, covering the range of applications from single small buildings to community district heating networks, and some of them are listed under [45].

Underground thermal energy storage

- *Aquifer thermal energy storage* is composed of a doublet, totaling, two or more wells into a deep aquifer that is contained between impermeable geological layers above and below.
- *Borehole thermal energy storage* can be constructed wherever boreholes can be drilled, and are composed of one to hundreds of vertical boreholes, typically with a diameter of 155mm.
- *Cavern or mine thermal energy storage* are possible in flooded mines, purpose-built chambers, or abandoned underground oil stores, like the old crystalline hardrock mines in Norway.

Surface and above ground technologies

- *Pit storage* is lined, shallow, dug pits that are filled with gravels and water as the storage medium. The pits are covered with a layer of insulation and then soil, and are used for agriculture or other purposes.
- *Large-scale thermal storage with water* is storage tanks that can be built above ground, insulated and then covered with soil.

- *Salt hydrate technology* achieves significantly higher storage densities that water-based heat storage.

5.5.1 Geothermal Energy Storage

Geothermal resources are thermal energy that is found in the Earth's crust, in active areas on or near its surface and at deeper depths. Hot water or steam is injected through wells to harness the heat found at shallow depths. The total installed capacity globally of geothermal energy storage was in 2016 12.7GW, which was an increase of 26% from 2010 [46]. Geothermal is a solid renewable energy source with low and predictable O&M cost, long lifetime and can provide energy to larger areas. Although, the investment cost is relatively high and further quality research is necessary to develop flawless systems. The geothermal energy storage need active management of the reservoir and production profile to maintain production at the designed capacity factor. The capacity factors of geothermal energy storage systems varies between 60% to 85%, which depends on the age and installation of the system.

5.6 Battery Energy Storage System

The use of energy storage worldwide has increased over the last years to a total of 193.30GW in 2017 [47], and ESS is considered as a key element for enabling smart grids for future power systems. In particular BESS employing battery technology may offer the greatest potential for large-scale integration of RES. The purpose of BESS is to compensate the variations and fluctuations in the amount of power generated from the RES, since they are highly dependent on the season and weather conditions [48]. Load shifting, postponing power grid constructions and improving power system security are other improvements that energy storage has significant impact on [49]. In Fig. 23 is the simplified operational principle of a typical grid integrated BESS system illustrated.

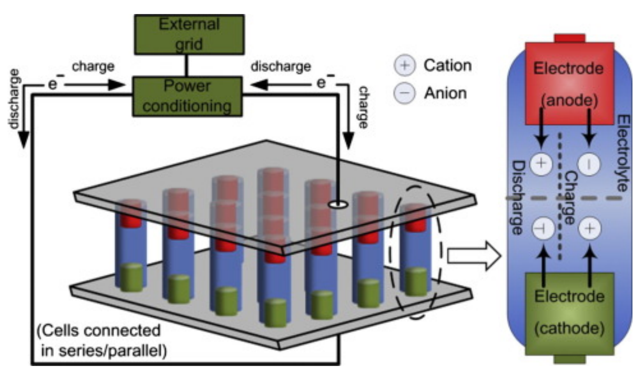

Figure 23: Battery energy storage system operation [40]

In an economic point of view, battery storage can be used to store excess electricity generated from PV systems when the time-of-use price is lower for selling back to the grid when the time-of-use price is higher. In times when the PV systems is not delivering electricity, the battery storage can also be used to purchase electricity from the grid when the time-of-use pricing is lower and sell back to the grid when the time-of-use pricing is higher [50].

5.6.1 Battery Technology

BESS store electrical energy in the form of chemical energy. When discharged, chemical energy within the battery is converted into electrical energy for supply to an external circuit. During charging, the reverse is true and electrical energy is converted to chemical energy within the battery [51].

Battery technology can be split into primary and secondary batteries. Primary is not rechargeable batteries and secondary is rechargeable. Secondary batteries offer the greatest potential for integration of RES for BESS, and has already been used for several decades in a wide variety of applications [52].

Secondary batteries can further be split into two categories; conventional battery technology and flow battery technology. Both conventional and flow batteries works by converting chemical energy into electrical energy [51]. Usually the conventional batteries are lithium-ion, lead-acid, sodium-sulphur and nickel-cadmium, whereas flow batteries usually consider canadium redox and zinc-bromine [52]. The fundamental difference between conventional batteries and flow batteries comes down to how the energy is stored. Conventional batteries stores the energy as electrode materials, when flow batteries stores the energy as the electrolyte in the cells [49].

Characteristics and properties	Conventional battery technology				Flow battery technology	
	Lithium-ion	Lead-acid	Sodium-sulphur	Nickel-cadimium	Vanadium redox	Zinc-bromine
Nominal cell voltage [V]	3.7	2.0	2.08	1.3	1.4	1.8
Rated power [MW]	50	20	8	40	3	2
Energy density [Wh/l]	400	80	300	150	35	65
Power density [W/l]	10,000	700	180	600	2	25
Cycle efficiency [%]	97	80	90	83	85	75
Cycle life [cycles]	10,000	1,800	4,500	2,500	12,000	2,000
Daily self-discharge rate [%]	0.10	0.10	0	0.20	0	0
Capital power cost [US$/kW]	1,200-4,000	300-600	1,000-3,000	500-1,500	600-1,500	700-2,500
Capital energy cost [US$/kWh]	600-2,500	200-400	300-500	800-1,500	1500-1,000	150-1,000

Table 8: Characteristics and properties of various battery technologies [53]

Table 8 compares the different battery technologies and relevant parameters. It also compared the technology cost. There is no surprise that lithium-ion characteristics outperforms the other battery technologies compered in the table, although the cost is also way higher. Lead acid is the oldest battery storage technology and still widely used, due to advantages as low cost, negligible maintenance requirement and low self-discharge rate [51].

5.6.2 Battery Storage Sizing

The motivation for an effective sizing of the battery for ZEB villages, such as Skarpnes, is to minimize the cost compared to the lifetime of the battery, while the battery capacity covers the electricity demand and peaks. It is also a motivation to reduce the net power purchase from the grid subjected to the load, minimize the battery aging and peak power production [50]. So, the largest capacity of the battery isn't necessary the best solution. A large battery who is selling more electricity to the grid than a smaller battery, can be less profitable if it needs more time to earn back the purchase price. Although, larger batteries has normally longer lifetime and better assumptions for handling the peaks. So, its an overall evaluation.

Selecting the most efficient size of the battery storage is one of the main issues regarding the preparatory work of the installation of BESS. In this process there are four control parameters that need to be considered; the depth of discharge (DoD), battery capacity, maximum battery charge and discharge power, and the utility rating [54]. The DoD defines the lower and upper limits of the battery's state of charge. The capacity and the charge/discharge power limit specify the battery size. The utility rating defines the current electricity price and feed in tariff.

Battery storage systems are being progressively used in distributed renewable energy generation nowadays. Since lithium-ion is an expensive solution, several actors in the marked have used lead-acid batteries in BESS. In addition to be an inexpensive cost solution, lead-acid batteries has a reasonable annual performance in dealing with irregular loads, easy accessibility and is also largely recyclable [55]. However, because available capacity decreases under deep, fast and high power discharge, there are shortcomings such as low energy density, lower life expectancy, environmental pollution etc [49]. Understanding of the damaging effects of irregular loads on the performance of lead-acid batteries cannot be underestimated. In contrast with the capital cost, the physical size of the battery is rarely a challenge for BESS placed outside of the private homes.

5.6.3 Battery Lifetime

In [55], life prediction of lead-acid batteries for micro-generation storage system is evaluated. This evaluation is also connected to the optimal sizing of the battery. In this rapport a building integrated PV (BIPV) system of 2.5kW is considered, among other RES. Lead-acid batteries with different parameters is used to create the most accurate general lifetime algorithm for BESS in micro generations.

The rapport [55] found a clear and intuitive trend between how much energy the battery is having to process and the lifetime. Also, the larger batteries show an improved lifetime for a given annual export compared with smaller batteries. Figure 24 shows the result from the different tested batteries. These results show a linear relationship between battery lifetime and battery size. This enables the formulation of an approximate design equation:

$$T = \frac{329.9}{E_e} \cdot S \tag{1}$$

Where T is the predicted lifetime of the battery in years, E_e is the annual export available from the on-site generation ($kWh/year$), and S is the size of the battery in kWh. The results calculated in [55], indicates that Eq. 1 is a suitable design equation, although it became less suitable for smaller batteries. This is partly due to smaller batteries not displacing the same percentage of available export, so the value for E_e in Eq. 1 becomes less suitable to describe the amount of energy being processed by the battery. E.g. a very small battery might not be able to store all the available export from a site producing a large amount of export. However, an oversized battery will be under-utilized for significant periods of the year if the export is relatively small.

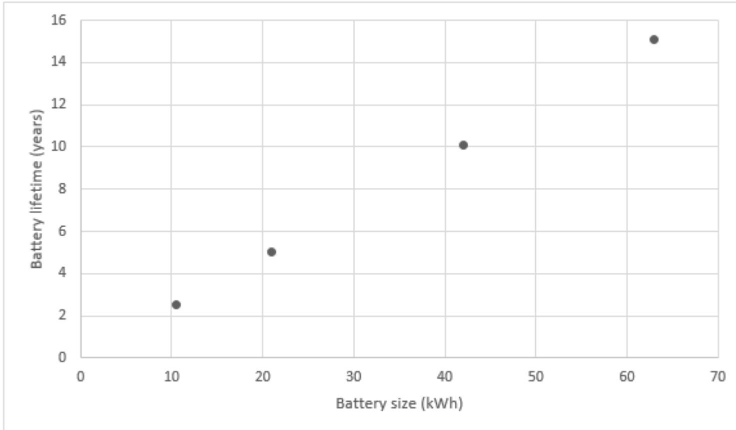

Figure 24: Graph comparing the lifetime and size of battery [55]

6 Microgrid Planning

The concept of microgrid has originally introduced to optimize the effectiveness of operation and control for the increase of DG in the distribution network, which offers great economic and reliable advantages for the power consumers [56]. Although, this advantages must be investigated and compared with the investment cost of the microgrid to secure complete returns and justify the distribution of the microgrid. Its difficult to make a complete evaluation of the economic benefits of a microgrid since its a large amount of uncertain data involved. Therefore is an effective planning model necessary to secure the economic sustainability of the microgrid [56].

6.1 Microgrid Planning Model

This section is based on the planning book of power grids from Sintef, and guidelines for planning of microgrids developed by IEC [56][41]. The planning systematic is illustrated in Fig. 25 and Appendix C, and is structured in four stages:

1. Pre-studies
2. DG and microgrid planning
3. Technical requirements
4. Evaluations

6.1.1 Stage 1: Pre-Studies

The first planning step is to survey the microgrid demands, available resources, energy production and determined the load consumption of the microgrid. It must also be decided if the microgrid is either isolated or grid-connected, and which architecture the microgrid will be designed as.

Load forecast
A load forecast is necessary to determine the size of the components and the dimension of the microgrid. Under is a list of useful data in a load forecast:

- Demographic and geographic data.
- Information regarding electric energy and energy balancing.
- Historical energy consumption in the area.
- The type of costumers and their consumption (household, industry, school).
- Load control potential.
- Analysis of changes in load characteristic, and integration of DG.

Analysis of the resources
Potential renewable energy production and other local energy resources should be analyzed. Information regarding historical meteorologic data, geographic preconditions, and the availability of area must be considered at this stage.

6.1.2 Stage 2: DG and Microgrid Planning

Based on the research from Stage 1 can several microgrid alternatives be developed. In this stage will the DG and ESS be selected and optimized, and an investment analysis of the alternatives created. Also adjustable energy sources will be decided in this stage, where its important to analyze the reliability from supply and similar. Criteria to choose adjustable energy sources are reliability, cost effective, and local availability. The adjustable energy sources are selected due to uncertainty regarding the uncontrollable DG units, and to optimize the reliability and economic.

The balance between production and consumption has to be considered, and especially in isolated microgrids is this critical. This is not a critical situation to grid-connected microgrids, since electricity can be purchased from/to the grid. Although, with limited purchase capacity from the microgrid to the grid will this be more important to consider.

6.1.3 Stage 3: Technical Requirements

Principle and technical requirements of grid-connected DG units are specified in IEC/TS 62786, and is also applicable to DG units in grid-connected microgrids [41]. Regular methods of DG control can be:

- Voltage- and frequency control.
- Active- and reactive power regulation.
- Immunity of frequency changes.
- Fault ride through capability.

Technical requirements of DG units in grid-connected and isolated microgrids
The frequency and voltage in grid-connected microgrids can be regulated by the distribution network, and the DG units has to fulfill local regulations and technical demands in IEC/TS 62786.

Isolated microgrids must be self-sufficient by DG and ESS, and the size of the components has to be optimized for normal operation independent on the weather conditions. This requires minimum one adjustable DG to control the frequency and voltage. Figure 25 is the planning model for systematic integration of DG from Sintef illustrated in a flowchart.

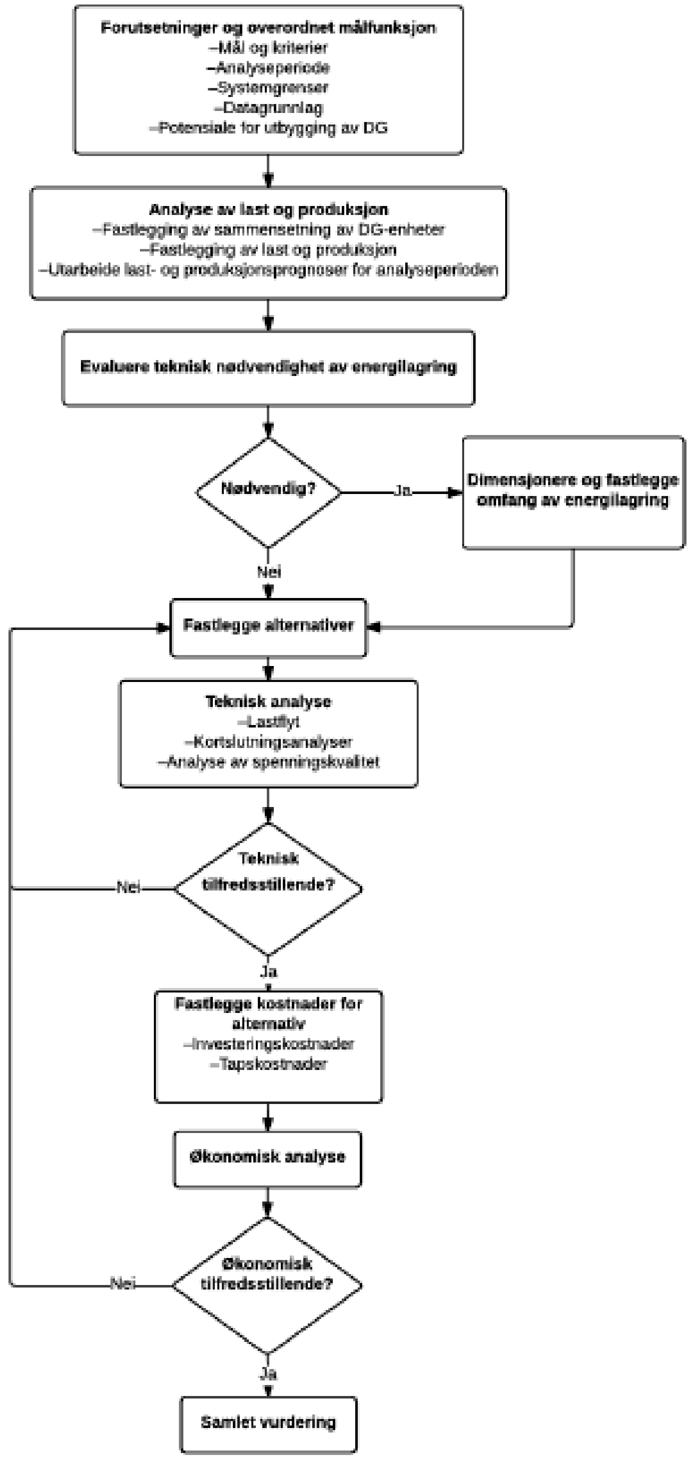

Figure 25: Flowchart for planning systematic of DG units [13]

Technical requirements of distributed lines in microgrid
The legal terms of distributed lines in microgrids depends on ownership and voltage level of the microgrid. *Forskrift om lavspenningsanlegg* is applicable for microgrids not owned by DSOs, e.g. hospitals, residential areas, schools, etc.

Technical requirements of the grid connection in microgrid
Grid-connected microgrid must not disturb the delivering quality and stability in the distribution network, and therefore is it important that the POC fulfills the IEC standard of maximum short circuit current. The POC must be able to be controlled either manually or automatic. Also the microgrid grounding must be identical to the distribution network, since the grounding affects the reliability and security in the microgrid.

Technical requirements of protection schemes and control systems
The protection schemes in a microgrid must be capable of handling short circuit currents of both the distribution network and DG units in the microgrid. The control system ensures that microgrid is operating continuously and economically. Grid-connected microgrid has to harmoniously switch from grid-connected to island mode.

6.1.4 Stage 4: Evaluation

Supply reliability
An evaluation of the supplying reliability should be done. The expected supply reliability can be found with research on error and error consequences in the microgrid. Errors might be related to the distribution network, communication and IT system.

Environmental concerns
The utility of the microgrid should be evaluated in context with environmental consequences, so it can be define what is acceptable footprint in the nature.

Possibility of expansion
An evaluation of the possibility for expansion of the microgrid.

Grid interaction
The interaction between the microgrid and the distribution network should be evaluated. In an isolated microgrid should the possibility of grid connection in the future be evaluated.

Economic evaluation
An economic evaluation is necessary to analyze relevant benefits and costs. There are two main issue to consider; on-site generation from the customer perspective and the traditional utility economics of expansion planning from the utility perspective. Based on this is the main benefits an increased reliability for microgrid participants, general reliability improvements, waste heat recovery and generation adequacy [4]. Another concern regarding microgrid economic is the relationship of the microgrid to the distribution network [57]. These type of problems are related to the interface between customers and utilities, for example the need to provide a real-time price signal to the microgrid so that optimal use of resources by both the microgrid and grid can be achieved simultaneously. Microgrids has also unique aspects that will require innovation to optimize the microgrid economically.

The development costs can be divided into microgrid development costs and costs related to DSOs. The first set of costs is related to microgrid development, which involves specific investment in controllers, protection devices, ESS, installation, and O&M expenditures (staff, losses on ESS, maintenance of the equipment's etc.). Therefore is the operation cost of microgrids under optimal control relying on the configurations, optimization method and benchmark model of the microgrid. The second set of costs is related to the DSOs expenses that may result from potential investment requirements in order to overcome technical issues, such as excessive voltage regulation, fault levels, voltage unbalance and overloading [4]. This is illustrated in Fig. 26.

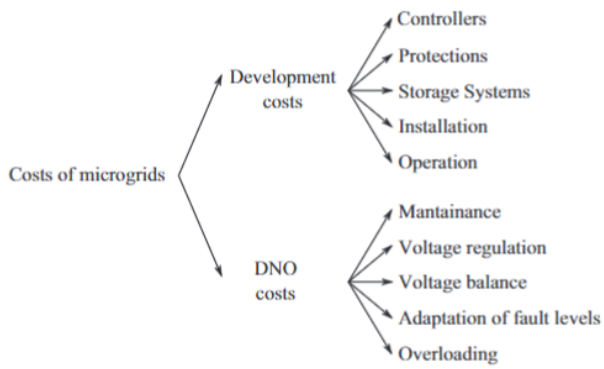

Figure 26: Costs related to microgrid systems [4]

6.1.5 Microgrid Modelling

Modelling is important to achieve acceptable control of the microgrid. In Fig. 27 is the different AC microgrid models illustrated. The table shows that most of the models are using droop control, assume constant load and analysis microgrid both grid-connected and island mode. Some of the models are including ESS, investigating dynamic models and possible situations in a microgrid. Comparing the software used in modeling microgrid, has Homer Energy been the most comprehensive software. Other softwares suitable for microgrid modeling are EADER, DER-CAM, Matlab-Simulink and PSCAD/EMTDC [4].

Model	Distribution	DG	SS	Loads	Mode	Control
Admittance matrix	Three-phase	Constant power	No	Constant power	Both	Droop
DC source with non-linear equations that are linearised	Single-phase	First order transfer functions	No	RLC circuit	Both	Droop
DC source with equations in state-space	Single-phase	DC source and VSC	No	RLC circuit	Island	Droop
State space in a common reference frame and linearisation	Single-phase	DC source and VSC	No	Constant power	Both	Droop
State space in a common reference frame and linearisation	Single-phase	Synchronous generator based DG and power	No	Constant power	Both	Droop
Small signal analysis	Single-phase	Non-linear equations	First order transfer functions	Constant power	Island	–[a]
Multilevel type control and management scheme supported by a communication infrastructure	Single-phase	Dynamic model based on the characteristics of each type of generator	Constant DC voltage sources coupled by power electronics devices	Two types: constant impedance and motor loads	Both	Droop
Electrical equations in admittance form	Three-phase	Coupled by inverter droop	Coupled by inverter droop	Coupled by inverter droop	Both	Droop
System matrices based on four defined complex vectors	Single-phase	Coupled by power electronics and two types: active and reactive power regulated and voltage-frequency regulated	No	No	Both	Droop
Based on hub model	Single-phase	Energy hub model	Energy hub model	Constant power	Island	–[a]

[a] No control considered.

Figure 27: AC Microgrid models [4]

6.1.6 Uncertain Variables in Microgrid Modelling

The consumption load in a microgrid can be estimated with acceptable accuracy, although long-term load forecasts will be an uncertain variable for microgrids [56]. The variable load is difficult to estimate since it depends on weather variations, different prices during the day, and costumer decisions. Since RESs, like PV and wind, often are used in microgrids will the power production varies a lot. The typical pattern for power production by RES does necessarily not match the power consumption by the consumers, and the microgrid needs other DG or ESS in the system.

The market price forecast can also be an uncertain variable since there is a lot of uncertain factors involved in the forecast process, like offers from generation companies, transmission network congestion and losses, and costumer participation with ability to respond to market price. The market price (e.g. electricity price in real time) is the most significant source to uncertainty in the planning of a microgrid, since it largely affect the initiative for DG units [56].

The last main type of uncertainty is islanding. In grid-connected mode will the microgrid switch to islanding mode if there is disturbances on the distribution network, and connected when the disturbance is fixed. However, the time and duration of such disturbances are not known to microgrids. Although, for microgrids that infrequently are switching to islanded mode could it be significant social cost savings and load point reliability improvements offered by microgrids during major outages (e.g. natural disasters) which would justify the islanding design as part of microgrid planning decisions [56].

6.2 Alternative Planning Model for Microgrid

In Fig. 28 is the flowchart of an alternative microgrid planning model where the original planning problem is decomposed to investment problem as the master problem, and operation as sub-problem.

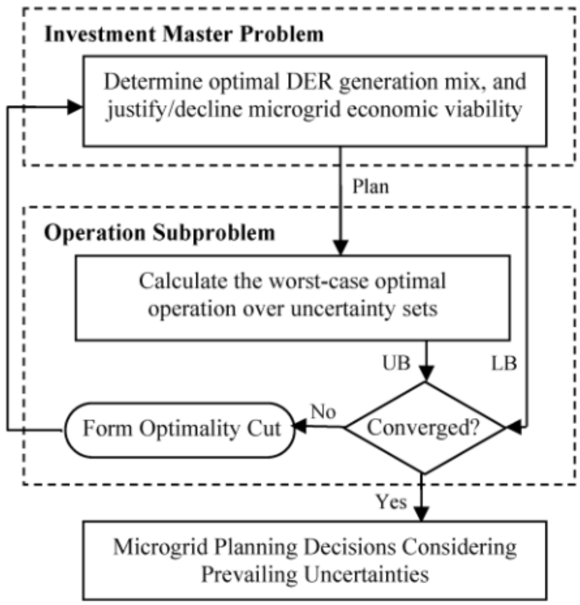

Figure 28: Flowchart of an alternative microgrid planning model with uncertain parameters [56]

Specific features of the alternative microgrid planning model are listed as follows [56]:

- Microgrid investment decision: The proposed model will decide if the microgrid is profitable, and justify or decline the economic sustainability of distribute the microgrid.
- Optimal DG selection: The optimal composition of DG units to minimize the total planning cost is determined in the alternative model based on economic and reliability considerations, and should also include the possibility of switching to islanded mode.
- Inclusion of uncertainties: It is adopted a solid approach to incorporate errors from load forecasts, renewable production, market prices and uncertainty regarding islanded mode.
- Time-scale considerations: The short-term operation and long-term investment problems are decoupled using a decomposition method. The short-term operation includes hourly operation of DG units and interaction between microgrid and main grid, while the long-term problems incorporates decisions on DG investments. The two problems are linked via optimal cuts generated in the operation sub-problem.
- Microgrid islanding consideration: For grid-connected microgrids are the ability of islanded mode an significant advantage, and is included in the proposed model. The improved reliability of microgrids with islanded mode is translated into economic terms using VOLL/KILE. The obtained cost of unserved energy is included in the objective of the planning model to consider the reliability.

VOLL, as described here, has the same intentions as KILE in Norwegian context. KILE (*kvalitetsjusterte inntektsrammer ved ikke levert energi*) is an incentive regulation to give the power companies economic motivations to correct resource allocation within the affects and terms given by the Norwegian governments [58]. The cost of not delivered energy, which represents the reliability of the microgrid, is defined as the number of interrupted loads multiplied with the value of lost load (VOLL). KILE is the energy price for compensating of interruptions at the consumers, which depends on several factors like the type of consumer, the number and length of the the interruptions, and also the time period of the interruption. A higher KILE is equivalent with more critical load [56].

7 Planning of Linnheia Microgrid

7.1 Background

Linnheia in Aust-Agder, Norway, is a planned residential area for future villages of different types of housings. Block Watne, one of the largest housing construction companies in Norway, has a local agreement with Grimstad County to develop area regulation over the area *Linnheia Nord*, see Appendix D.

Block Watne consider microgrid as a possible solution in the area B7, based on the topology, area and planned number of new houses. Although, the economic investment must be reasonable and the concept easy to understand for future inhabitants. It also has to be a grid-connected microgrid, which can be turned into island mode when necessary, and has the opportunity to sell excess electricity to the grid. The master thesis is made in collaboration with Nettpartner AS, and it is desirable to create realistic microgrid-scenarios which can be further investigated. Table 9 shows relevant information about the microgrid.

Microgrid Linnheia Nord			
General information		**Energy consumption [%]**	
Microgrid area [m^2]	4000	Space heating	17.4
MASL [m]	<50	Hot water	39.1
Number of houses [-]	40	Lighting	12.2
House area [m^2]	152	Technical equipment	23.0
Power peak per house [kWp]	6	Other	8.3
Power peak microgrid [kWp]	240		

Table 9: Microgrid Linnheia Nord

7.2 Method

The microgrids is planned by using the guidelines from Sintef and IEC, mentioned in Section 6, and in the software Homer Energy, which is used to find optimal solutions in the planning stage. Globally Homer Energy is the leading software to optimize microgrids, and can combine both traditional- and renewable energy sources, ESS and load control to plan a cost effective and reliable microgrid. Homer can also modulate thermal loads and energy sources, with respect to the given restrictions and load values. *Homer Optimizer* is a function in the software which optimizes the components to find suitable amount and size to meet the microgrid demands. By using "generic" components is average price and function adjusted by Homer, which is beneficial if real component information is not available. Homer cooperate with several different companies, and collects prices and relevant information to make the simulations more realistic. Also weather data from the whole world is included in the software and is delivered by *NASA Surface meteorology and Solar Energy database*.

7.3 STAGE 1: Pre-Studies

7.3.1 Load Analysis Linnheia Microgrid

It will be developed a load forecast for the future energy and power consumption, which will be essential for the planning of the microgrid. Load values from *Smart Village Skarpnes* is used to make a realistic load forecast of the microgrid in Linnheia. Smart Village Skarpnes, located outside of Arendal, was build for research on ZEB and its impact on electricity demand and power quality [59]. The village consists of five family houses build as per passive house standard NS3700 [60], with 7.36kWp BIPV capacity on each house. The load values from the house *T10O* is used since the owner has daily charged his EV at home, and this will be a realistic future scenario for new family houses in Norway. The load consumption and PV production is shown in Fig. 29. Although, a more accurate load forecast for Linnheia Nord is necessary before a microgrid can be build.

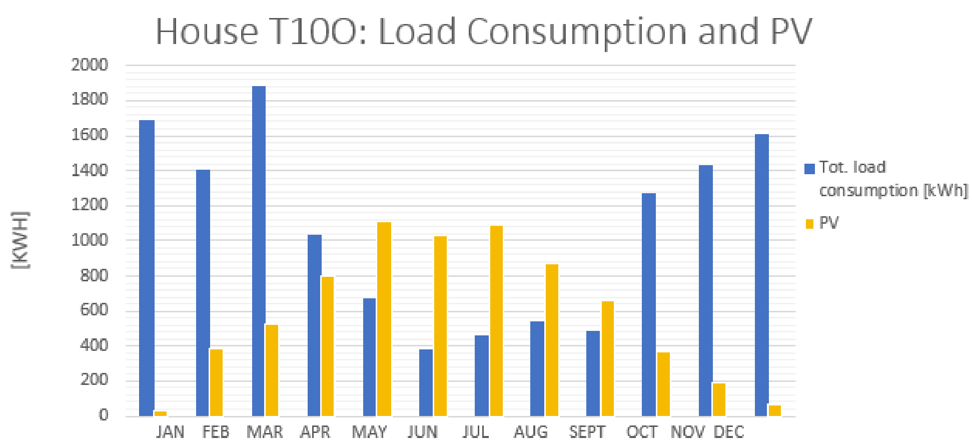

Figure 29: Load consumption and PV production in House T10O

40 similar energy effective passive family houses will be established in Linnheia Microgrid, and home-charging for EV is included at each house. Annually load per house will be around 10 314kWh with a total of 412 560kWh for the microgrid. In Norwegian homes, the average electricity consumption of space heating is 64% of the total consumption and hot water is 15% [61], while the space heating in the nZEBs build in Skarpnes is 17.4% of the total consumption and hot water is 39.1% [62].

In an island mode situation, the estimated total non-flexible load will be reduced to one half of the total consumption, to make the microgrid sustainable over a longer period, independent of weather conditions and local power production. This is illustrated in the Homer Energy simulations by *Electric Load #1* and *#2*. This could be conducted by controlling the high power consumption, e.g. regulate charging of EVs, the use of washing machine and similar operations, while the microgrid is islanding.

Load Scenarios
Three different load scenarios are evaluated in the planning, where the total load consumption of Linnheia Microgrid is 412 560kWh/yr.

- **Scenario 1**: This scenario consists of a district heating system which covers the space heating of the whole microgrid. Of the total consumption, the non-flexible load is 82.6% and the thermal load 17.4%. The thermal load is added to the thermal bus, and simulates the district heating system together with a boiler. Both the boiler and a CHP micro-gas turbine are provided by natural gas with a price of 0.30$/m^3$ given by Homer.
- **Scenario 2**: The thermal load is not included in this scenario, so the load is 100% non-flexible. All heating is therefore electric, and in island mode will the total consumption be reduced to one half. This gives a higher total electric consumption than scenario 1, which has to be considered during the dimensioning of the microgrid.
- **Scenario 3**: This scenario uses the values for the geothermal energy storage used in Eid County, further described in Section 7.3.5. All the space heating and hot water will therefore be covered by the geothermal storage, which is 56.5% of the total energy consumption. Remaining 43.5% is non-flexible electric load.

Quality Evaluation
The different load scenarios are made to illustrate methodology and to develop several alternatives of energy supply to Linnheia Nord. The load scenarios are significantly simplified which gives some uncertainties that can lead to inconclusive results. Although, by comparing the results they will still give valuable information.

The greatest uncertainty in scenario 1 is the district heating system. The value used for thermal requirement is the same as in Smart Village Skarpnes, where they utilize heat pumps for heating. The cost of the district heating system is not specified since the extent of it is unknown. Heat storage is not a function in Homer, and the geothermal energy storage in scenario 3 is based on the pre-study made by Eid County. However, the pre-study in Eid County and Linnheia Microgrid is relatively similar, and therefore used.

Without a heating in scenario 2 is the microgrid extremely dependent on the grid connection. The size of the ESS must be customized to cover energy demand for a longer period, if the microgrid is forced into island mode. This could make the system more expensive and fragile.

7.3.2 Evaluation of Available Energy Resources

The local energy resources must be considered, and Homer Energy is collecting monthly average data for wind, sun and temperature from *NASA surface meteorology and solar energy database.*

Solar power
PV panels in Norway has high efficiency since the temperature rarely is higher than 20°C. The data from *NASA surface meteorology and solar energy database* is based on average values from 1983 to 2005, and for Linnheia is the annual average solar irradiation $2.84kWh/m^2/day$, illustrated in Fig. A.63.

Wind power
Linnheia is close to the coast with annual average wind speed of 6.45 m/s, and is under 50 MASL. It is possible in the residential area to have micro-wind turbines on strategic places, although an offshore wind farm would be the most effective and powerful solution. As shown in Fig. 13, the wind resources are more suitable closer to the west-coast of Norway, and this must be taken into consideration. Furthermore, there is more wind during the winter, and as a result of that will wind turbines combined with PV systems be a more preferable combination. Annual wind speed in Linnheia is illustrated in Fig. A.62.

Temperature
Temperature in it self is not a resource, however the production from energy sources and energy storage in batteries depends on the temperature, and this is the reason why temperature is part of the resource analysis. Linnheia has an annual average temperature of 6.69°C, and the temperature variations during the year is shown in Fig. A.61.

Hydro power
Hydro power will not be relevant for the thesis whereas other energy resources will be considered instead.

7.3.3 DG and ESS

PV system
It is used a "generic" PV system in the Homer simulations that is optimized in 1kW intervals. The PV capacity is spread to the roofs of the houses in BIPV systems. Relevant information is shown in Fig. B.66 in the Appendix B. The price of PV systems has decreased over the past years, as a consequence of the components price drop and increased competition in the market. Analysis from IRENA show that an average residential PV system did cost 1 388$\$/kW$ in 2017 [46]. The decrease over the last seven years has been drastically, where the cost in 2010 was 4 394$\$/kW$, illustrated in Fig. 30.

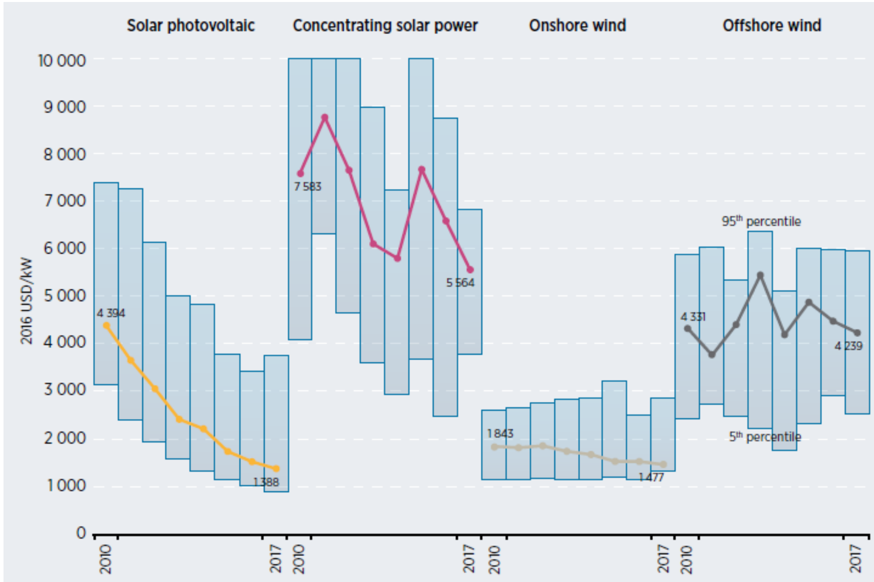

Figure 30: Global average total installed cots for solar PV, CSP, onshore and offshore wind, 2010-2017 [46]

Wind turbine

In the Homer simulations are "generic" wind turbines used to optimize the scenarios. It is possible to optimize with several different turbine sizes in Homer, although in this thesis is Generic 1, 3 and 10kW wind turbines been just in the simulations. The cost of the turbines is normally lower per kW with larger turbine size. Analysis from IRENA shows that an average onshore wind turbine did cost 1 $477\$/kW$, while offshore cost 4 $239\$/kW$, illustrated in Fig. 30. The cost of wind turbines has been stable over the last seven years, however it has been done more research on wind power for the last years and this will probably reduce the cost in the future.

Information regarding the selected wind turbines is illustrated by Fig. B.64 and Fig. B.65 in Appendix B. In the simulations is the minimum limit for number of wind turbines set to three, and to gain more reliability if a situation occur like e.g. the destruction of one of the turbines. It will also make it easier to expand the power plant in a later stage.

Converter

The converter connects the AC and DC bus. The size of the converter is optimized by Homer to be suitable for the system. Relevant converter information is shown in Fig. B.67 in the Appendix B.

CHP gas turbine with heat recovery

In scenario 1 is CHP gas turbine with heat recovery used, and the size of the gas turbine is set to be 10kW. The Homer Optimizer function is not available to gas turbines, so it is manually customized. Gas turbines with higher output will reduce the renewable penetration in the microgrid, and is therefore optimized to be 10kW in the scenario. This is illustrated in Fig. B.68 in Appendix B.

Hydrogen storage
Hydrogen has also been evaluated as an energy storage opportunity. The hydrogen could either be transported to Linnheia, or it could be produced nearby by using the excess power produced in the microgrid. This could be a similar construction as in Utsira, shown in Fig. 21 from Section 5.4. Unfortunately, without a hydrogen plant nearby will transport of hydrogen over long distances not be an environmental friendly solution, and since local production by excess power is still in a trial stage is this not further investigated as an option in the thesis.

Electrical energy storage
The size of the Linnheia Nord microgrid is suitable for BESS, and the lithium-ion is the preferred battery technology. Compared to other battery technologies has lithium-ion qualities like low weight, long lifetime and high storage capacity. In 2016 was the average market cost of a lithium-ion battery 273$/kWh [63], and is assumed to decrease even further over the coming years. The selected BESS is illustrated in Fig. B.69 in Appendix B.

Other alternatives
Mechanical storage systems like CAES and FESS is also evaluated. Although, since the technologies are not well established in Norway, requires knowledge to operate and is not in accordance with the guidance from the house builder company Block Watne, that wants the settlers to be confident with the selected solution, are these technologies not further investigated. In the surrounding areas around Linnheia is it not relevant to establish a PHS system, and capacitors is not alone suitable for this microgrid based on the characteristics given in Section 5.3.

7.3.4 District Heating System

District heating system is used in scenario 1. The boiler, illustrated in Fig. 31 symbolize the district heating system and uses natural gas, since Norway is producing and exporting annually large amounts of natural gas [64]. The district heating system could also be an incineration plant, bio energy plant, geothermal storage or similar constructions. However, in Homer will the pricing of the system on natural gas be more accurate, and is therefore selected. The district heating system is illustrated by Fig. B.70 and the thermal load, Fig. B.71, in Appendix B.

According to *Energiloven* [33] is the size of the district heating system not licensable and energy supply can be based on volunteer agreements between those involved. The system can be subsidized by the government, Enova or municipal support, and the subsidies from Enova is controlled by the power contribution of the district heating. In scenario 1 is the annual thermal load of the microgrid approximately 230 000kWh, and with a power contribution of 100kW from the district heating system, can Enova subsidize an estimate of 120-180 000NOK [65].

The selected area in Linnheia Nord is $4000m^2$ and it will be manageable to connect all the 40 houses to the district heating system. Each house in Linnheia has a total floor area of $154m^2$, which gives a total of $6160m^2$ in the microgrid. Its difficult to estimate the cost of the system, although Enova made a barrier study for expansion of district heating systems [66] that gives an indication of the system price. The study estimated the costs of different district heating systems in different regions in Norway. In Tab. 10 is the cost of a district heating system with a pellet boiler and waterborne heat suitable for Linnheia Microgrid illustrated. The total cost of 3.48 MNOK, approximately $433

160, will be the capital cost of the district heating system. In addition there is the cost of O&M, as well as fuel.

Investment	**Cost per** $[m^2]$	**Total cost**
Installation cost waterborne heat	500 NOK	3.08 MNOK
Pellet boiler (included top load, silo and feeding system)		0.40 MNOK
Total		3.48 MNOK

Table 10: Investment cost of a pellet boiler and waterborne heat in Linnheia Microgrid

In the same study from Enova is the estimated pellet price in Aust-Agder 24-27 øre/kWh. Although, there is not pellet production in Aust-Agder, so Linnheia has to import from either Vestfold or Buskerud [66]. This will include transportation expenses and emission from the transport.

In the scenarios with district heating system can a thermal load controller (TLC) be included to allow excess electrical production to serve loads on the thermal bus. The TLC is optimized to lowest necessary size and estimated to cost 200$/kW.

7.3.5 Geothermal Energy Storage

Geothermal is a mature, commercially available technology that can provide low energy cost collected from the Earth's crust. The cost of geothermal power plants vary a lot, based on the location. The O&M cost is low and predictable, and the plant can operate for several decades without major engagement [46]. Although, the total installed cost of a geothermal power plant can be high and consists of:

- Exploration and resource assessment cost.
- Drilling costs for production and re-injection costs, as well as additional working capital.
- Field infrastructure, the geothermal fluid collection and disposal system, and other surface installations.
- Costs of the power plant.
- Project development and grid connection costs.

Geothermal energy storage is used in scenario 3 and is covering both space heating and hot water. Homer Energy does not have a geothermal storage function, although a self composed geothermal storage system in Homer is used in scenario 3 based on the example from Eid County. This is illustrated in Fig. B.72 in Appendix B.

Eid County in Western Norway, has planned a residential estate of 38 new houses with shared geothermal storage from a communal heating plant [67]. The proposal consists of 13 wells with a diameter of 140mm at 150 meters deep, in combination of a 140kW heat pump, that annually deliver 530 000kWh. The total investment cost, including infrastructure, wells and heating plant, is estimated to be approximately 5.6MNOK, and the calculation is illustrated in Tab. 11. With a calculated annual heat factor of 3.3 will the system save approximately 350 000kWh each year.

Infrastructure	2 100 000NOK
Wells	1 400 000NOK
Heating plant	2 100 000NOK
Total	5 600 000NOK

Table 11: Estimated cost of geothermal storage in residential estate in Eid County [67]

The heating plant is centrally located in the residential area, with two pipe circuits of water to supply each part of the area. One of the pipe circuits has water with high temperature for space heating and tap water. The other pipe circuit has low water temperature and is used for cooling. Each circuit has an estimated total length of 3 000 meters.

The planned geothermal energy storage in Eid County gives a reasonable indication of the investment cost of a potential similar project in Linnheia, where the number of houses and heat demand is almost the same. Subsidies from the government, Enova or municipal support can also make the investment more profitable. The same subsidize as mentioned in Section 7.3.4, applies to geothermal storage.

7.4 STAGE 2: DG and Microgrid Planning

Creating scenarios

The grid-connected microgrid in Linnheia Nord should be as grid-independent as possible in order to operate in island mode in both daily operation and also in critical situations where the grid connection can be gone for a longer time period. Its desirable to have as high renewable penetration as possible in the microgrid, and its prepared several different alternative solutions to supply the microgrid, illustrated in Tab. 12. All of the scenarios are grid-connected and the components are optimized by the Homer Energy software. Scenario 1 consists of a district heating system with a thermal load, while scenario 3 has a geothermal energy storage which is simulated without a thermal load. Scenario 2 does not have a connected heating system and has to rely on electricity for heating. However, an ESS is connected to store excess energy in periods with lower energy production. ESS is not necessary in scenario 1 with CHP gas turbine, since the gas turbine can produce power when the consumption is higher then the renewable energy production. Every scenario is simulated with BIPV system, and are optimized with and without wind turbines. The scenarios are selected intentionally to cover the demands of different relevant microgrids.

	Energy Source				Energy Storage		Load Type	
	PV	**Wind**	**Boiler**	**Gas Turbine**	**Battery li-ion**	**Geo-thermal**	**Thermal Load**	**Two Electric Loads**
Scenario 1.1 (SC1.1)	Yes	Yes	Yes	Yes	No	No	Yes	Yes
Scenario 1.2 (SC1.2)	Yes	No	Yes	Yes	No	No	Yes	Yes
Scenario 2.1 (SC2.1)	Yes	Yes	No	No	Yes	No	No	Yes
Scenario 2.2 (SC2.2)	Yes	No	No	No	Yes	No	No	Yes
Scenario 3.1 (SC3.1)	Yes	Yes	No	No	No	Yes	No	Yes
Scenario 3.2 (SC3.2)	Yes	No	No	No	No	Yes	No	Yes

Table 12: The different scenarios for Linnheia Microgrid

In the different alternatives is the software Homer Energy used to optimize the components in the microgrid to find the solution with lowest total cost over the project lifetime, with given restrictions. The main restrictions are energy consumption, costs during the lifetime of the project, available energy resources and DG characteristics.

7.4.1 Scenario 1

System design

In this scenario is the grid-connected microgrid provided with electricity from BIPV system on the roofs and from deployed wind turbines, and heat from a district heating system with a boiler and CHP micro-gas turbine. The microgrid is also optimized with and without wind turbines. An ESS was evaluated, although with an adjustable CHP gas turbine was the need of energy storage limited. Implementation of a TLC was also evaluated to increase the renewable penetration of the system by utilize the excess power to supply the district heating system. Unfortunately was the efficiency of the integration compared to the economics limited, and therefore not included in the microgrid. The microgrid system is illustrated in Fig. 31 where the total system power peak is 221.42kWp. The components are optimized by Homer Optimizer and the design pages are shown in Appendix B.

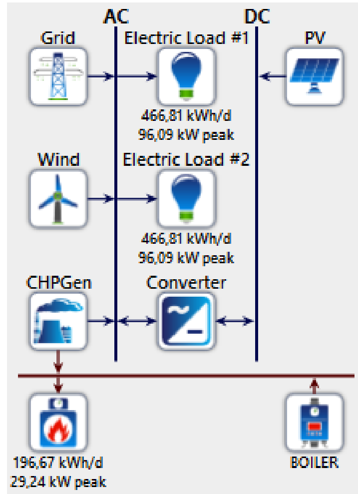

Figure 31: System design scenario 1

The results from the optimization is illustrated in Fig. 32, where the architecture and total cost is included. Both with and without wind turbines are included in the figure. NPC stands for *net present cost*, and is the present value of all the costs of installing and operation over the project lifetime. The value of the components are given in kW, although the wind turbines are given in quantity of 3kW wind turbines. In this picture is not the capital cost of the district heating system included, although it is implemented in *Cost summary* at the end of the section.

Architecture					Cost	
PV (kW)	Wind	CHPGen (kW)	Grid (kW)	Converter (kW)	NPC ($)	Initial capital ($)
375		10,0	100	163	$ 1,32M	$ 919 670
345	3	10,0	100	145	$ 1,32M	$ 903 574

Figure 32: Optimization results in scenario 1

Electric production

The monthly electric production from each of the energy sources are illustrated in Fig. 33 with wind turbines, and without wind turbines in Fig. 34. The overall monthly production is almost the same during the whole year, and is naturally mostly covered by PV power in the summer half of the year. In the winter half is the wind more influential, while the CHP micro-gas turbine is stabilized on 10kW during the whole year. When the production is lower than the consumption in the microgrid, is the microgrid consumed be the grid.

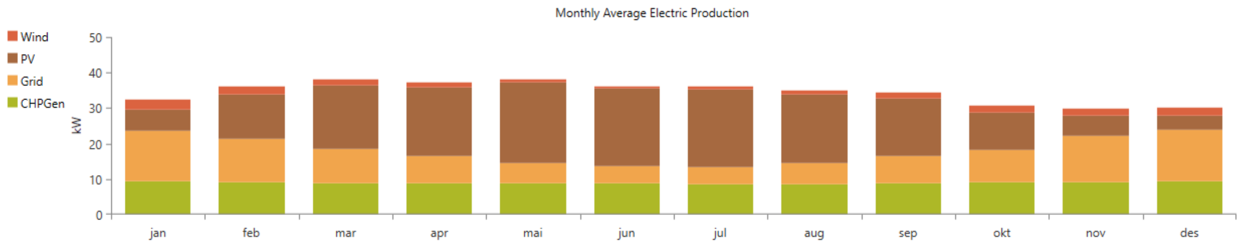

Figure 33: Electric production in SC1.1

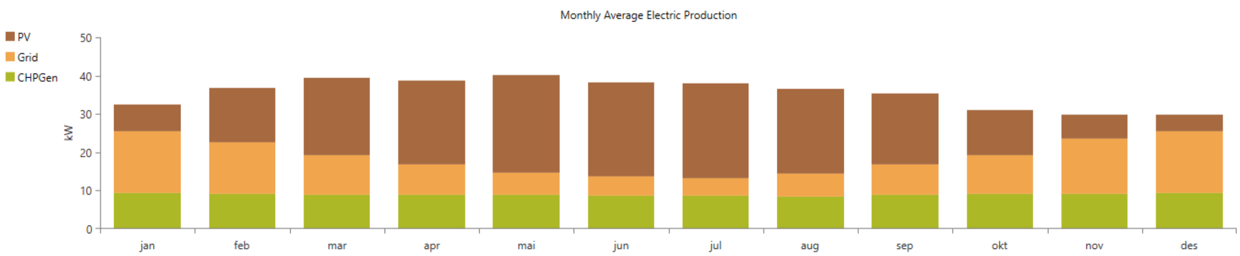

Figure 34: Electric production in SC1.2

Table 13 compares the parameters from the two scenarios. The annual wind production is optimized to only 4.81% of the total production. The difference between the parameters from the two scenarios is therefore minimal. The electricity production from the CHP is shown in the table.

	Scenario 1.1		**Scenario 1.2**	
Production	**[kWh/year]**	**%**	**[kWh/year]**	**%**
PV	352 319	60.7	383 438	63.7
CHP el.	51 941	8.9	49 990	8.3
Wind Turbine	14 516	2.5	0	0
Grid Purchase	162 028	27.9	168 806	28.0
Total	580 803	100	602 233	100

Table 13: Comparing electric production in scenario 1

In Tab. 14 is the operation data for the components illustrated. The small wind turbine size makes the difference between the two scenarios minimal. The capacity factor is the ratio of the electrical outputs over a given period of time to the maximum possible electrical output over that period. The levelized cost shows the cost per kWh, and the amount of operation hours per year is also shown in the table.

	Scenario 1.1			Scenario 1.2		
	PV System	**CHP**	**Wind Turbine**	**PV System**	**CHP**	**Wind Turbine**
Mean Output [kW]	40.2	6.74	1.66	43.8	6.73	0
Capacity factor [%]	11.7	59.3	18.4	11.7	57.1	0
Hours of Operation [h/yr]	4373	7 710	7038	4373	7 426	0
Levelized Cost [$/kWh]	0.165	0.087	0.368	0.165	0.087	0

Table 14: Comparing operation parameters in scenario 1

Thermal load

In Fig. 35 is the thermal load in scenario 1 illustrated. The CHP and boiler are covering the demand with respectively 77.4% and 22.6% of the total annual thermal energy production of 72 225kWh/yr. The CHP, with an output of 10kW, is optimized to contribute with both heat and electricity to the microgrid during the year. The boiler is covering the remaining thermal demand. Both power outputs are illustrated in Fig. 36 and Fig. 37. The thermal load of SC1.1 and SC1.2 is approximately the same, and therefore is only the illustrations from SC1.2 used in this section.

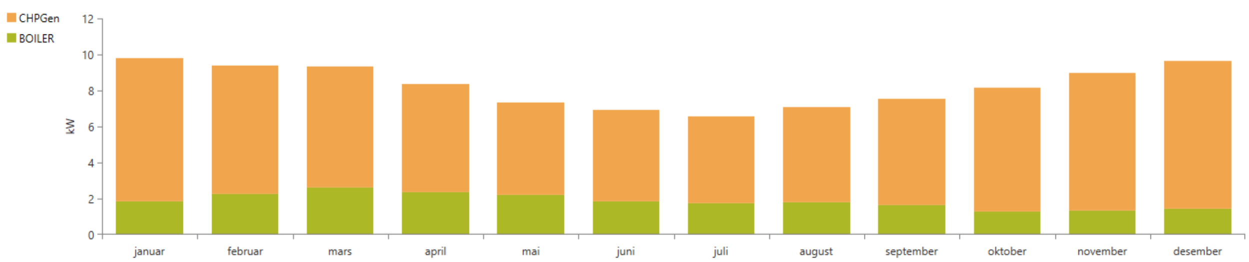

Figure 35: Thermal load scenario 1

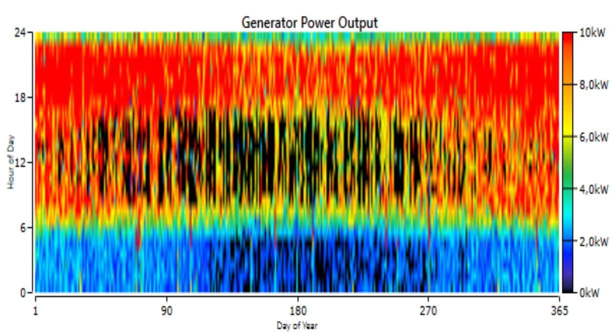

Figure 36: Power output CHP micro-gas turbine

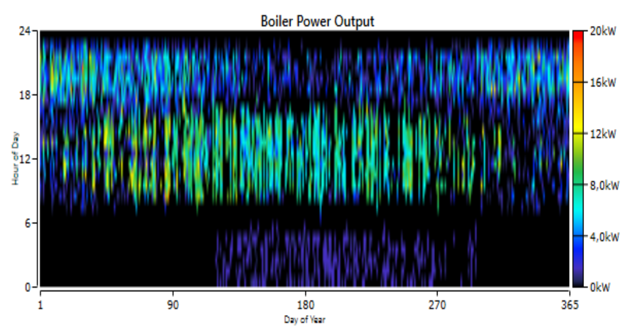

Figure 37: Power output boiler

Trading of electricity with the grid
The annual net energy purchase of the microgrid is set to 0kWh, and maximum power peak to 100kWp. This is further described in Section 7.4.4. As illustrated in Tab. 15 is the annual net energy purchased -61kWh, and since the PV system is the dominant energy source, is it as expected higher amount of energy sold than purchased during the summer months, and vice verse in the winter. The energy charge column is the total amount of energy charge per kWh and is calculated from the net energy purchased. The values from the demand charge is calculated based on the feeding tariffs per kW from Agder Energi, and is also further described in Section 7.4.4. Figure 38 and Fig. 39 illustrates graphically the energy trading from/to the grid per hour each day. The pattern of the grid trading from SC1.1 and SC1.2 is approximately the same, and therefore is only the illustrations from SC1.2 used in this section.

Month	Energy Purchased [kWh]	Energy Sold [kWh]	Net Energy Purchased [kWh]	Peak Demand [kW]	Energy Charge [$]	Demand Charge [$]
January	22 752	5 526	17 226	100	1 337.55	2 945.10
February	17 167	9 609	7 558	100	740.28	2 970.36
March	14 554	14 837	-283	100	296.73	2 980.31
April	11 161	18 397	-7 235	100	- 119.50	2 929.21
May	8 963	23 425	-14 462	100	- 724.58	787.72
June	7 355	22 306	-14 952	91	- 747.08	683.37
July	7 354	23 448	-16 094	100	- 803.56	755.02
August	9 428	17 729	-8 301	100	- 420.41	766.80
September	11 794	15 554	-3 759	100	- 198.29	879.66
October	15 402	9 958	5 444	100	253.05	876.27
November	19 887	4 568	15 318	100	1 182.06	2 927.78
December	22 989	3 550	19 440	100	1 452.10	2 919.12
Annual	168 806	168 906	-101	100	2 248.38	22 420.73

Table 15: Electricity trade with the grid scenario 1

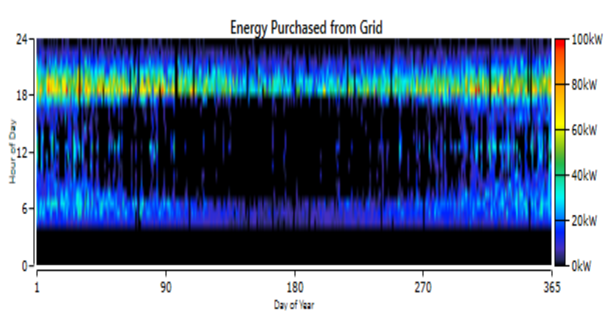

Figure 38: Electricity purchased from grid

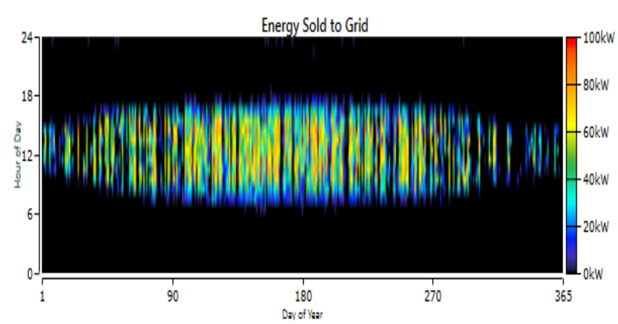

Figure 39: Electricity sold to grid

Cost summary

Table 16 and Tab. 17 shows the cost summary throughout the project lifetime of 25 years. The capital cost in SC1.2 is $16 096 more expensive than in SC1.1. In year 20 does the wind turbines need to be changed, however the salvage value of the wind turbines in year 25 is just 25% lower than the purchase price when the project lifetime ends. This gives a satisfying potential sale price, or better budget if the microgrid continues to operate after 25 years. The difference in NPC of the two scenarios is only $5 441, which is a small share of the total budget. O&M is the costs associated with O&M of the component, and the total O&M cost is the O&M cost of the whole system. The grid O&M cost is the annual cost of buying power from the grid, subtracted any revenue earned from selling power to the grid [68]. Other O&M costs related to the grid is not included in the calculations.

The PV system and wind turbine has annual O&M costs during the lifetime, while the micro-gas turbine and district heating system has fuel expenses, and the grid has purchase costs to Agder Energi. The capital cost of the district heating system is determined by using the barrier study from Enova, mentioned in Section 7.3.4, and the thermal energy demand for Linnheia Microgrid. A pellet boiler where used in the Enova study. The price of a natural gas boiler was not given in the report, and the price of the pellet boiler is therefore used in the capital cost calculations. The capital cost of the boiler includes the whole cost of the district heating system.

District heating systems can last for several decades with correct operation and maintenance. The salvage of the district heating system in Linnheia is not calculated, which gives a bit incorrect values for the system and the NPC.

Component	**Capital** [$]	**Replacement** [$]	**O&M** [$]	**Fuel** [$]	**Salvage** [$]	**Total** [$]
Wind Turbines	54 000	16 837	6 903	0	-9 436	68 304
Boiler	433 159	0	0	6 443	0	439 602
CHP	100	149	49	57 766	-3	58 061
PV System	737 514	0	7 385	0	0	744 900
Grid	68 459	0	312 916	0	0	381 375
Converter	43 500	18 151	0	0	-3 378	58 272
System Total	1 336 732	35 137	327 254	64 209	-12 818	1 750 515

Table 16: Cost summary of SC1.1

Component	**Capital** [$]	**Replacement** [$]	**O&M** [$]	**Fuel** [$]	**Salvage** [$]	**Total** [$]
Boiler	433 159	0	0	7 457	0	440 616
CHP	100	145	47	55 596	-6	55 883
PV System	802 173	0	7 933	0	0	810 106
Grid	68 459	0	315 354	0	0	383 813
Converter	48 937	20 419	0	0	-3 800	65 556
System Total	1 352 828	20 565	323 334	63 054	-3 807	1 755 956

Table 17: Cost summary of SC1.2

7.4.2 Scenario 2

System design

In this scenario is the grid-connected microgrid simulated without a thermal load, and BIPV system is included on the building roofs. The system is optimized with and without wind turbines. A lithium-ion ESS is used to store excess energy and to balance the energy flow in the system. The microgrid system is illustrated in Fig. 40 where the total system peak is 232.68kWp. The components are optimized by Homer Optimizer and the design pages are shown in Appendix B.

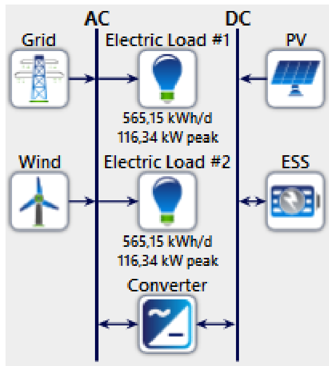

Figure 40: System design scenario 2

The results from the optimization is illustrated in Fig. 41, where the architecture and total cost is included. Both with and without wind turbines are included in the figure. NPC is the present value of all the costs of installing and operation over the project lifetime. The value of the components are given in kW, although the wind turbines are given in quantity of 10kW wind turbines.

Architecture											Cost	
[warning]	[PV]	[Wind]	[ESS]	[Grid]	[Converter]	PV (kW)	Wind	ESS	Grid (kW)	Converter (kW)	NPC ($)	Initial capital ($)
	[PV]		[ESS]	[Grid]	[Converter]	549		551	100	154	$ 2,21M	$ 1,62M
	[PV]	[Wind]	[ESS]	[Grid]	[Converter]	141	16	80	100	156	$ 1,91M	$ 1,27M

Figure 41: Optimization results in scenario 2

Electric production

The monthly electric production from each of the energy sources are illustrated in Fig. 42 with wind turbines, and without wind turbines in Fig. 43. In SC2.1 is the total wind capacity 160kW, while the PV capacity is 141kW. This gives higher total electric production during the winter months and lower in the summer, which is suitable compared with a Norwegian consumption pattern. Without wind turbines in SC2.2 is the electric production reversed with the highest production in the summer, and with PV capacity as large as 549kW. The grid and ESS are balancing when the production is not covering the consumption of the microgrid. Since there is no thermal load with an integrated heating system, must the houses be heated by other applications, like electrical radiators, air-air heat pump or water-air heat pump.

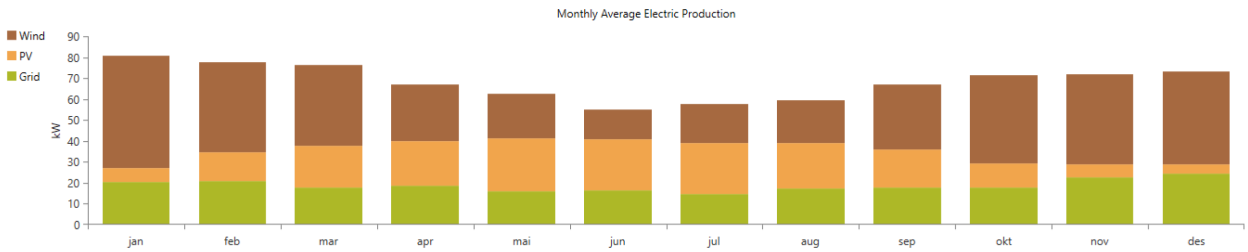

Figure 42: Electric production in SC2.1

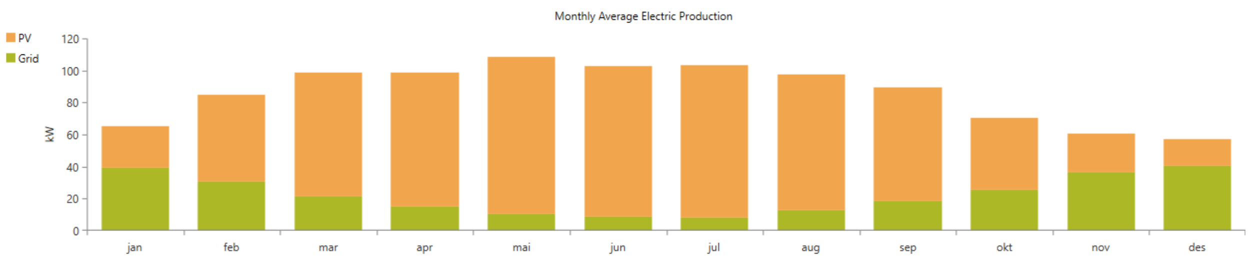

Figure 43: Electric production in SC2.2

The kW in the two graphs are noticeably different. This is due to the large ESS in SC2.2 that is covering the rest of the total consumption. This does not appears in the graphs of electric production.

Table 18 compares the parameters from the two scenarios. The wind turbines produce over twice as much electricity as the PV system in SC2.1, and is the dominant energy source. In SC2.2 does the PV system produce over three quarters of the electricity, although with only one energy source will this system be fragile. It is also interesting to see that the difference in total electric production in the two scenarios are 157 919kWh/yr, and therefore will the amount of electricity sold to the grid be higher. Furthermore, the system will be more affordable by increasing the grid sale capacity, so the excess energy can be utilized.

	Scenario 2.1		**Scenario 2.2**	
Production	**[kWh/year]**	**%**	**[kWh/year]**	**%**
PV	144 556	24.2	590 982	74.2
Wind Turbine	289 977	48.5	0	0
Grid Purchase	163 610	27.4	195 080	25.8
Total	598 143	100	756 062	100

Table 18: Comparing electric production in scenario 2

In Tab. 19 is the operation data for the components illustrated. In SC2.2 is the total mean output significant higher than in SC2.1, which is due to only one energy source. The capacity factor is the ratio of the electrical outputs over a given period of time to the maximum possible electrical output over that period. The levelized cost shows the cost per kWh, and the amount of operation hours per year is also shown in the table.

	Scenario 2.1		**Scenario 2.2**	
	PV System	**Wind Turbine**	**PV System**	**Wind Turbine**
Mean output [kW]	16.5	33.1	64.0	0
Capacity factor [kW]	11.7	20.7	11.7	0
Hours of operation [h/yr]	4 373	7 174	4 373	0
Levelized cost [$/kWh]	0.168	0.273	0.165	0

Table 19: Comparing operation parameters in scenario 2

Electrical energy storage
Since the microgrid in scenario 2 only has NDES is it depending on an ESS to store excess energy to periods with lower electricity production than consumption. The ESS is optimized by intervals of 1kWh, and are connected in parallel with the optimized amount of 1kWh batteries. In SC2.2 is the ESS significantly larger than in SC2.1, which is due to only one NDES in the microgrid. In Tab. 20 is the ESS in the scenarios compared, where usable nominal capacity is the amount of energy that can be withdrawn from it at a particular constant current, starting from a fully charged state. The annual throughput is the annual amount of energy that cycles through the ESS. Throughput is defined as the change in energy level of the ESS, measured after charging losses and before discharging losses [69].

	Scenario 2.1	**Scenario 2.2**
Batteries [quantities]	80	551
Nominal Voltage [V]	3.70	3.70
Usable nominal capacity [kWh]	65.4	450
Expected lifetime [years]	7.99	13.7
Annual throughput [kWh/year]	27 267	109 824

Table 20: Comparing ESS in scenario 2

In Fig. 44 and Fig. 45 is the state of charge (SoC) of the ESS during the year illustrated in a graph that separate from hours of the day and percentage of SoC. The SoC variations of the ESS in SC2.1 occurs more rapidly than in SC2.2, which is due to the battery size, and the combination of wind and PV in SC2.1. The lifetime of the ESS in SC2.2 is therefore longer.

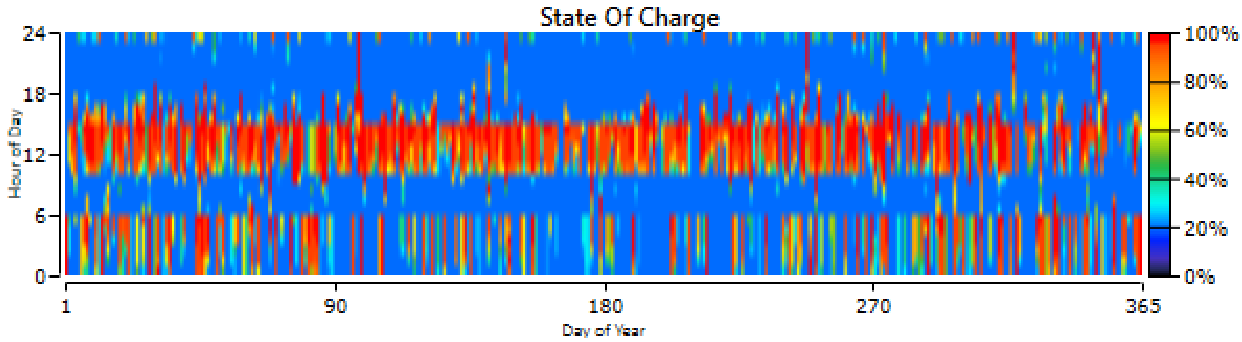

Figure 44: State of charge of ESS in SC2.1

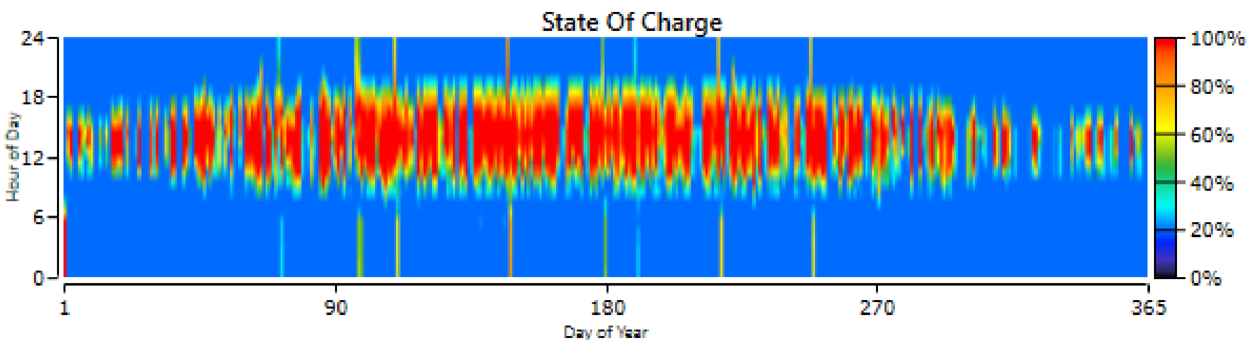

Figure 45: State of charge of ESS in SC2.2

Trading of electricity with the grid

The annual net energy purchase of the microgrid is set to 0kWh, and maximum power peak to 100kWp. This is further described in Section 7.4.4. Table 21 and Tab. 22 shows the electricity trading with the grid for respectively SC2.1 and SC2.2. The net energy purchased values is completely opposite in the two scenarios, due to the selection of NDES.

Month	Energy Purchased [kWh]	Energy Sold [kWh]	Net Energy Purchased [kWh]	Peak Demand [kW]	Energy Charge [$]	Demand Charge [$]
January	15 058	17 180	-2 123	100	216.51	3 359.04
February	13 915	14 184	-269	100	283.78	3 266.30
March	13 152	15 916	-2 763	100	144.15	3 359.04
April	13 323	12 793	530	100	310.68	3 265.43
May	11 876	13 439	-1 563	100	-89.75	863.60
June	11 921	10 119	1 803	100	76.63	869.67
July	10 869	13 199	-2 330	100	-126.64	828.81
August	12 764	11 194	1 571	100	64.26	918.73
September	12 871	14 618	-1 748	100	-99.94	924.12
October	13 359	16 575	-3 216	100	-173.07	976.50
November	16 317	13 540	2 777	100	485.71	3 266.86
December	18 183	12 918	5 266	100	648.59	3 305.22
Annual	163 610	165 675	-2 066	100	1 740.93	25 203.31

Table 21: Electricity trade with the grid SC2.1

Month	Energy Purchased [kWh]	Energy Sold [kWh]	Net Energy Purchased [kWh]	Peak Demand [kW]	Energy Charge [$]	Demand Charge [$]
January	29 974	5 882	23 093	100	1 760.53	3 359.04
February	20 519	10 198	10 321	100	948.45	3 359.04
March	16 089	16 330	-241	100	331.60	3 359.04
April	10 980	21 055	-10 075	100	-263.80	3 359.04
May	7 934	27 129	-19 194	100	-957.49	865,35
June	6 371	27 179	-20 808	100	-1 035.63	778.73
July	6 023	28 256	-22 233	83	-1 105.73	713.22
August	9 398	20 965	-11 567	100	-581.85	829.89
September	13 470	18 349	-4 879	100	-255.42	995.99
October	19 003	11 872	7 131	100	322.65	974.84
November	26 287	5 246	21 041	100	1 601.71	3 347.70
December	30 033	3 121	26 912	100	1 972.00	3 321.78
Annual	195 080	195 579	-499	100	2 747.03	25 254.67

Table 22: Electricity trade with the grid SC2.2

Figure 46-49 illustrates the energy purchased and sold to the grid. Energy sold in SC2.2 has a high amount of peak values during day time. With a higher sale capacity limit than 100kW would this alternative be more efficient, and the microgrid could sell even more electricity to the grid. In SC2.1 is the sale during the day better distributed, which is more suitable with the settings of the advanced grid.

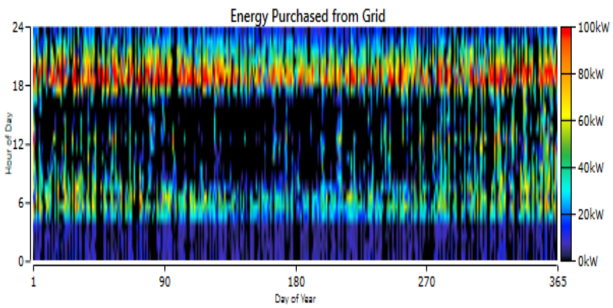

Figure 46: Electricity purchased from grid SC2.1

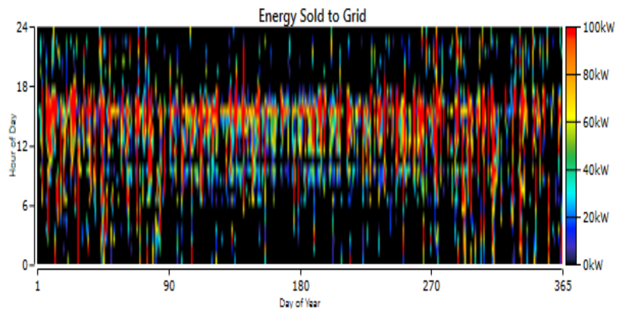

Figure 47: Electricity sold to grid SC2.1

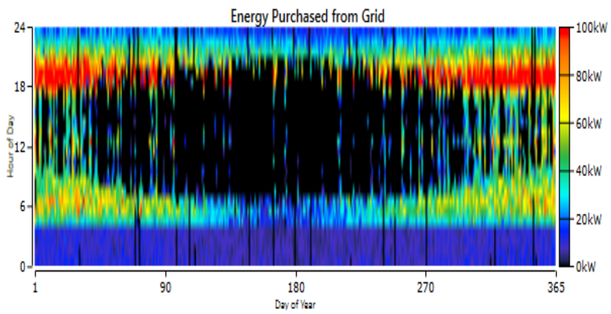

Figure 48: Electricity purchased from grid SC2.2

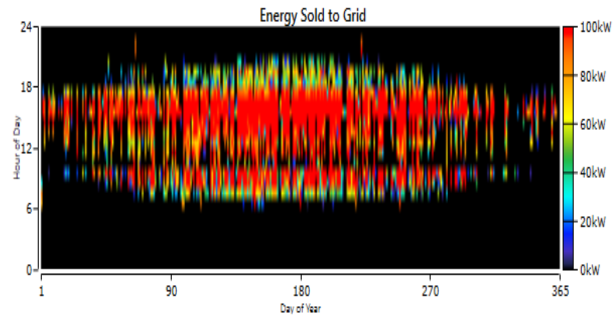

Figure 49: Electricity sold to grid SC2.2

Cost summary

As illustrated in Tab. 23 and Tab. 24 is the total system cost of SC2.2 significantly more expensive than SC2.1 that has both wind turbines and PV system. Even if SC2.1 must replace the wind turbines after 20 years, will the high capital cost of the PV system and ESS in SC2.2 exceed the capital and replacement costs in SC2.1.

Component	**Capital [$]**	**Replacement [$]**	**O&M [$]**	**Salvage [$]**	**Total [$]**
Wind Turbines	800 000	249 443	102 266	-139 799	1 011 911
ESS	48 000	60 930	10 226	-9 739	109 418
PV System	305 831	0	3 731	0	309 563
Grid	68 459	0	344 437	0	412 896
Converter	46 812	19 533	0	-3 635	62 709
System Total	1 269 103	329 907	460 662	-153 174	1 906 499

Table 23: Cost summary of SC2.1

Components	**Capital [$]**	**Replacement [$]**	**O&M [$]**	**Salvage [$]**	**Total [$]**
ESS	330 600	148 666	70 436	-13 655	536 046
PV System	1 171 068	0	11 056	0	1 182 125
Grid	68 459	0	357 955	0	426 414
Converter	46 316	19 326	0	-3 597	62 045
System Total	1 616 443	167 992	439 448	-17 253	2 206 631

Table 24: Cost summary of SC2.2

7.4.3 Scenario 3

System design

Homer Energy does not have a geothermal energy storage component, although in this scenario is the geothermal energy storage self-composed and optimized to match the load demands of the microgrid. Therefore is the total energy consumption only split into Electric Load #1 and #2, and not any thermal load, shown in Fig. 50. This will be further described in this section. Again is the scenario optimized with and without wind turbines, with a size of 3kW per turbine. The grid and PV settings maintains the same, and the total system peak is 232.68kWp. The design pages are shown in Appendix B.

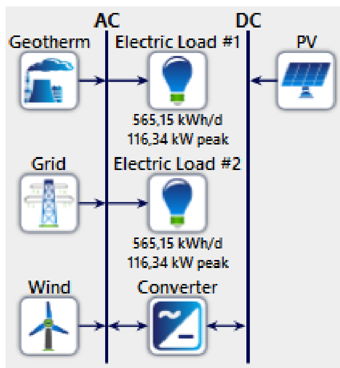

Figure 50: System design scenario 3

The results from the optimization is illustrated in Fig. 51, where the architecture and total cost is included. Both with and without wind turbines are included in the figure. The geothermal energy storage output is fixed and set to be 100kW.

Architecture						Cost	
PV (kW)	Wind	Geotherm (kW)	Grid (kW)	Converter (kW)		NPC ($)	Initial capital ($)
178	3	100	100	123		$ 1,62M	$ 1,24M
194		100	100	134		$ 1,59M	$ 1,23M

Figure 51: Optimization results in scenario 3

Energy production

Unlike scenario 1 is the thermal energy illustrated in the electric production graphs, Fig. 52 and Fig. 53. It was not possible to add it as a thermal load, which can be misleading. Furthermore, PV, grid and wind has the same structure as mentioned in section 1 and 2.

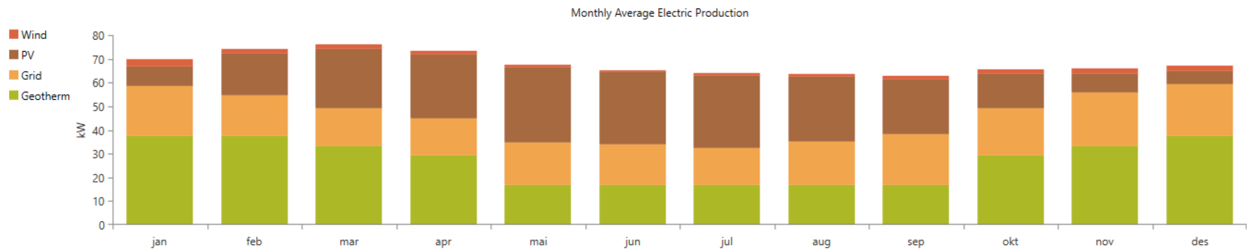

Figure 52: Electric production in SC3.1

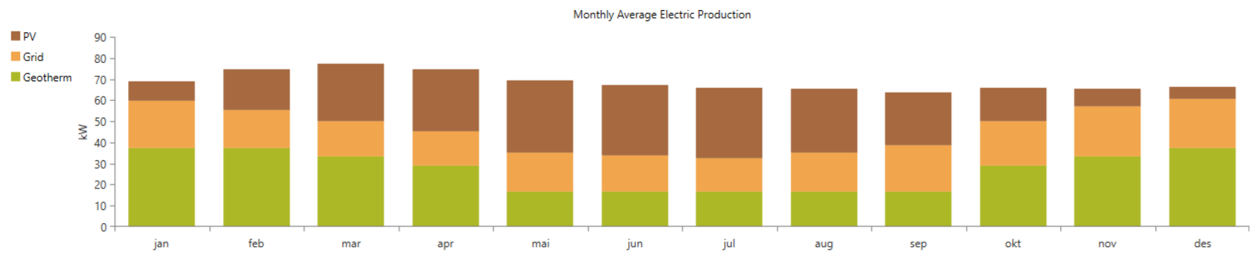

Figure 53: Electric production in SC3.2

In Tab. 25 is not geothermal energy storage included, since its not electric production. The table shows that PV is the dominant energy resource, while the wind turbines is optimized to the minimum amount of turbines. The ratio between grid purchase and the PV system is almost the same in both scenarios.

	Scenario 3.1		**Scenario 3.2**	
Production	**kWh/year**	**%**	**kWh/year**	**%**
PV	181 633	50.4	198 110	53.9
Wind Turbine	14 516	4.0	0	0
Grid Purchase	164 371	45.6	169 359	46.1
Total	360 520	100	367 469	100

Table 25: Comparing electric production in scenario 3

In Tab. 26 is the operation data for the components illustrated. Since the geothermal energy storage is self composed and might have some deviation, is it not included in the table.

	Scenario 3.1		Scenario 3.2	
	PV System	Wind Turbine	PV System	Wind Turbine
Mean output [kW]	20.7	1.66	22.6	0
Capacity factor [kW]	11.7	18.4	11.7	0
Hours of operation [h/yr]	4 373	7 038	4 373	0
Levelized cost [$/kWh]	0.167	0.368	0.167	0

Table 26: Comparing operation parameters in scenario 3

Geothermal energy storage

The geothermal energy storage settings in Homer Energy is customized to match the thermal load of space heating and hot water in the microgrid. The costs of the geothermal energy storage system is based on the similar system as in Eid County, which is further described in Section 7.3.5. The settings are supposed to be as accurate as possible, although it can be inaccurate in some areas. E.g. the system has a fixed 100kW output which is preset for the whole year, illustrated in Fig. 54. The thermal demand in the microgrid will not necessarily perfectly match the settings, although it gives an indication and is also necessary to match the annual thermal energy demand of the microgrid. The fluid in the system is called *geothermal fluid* and is customized for this system. The system page is shown in Appendix B.

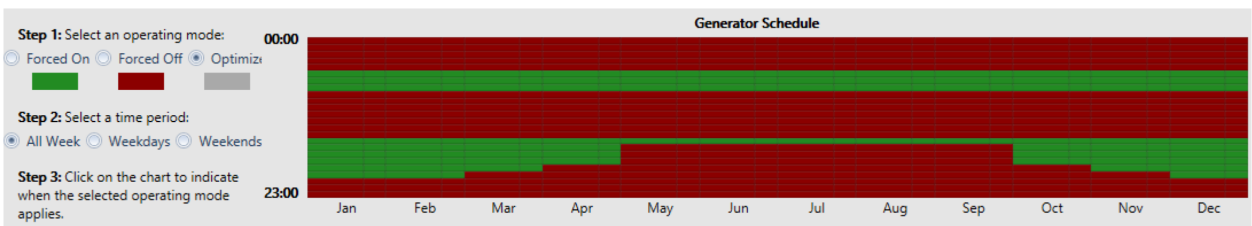

Figure 54: Scheduled annual on/off time of the geothermal energy storage system

Table 27 illustrates relevant parameters of the geothermal energy system. The annual thermal production is customized to match the thermal load of the microgrid, and since the output is fixed, is the mean output equal to the maximum output. A geothermal energy storage system can maintain for several decades, therefore is the lifetime of the system not included in the table.

Geothermal energy storage parameters	
Annual thermal production [kWh/yr]	233 700
Mean output [kW]	100
Hours of operation [h/yr]	2 337
Capacity factor [%]	26.7

Table 27: Geothermal energy storage parameters

Trading of electricity with the grid
The annual net energy purchase of the microgrid is set to 0kWh, and maximum power peak to 100kW. This is further described in Section 7.4.4. From March to August is the net energy purchased negative, which means the microgrid has sold more than it purchased from the grid. The energy sold is much higher during the summer, than in the winter, although the annual net energy purchased is -892kWh. The difference between SC3.1 and SC3.2 was minimal, so the values in the Tab. 28 is from SC3.1.

Month	**Energy Purchased [kWh]**	**Energy Sold [kWh]**	**Net Energy Purchased [kWh]**	**Peak Demand [kW]**	**Energy Charge [$]**	**Demand Charge [$]**
January	15 601	10 023	5 578	100	608.91	3 359.04
February	11 430	11 871	-441	100	222.23	3 280.20
March	11 870	14 762	-2 893	100	110.38	3 007.84
April	11 322	17 036	-5 714	100	-40.81	3 359.04
May	13 500	17 380	-3 880	100	-206.05	835.11
June	12 434	16 425	-3 991	100	-210.42	853.73
July	11 623	17 672	-6 049	100	-311.32	796.56
August	13 774	14 500	-726	100	-50.38	913.30
September	15 557	13 151	2 406	100	102.64	1 040.10
October	14 757	13 555	1202	100	43.97	1 105.71
November	16 256	10 150	6 107	100	649.04	3 359.04
December	16 247	8 739	7 508	100	718.16	3 359.04
Annual	164 371	165 263	-892	100	1 636.35	25 268.70

Table 28: Electricity trade with the grid scenario 3

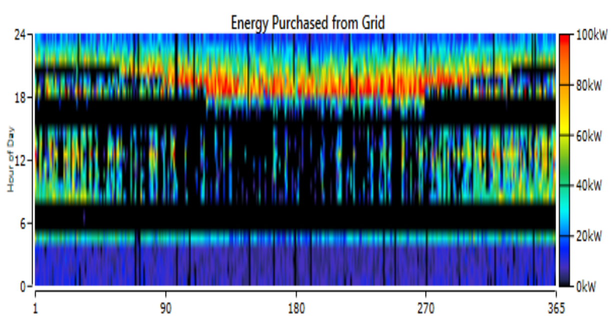

Figure 55: Electricity purchased from grid scenario 3

Figure 56: Electricity sold to grid scenario 3

Cost summary
Table 29 and Tab. 30 shows the cost summary throughout the project lifetime of 25 years. The costs of the geothermal energy storage is used from the similar project in Eid County, which has a capital cost of approximately 5.6MNOK. By using the exchange rate from 15.05.18 does this equals to $701 833. O&M costs are not included in the summary, however for heating plant of this size will it be naturally with some O&M costs. Since its only three wind turbines is the price difference minimal in the two scenarios.

Component	**Capital [$]**	**Replacement [$]**	**O&M [$]**	**Salvage [$]**	**Total [$]**
Wind Turbines	54 000	16 837	6 903	-9 436	68 304
PV System	382 869	0	4 383	0	387 253
Geothermal Energy Storage	701 833	0	0	0	701 833
Grid	68 459	0	343 936	0	412 395
Converter	37 049	15 459	0	-2 877	49 631
System Total	1 244 211	32 297	355 223	-12 313	1 619 418

Table 29: Cost summary of SC3.1

Component	**Capital [$]**	**Replacement [$]**	**O&M [$]**	**Salvage [$]**	**Total [$]**
PV System	417 103	0	4 673	0	421 776
Geothermal Energy Storage	701 833	0	0	0	701 833
Grid	68 459	0	347 116	0	415 575
Converter	40 195	16 772	0	-3 121	53 845
System Total	1 227 590	16 772	351 789	-3 121	1 593 030

Table 30: Cost summary SC3.2

7.4.4 Advanced Grid Settings

The advanced grid settings are the same in all three scenarios, and the grid is connected to the AC bus. In Fig. 57 is the sale and purchase capacity to/from the grid set to 100kW, due to the plus consumers agreement from NVE, mentioned in Section 3.3. The 100kW limit is normally set to each costumer, although without a given microgrid agreement in Norway will this limit be a good indication of the independence of the microgrid. 100kW is also a very predictable limit for Agder Energi, and makes it easier for them to control the power flow in the distribution network.

The maximum annual net grid purchase is set to 0kWh, which means the microgrid will produce more energy than it consumes. The costs of a grid extension over Linnheia Microgrid with a total a of 4000m^2 and 40 houses is given by Nettparner AS, and determined to be approximately 550 000NOK (≈68 459USD). This price includes LV distribution from the substation to each house, and estimated material costs. The determination is not coordinated with Agder Energi, and can therefore be a bit inaccurate. Nevertheless, it gives an indication of the expenses regarding grid extension.

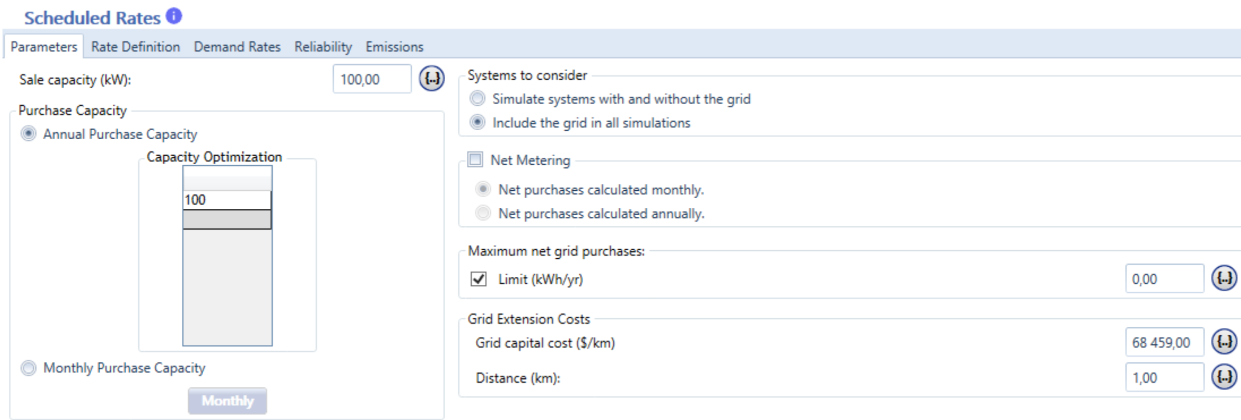

Figure 57: Advanced grid parameters

Table 4 in Section 3.3.1 describes the electricity tariffs given by Agder Energi in 2018. A new spot price is given each day by Nord Pool and in this thesis is the spot price from 26th of April used, which was 36.46EUR/MWh, converted to US dollars 44.43USD/MWh with the exchange rate from the same day [70]. Plus consumers connected to Agder Energi gets a sale price of spot price + 4øre/kWh, which is (0.04443+0.005)USD/kWh= 0.04945USD/kWh. In Fig. 58 is the grid rate scheduled for both summer and winter price.

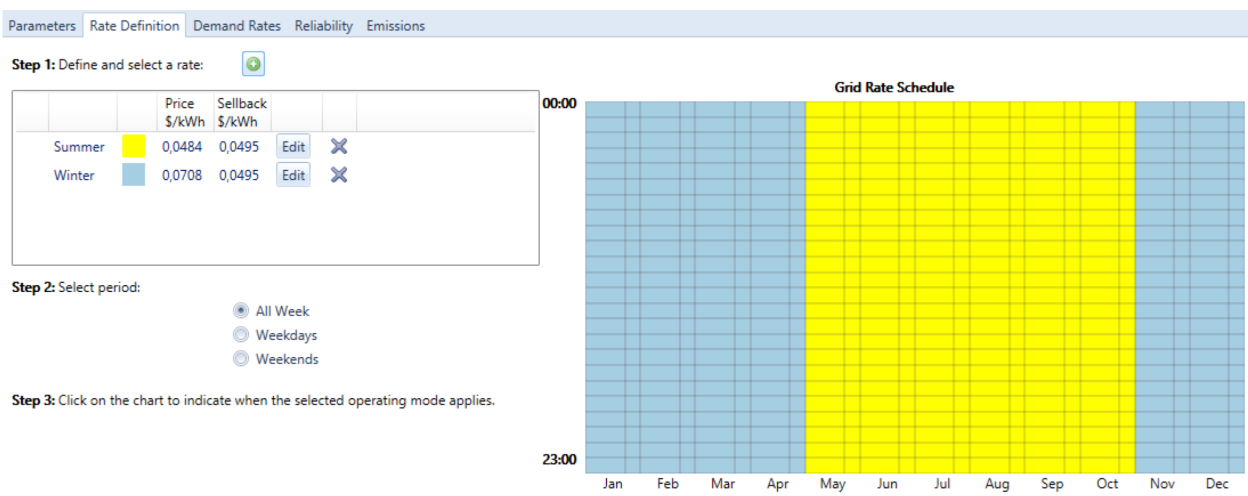

Figure 58: Advanced grid rate definition

The purchase price per kW/month from Agder Energi is given in Fig. 59. The purple and red colour describes the period when the ESS can be discharged, either to grid or microgrid. The green and yellow defines the periods when the battery can charge. The y-axis is the time of the day, and x-axis is the given month. The charge/discharge time is selected based on normal electricity consumption in family houses. Without this settings will the ESS in a grid-connected microgrid in Homer Energy just be a backup storage, which is not desirable for Linnheia Microgrid.

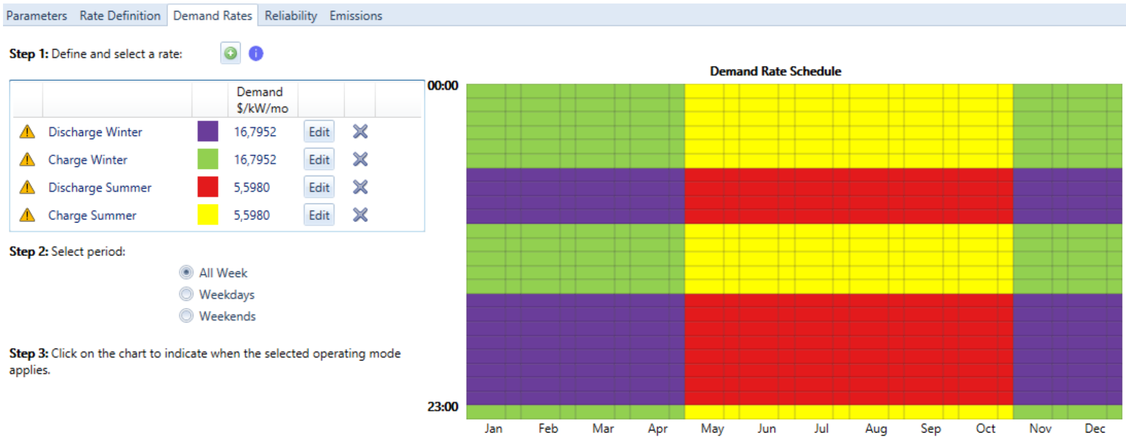

Figure 59: Advanced grid demand rates

In the reliability tab, illustrated in Fig. 60, is it possible to model an unreliable grid. In the simulations is random outages selected, where Homer Energy randomly sets up outages during the year. The mean repair time is set to 12 hours with variability of 10%. Homer tries to generate distinct, non-overlapping outages equal to the number specified for "Mean outage frequency (1/yr)", without considering scheduled outages. As it chooses the time-step index for each outage, Homer only chooses an index that does not overlap with an existing outage, if possible [71]. The Electric Load #2 is turned off during outages, as mentioned in Section 7.3.1.

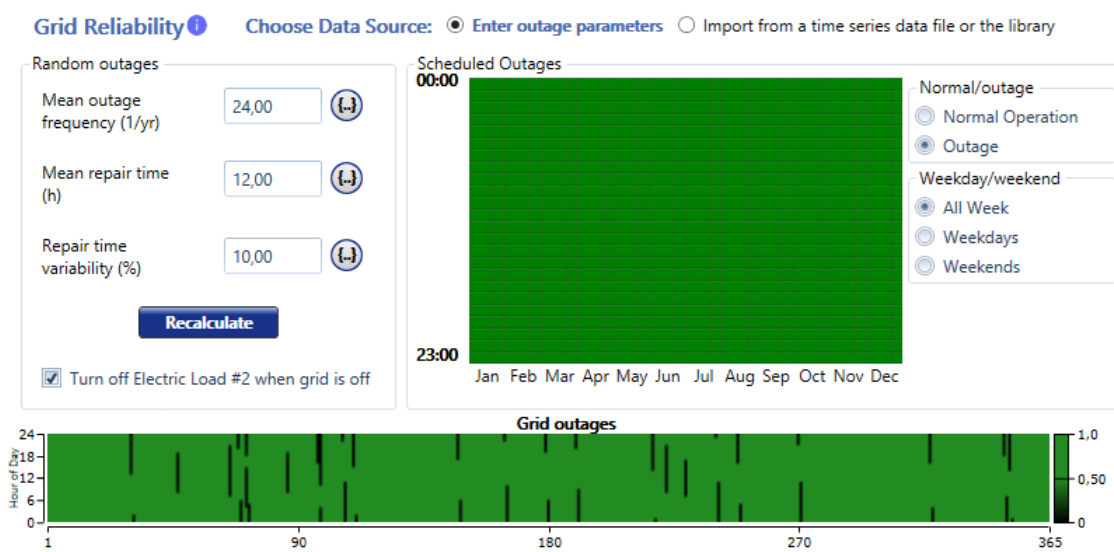

Figure 60: Advanced grid reliability

7.4.5 Calculations of Electric Parameters

There has not conducted regulatory calculations of the electric parameters in the microgrid simulations. Homer is constructed to give realistic simulations, that could be a benchmark for a microgrid construction. Although, as part of the planning must the electric parameters be calculated. According to the guidelines for microgrid planning from IEC is following calculations/simulations recommended:

- Load flow analysis for operation modules.
- Short circuit currents.
- Fault ride through capacity verification [41].

The last item is not relevant for isolated microgrids, since it involves measuring the microgrids resistance to errors from the distribution network.

7.5 STAGE 3: Technical Requirements

In this stage is the evaluation of the feasibility of the alternatives with respect to the technical requirements of voltage and load on the line. Based on the workload is this not a priority in the thesis, and therefore is it assumed that every solution meets the requirements without significant cost increases.

7.6 STAGE 4: Evaluation of Linnheia Microgrid

In this section will the scenarios be compared and analyzed, before selecting the most suitable scenario for Linnheia Microgrid. First must the version of each scenario be selected, i.e. with or without wind turbines, then will the three scenarios by compared. Finally will the selected scenario be evaluated and analyzed for further work.

7.6.1 Defining the Scenarios

Scenario 1
The cost difference between SC1.1 and SC1.2 was marginal, and the difference of the total system cost over 25 years was only $5 441. SC1.1 consists of three 3kW wind turbines which annually generates only 2.5% of the total electric production. In a grid-connected microgrid that consists of both a CHP micro-gas turbine and a boiler, becomes the wind turbines superfluous. The mentioned energy sources are all adjustable, and will therefore be a suitable match with a relatively large total PV capacity. Integrating a wind power plant will also generate some extra work related to finding relevant alternative areas for the power plant, planning the plant area, and apply for approval, among other things. For such a small energy source will this not be prioritized, and SC1.2 is therefore preferred.

Scenario 2
The difference between the total system cost in the two alternatives in scenario 2 are significant, where SC2.2 without wind turbines are $300 000 more expensive than SC2.1. The high amount of wind power in SC2.1 gives higher energy production during the winter months, and is therefore more suitable to the Norwegian power consumption, compared to SC2.2. SC2.1 consists of 16 10kW wind turbines. Realistic placements of a wind power plant of this size in the immediate vicinity of Linnheia Microgrid must be offshore. This requires governmental approval which can complicate the process. Also the price in the scenario is onshore wind turbines, which can deviate from offshore wind turbines. Nevertheless, SC2.1 is the most suitable alternative in scenario 2, and will be prioritized for further investigation.

Scenario 3
Scenario 3 has the same challenges as scenario 1, due to the simulation results. The total system costs in SC3.1 and SC3.2 is almost the same, and the wind turbines in SC3.1 are only producing 4% of the total electricity production. Therefore is the reasoning in scenario 3 the same as in scenario 1, and SC3.2 is the preferred alternative.

7.6.2 Comparing the Alternatives

There are uncertainties in all of the scenarios. Scenario 1 has the district heating system, scenario 2 has the wind turbine plant, and geothermal energy storage is the uncertainty in scenario 3. In the comparison between the scenarios will therefore the mentioned uncertainties not be considered in relation to unclarified factors regarding establishing of the components. Economic and operation factors will be higher emphasized in the evaluation. The size the components are compared in Tab. 31. The value of the micro-gas turbine in scenario 1 consists of both thermal energy and electricity.

Components	**Scenario 1**	**Scenario 2**	**Scenario 3**
PV System [kW]	375	141	194
Wind Turbines [kW]		160	
Converter [kW]	163	156	134
ESS [kWh]		80	
CHP [kWh/yr]	105 891		
Boiler [kWh/yr]	16 323		
Geothermal Energy Storage [kWh/yr]			233 700

Table 31: Comparing the components in the scenarios

The total system costs over 25 years are illustrated in Tab. 32. Scenario 3 has both lowest investment cost and total system cost of the three scenarios, although the O&M cost of the geothermal energy storage is not included in the total O&M cost in the scenario. The fuel cost in scenario 1 can be reduced by changing to an incineration power plant, however this will require further investigation. Scenario 2 is the only microgrid with only RESs combined with the grid-connection. Unfortunately, this alternative is also most expensive and is depending on the establishment of the wind power plant.

	Capital cost [$]	**Replace-ment [$]**	**O&M [$]**	**Fuel [$]**	**Salvage [$]**	**Total [$]**
Scenario 1	1 352 828	20 565	323 334	63 054	-3 807	1 755 956
Scenario 2	1 269 103	329 907	460 662	0	-153 174	1 906 499
Scenario 3	1 227 590	16 772	351 789	0	-3 121	1 593 030

Table 32: Comparing the economic in the scenarios

Some key factors of Linnheia Microgrid is discussed in Tab. 33, which gives an indication of both benefits and challenges of the scenarios. Scenario 1 and 3 are discussed together, due to their similarities, and eventual differences are remarked.

<table>
<tr><th></th><th>Scenario 1</th><th>Scenario 3</th><th>Scenario 2</th></tr>
<tr><td>Supply reliability</td><td colspan="2">Depending on the heating system to work, especially in the winter months. Scenario 1 also rely on the CHP to work.</td><td>Is self-sufficient by the RES, and is not depending on supply from heating system. Although, the grid connection is essential for this scenario.</td></tr>
<tr><td>Environmental concerns</td><td colspan="2">Beside the heating plant will the components blend seamlessly in the area. The emission from the natural gas is relatively low and can be neglected.</td><td>A wind power plant will be placed offshore, and make a significant footprint in the nature.</td></tr>
<tr><td>Possibility of expansion</td><td colspan="2">PV capacity can easily be expanded.</td><td>The expand of the wind power plant can be possible, by increasing the number of turbines or replacing existing turbines with larger ones. PV capacity can easily be expanded.</td></tr>
<tr><td>The scope of the construction</td><td colspan="2">The construction of the infrastructure of the piping system is comprehensive. Although, the required area will be relatively small compared to scenario 2, since most of it will be underground.</td><td>The wind power plant and ESS requires large areas.</td></tr>
<tr><td>Grid interaction</td><td colspan="2">The thermal load is covered by the heating systems, and the grid interaction is therefore easier to predict. Scenario 1 has a much larger PV capacity than scenario 3, which makes it a bit more unreliable.</td><td>The RESs can not be adjustable. Therefore is it harder to predict the grid demand from this microgrid, compared to the other alternatives.</td></tr>
</table>

Table 33: Evaluation of key factors in the scenarios

7.6.3 Choosing the Most Suitable Alternative

Based on a total evaluation of the different alternatives is it desirable to do further research on a microgrid with integrated heating system. Scenario 2 is the most expensive alternative, and is also less adjustable than the other alternatives. It is possible to get some of the expenses subsidized of the heating system, which can reduce the total costs of the microgrids in scenario 1 and 3. With a district heating system can waste be utilized, that could reduce some of the emissions from burning natural gas. It is several alternatives to effectively utilize the district heating system, and this must be further investigated.

Compared to district heating does not geothermal energy storage need fuel supply, and has no emissions. In this thesis does the geothermal energy cover both space heating and hot water, and will provide the whole residential area for decades. Although, costs regarding O&M is not included in the calculations, and must be further investigated.

Both scenario 1 and 3 are suitable alternatives of Linnheia Microgrid. Although, before further research on the total cost of the heating systems is available, will a conclusion be inaccurate. Therefore is not scenario 2 either ruled out, before necessary research is available.

7.6.4 Quality Analysis of the Simulations

Several simplifications and estimates are made during the planning stages, and is explained in the thesis. E.g. thermal and electric load, prices of components and O&M costs, and costs of heating systems. Before further research can be made, must the simplifications be further investigated to prevent potential system errors in the microgrid. The scenarios must satisfy the technical requirements of microgrids, which has not been investigated, due to limited time. Homer Energy also uses simplifications in the simulations, e.g. it is not considered that the energy production from PV panels will be lower over the years, or that the battery capacity will be reduced with frequent use. The price of the ”generic” CHP micro-gas turbine seems not realistic, and will probably be higher.

It is possible to specify degradation or growth in terms of percentage each year of the battery by using the *multi-year* function in Homer. Also grid price escalation, load growth and fuel price escalation can be modified, although this has not been done in the simulations.

The advanced grid settings must be clarified with Agder Energi. The purchase capacity of 100kW is set, due to plus consumers agreement from NVE, which is not confirmed to be applicable for microgrids. The grid tariffs is also from the plus consumers agreement, and can be adjusted by Agder Energi. The costs of grid extension is roughly calculated by Nettpartner AS, and needs a more detailed determination.

8 Conclusion

The thesis consists of two parts; the first is a literature study, and the last part is planning of a practical microgrid. The object of the thesis was to create a suitable design of Linnheia Microgrid, and to study microgrid technologies, microgrid barriers in Norway and relevant microgrid components. Relevant theory of distributed energy production, energy storage technologies and load control is also mentioned in the literature study.

In the literature study is the main microgrid technologies discussed. In the simulations are the microgrid scenarios constructed as grid-connected hybrid AC/DC microgrid architecture, due to both AC and DC components in the construction. This architecture combines the advantages for both AC and DC microgrids, like direct connection to the distribution network, which makes the architecture very reliable. Also the AC feeder allows existing infrastructure and loads to connect directly, and the DC feeder allows the use of a reduced number of simpler converters.

The lack of specific legal terms of microgrids in Norway makes it more challenging to establish microgrids. Although, The European Commission presented a package proposal in November 2016 that, among other things, enables local energy communities in European countries. The response from DSOs in Norway has been divided, and the skepticism is related to establishing procedures, energy prices and trading licenses, among other things. However, the DSOs are positive to the concept of local energy communities, if the legal requirements of selling/renting the grid is rational for both DSOs and consumers.

The literature study also consists of a microgrid planning model based on the planning book of power grids from Sintef, and guidelines for planning of microgrids developed by IEC. Its difficult to plan a microgrid with RESs and ESS, therefore has the simulation software Homer Energy been used, which takes into account variability in production and consumption to optimize the microgrid. The practical part of the thesis compares simulations of three different microgrid scenarios for Linnheia Microgrid, which are optimized with and without wind turbines. Based on the values available, was the scenarios with heating systems favourable. Both, district heating system and geothermal energy storage gave satisfying price and technical results. Although, the different systems has to be evaluated further before its reasonable to decide the construction. Not either the scenario without heating system is completely ruled out. However, the simulations showed that it can be possible to construct a microgrid in Linnheia that can be sustainable in the lifetime of 25 years.

The determined cost showed that scenario 3 with geothermal energy storage costs $170 000 less than scenario 1. Since the geothermal is covering hot water and space heating is the total RES capacity of only 194kW in the microgrid, and only consists of the PV system. This gives a very predictable operation, and low O&M and replacement costs. The PV capacity in scenario 1 is almost twice the size, however with CHP gas turbine is this construction also very predictable. Both scenarios has high capital costs, due to complicated and expensive infrastructure of the heating system.

There is more factors to consider in microgrid planning than in traditional grid planning, like production, energy storage and energy consumption. Its therefore important to include the entire system in the evaluation of the microgrid. The microgrid concept might need support from local authorities, or other stakeholders to really expand in numbers in Norway. Although, further development in DG components and system infrastructure could make microgrid communities even more achievable.

9 Recommendations

More research in the planning stage is necessary before Linnheia Microgrid can be further developed. Detailed price estimate over the lifetime of both district heating system and geothermal energy storage is necessary before a final evaluation of the project. With a detailed price estimate is it possible to get a concrete value of the subsidizes of the heating system. Analysis of aging of components (mainly PV and ESS) will make the simulations more accurate, including adding more sensitivity variables to the system as well.

Also a more accurate load forecast of the microgrid must be created. The load predictions used in the simulations are based on values from *Smart Village Skarpnes*, and since the houses in Linnheia Microgrid is currently not planned, could the annual load consumption be different. Legal terms of establishing an offshore wind power plants, and a feasibility study has to be investigated to have an adequate analysis of scenario 2. The prices used in the thesis is onshore wind turbines, which only gives an indication of the costs of the wind power plant.

Stage 3 (technical requirements) in the planning model from Sintef is not evaluated, due to limited time. Its critical to have a full evaluation of this stage. Opinions and demands from the DSO (Agder Energi) must also be considered, which require a settlement if a third part should be able to connect a grid-connected microgrid to the distribution network. Its also necessary to find out how the interaction between the DSO and the microgrid must be over the years. Another interesting investigation is to find the utility of the microgrid, compared to the total cost of the system.

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Appendices

A NASA Surface Meteorology Resource Databases

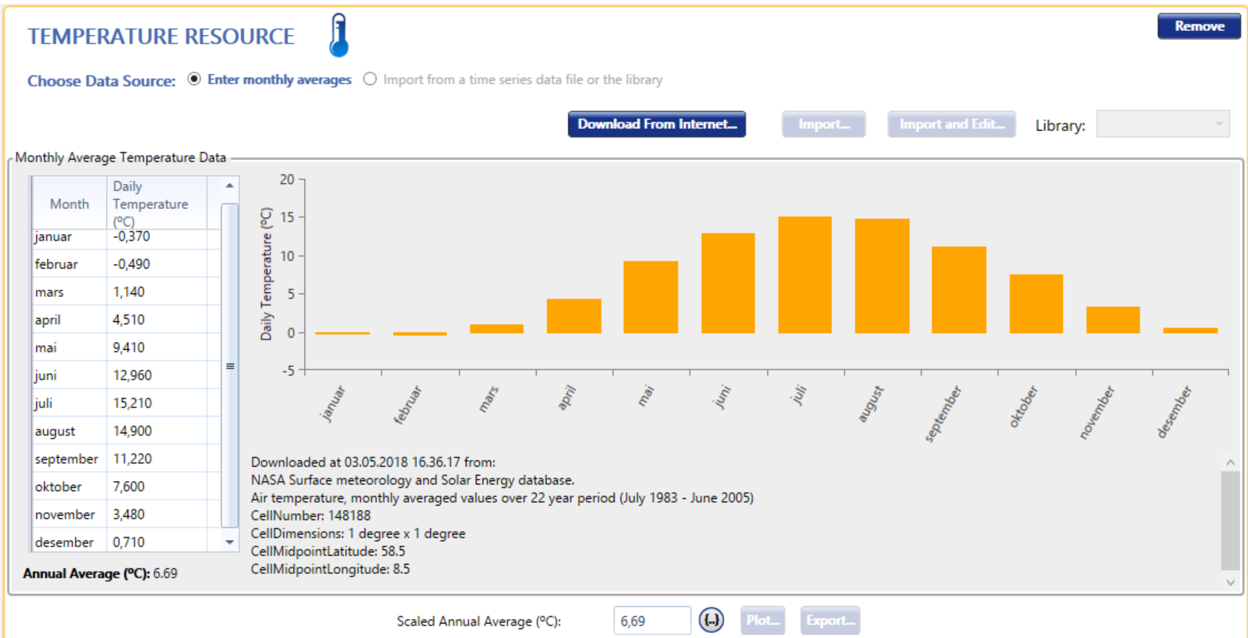

Figure A.61: Annual temperature Linnheia

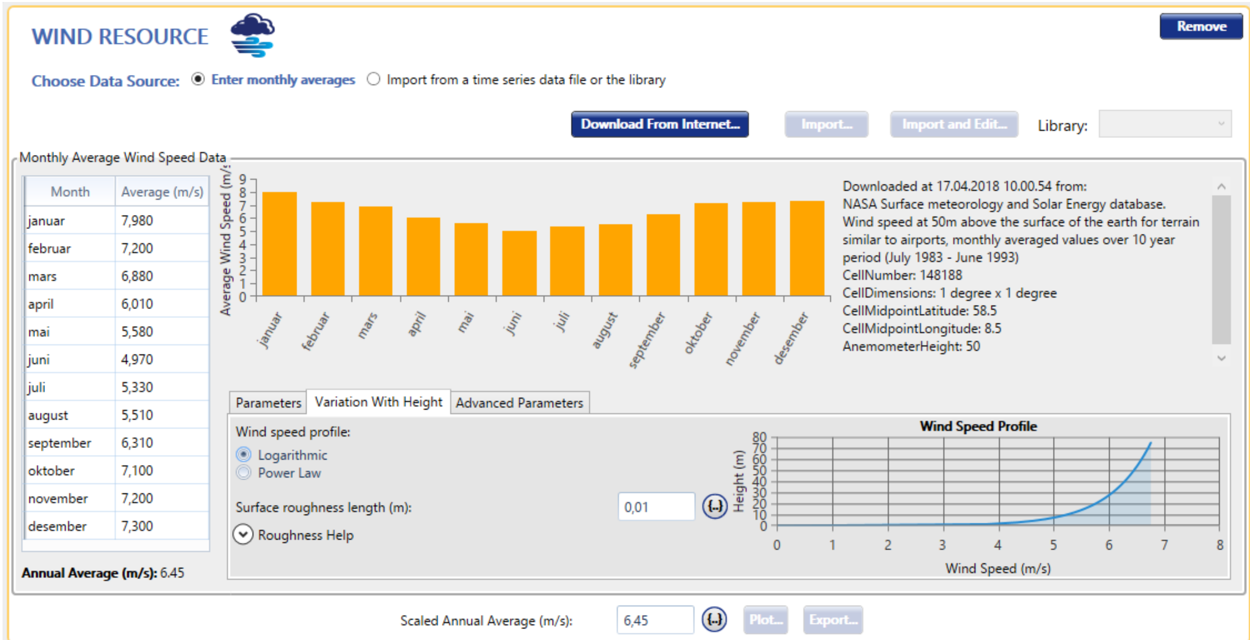

Figure A.62: Annual wind speed Linnheia

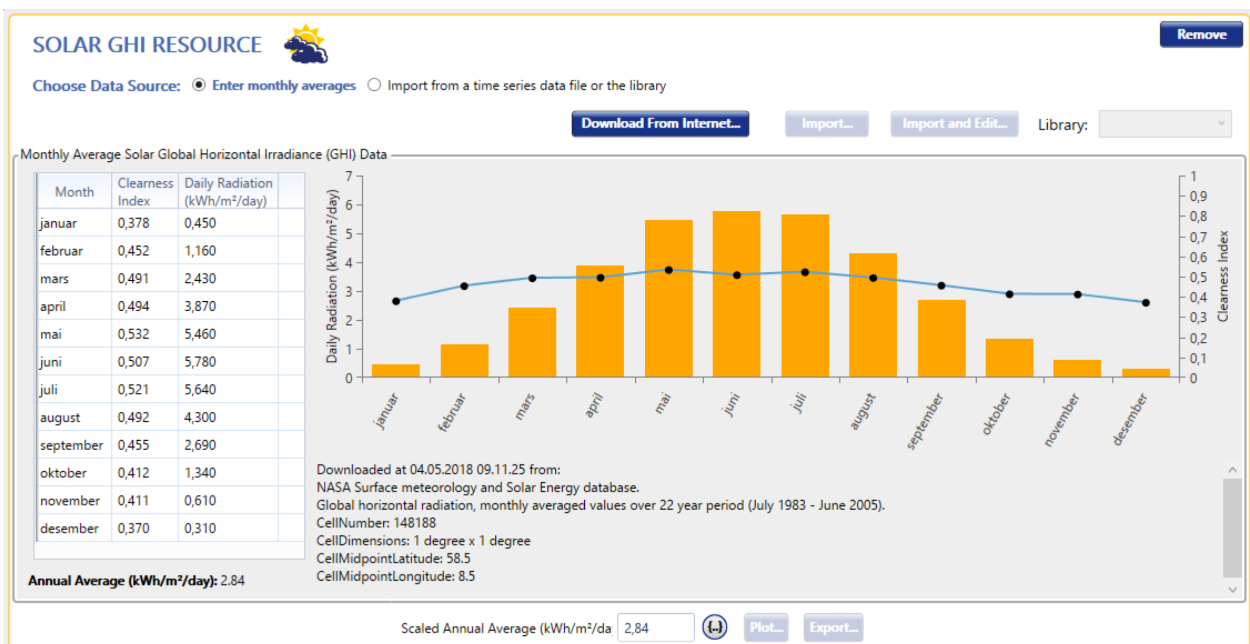

Figure A.63: Annual solar global horizontal irradiance Linnheia

B Homer Energy Data

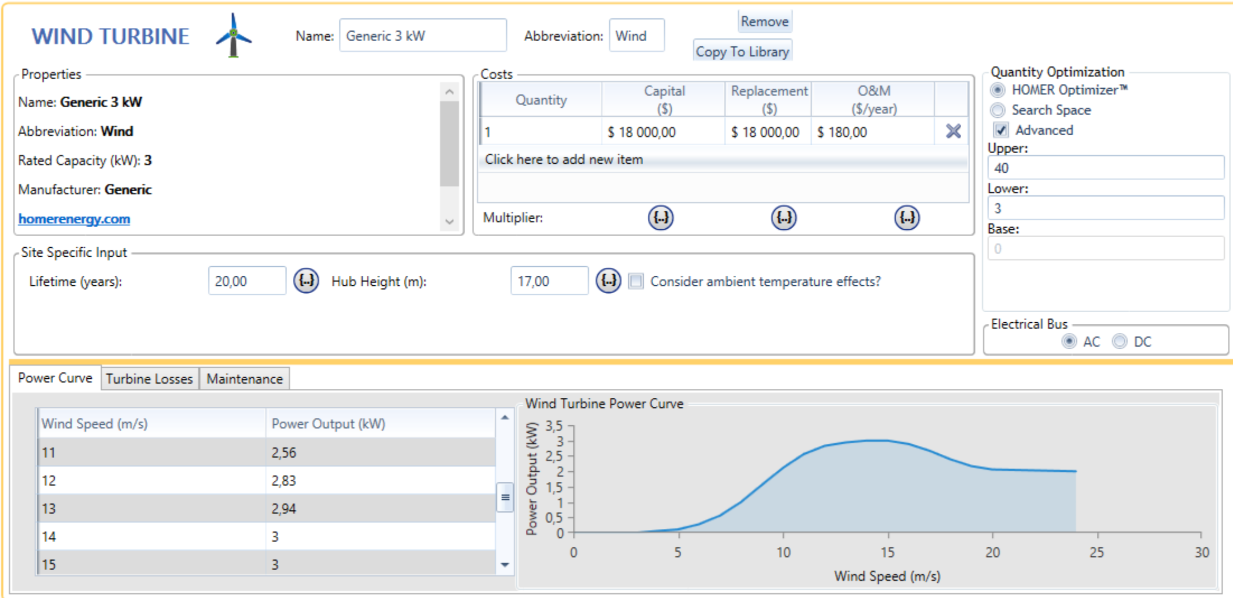

Figure B.64: Data 3kW wind turbine

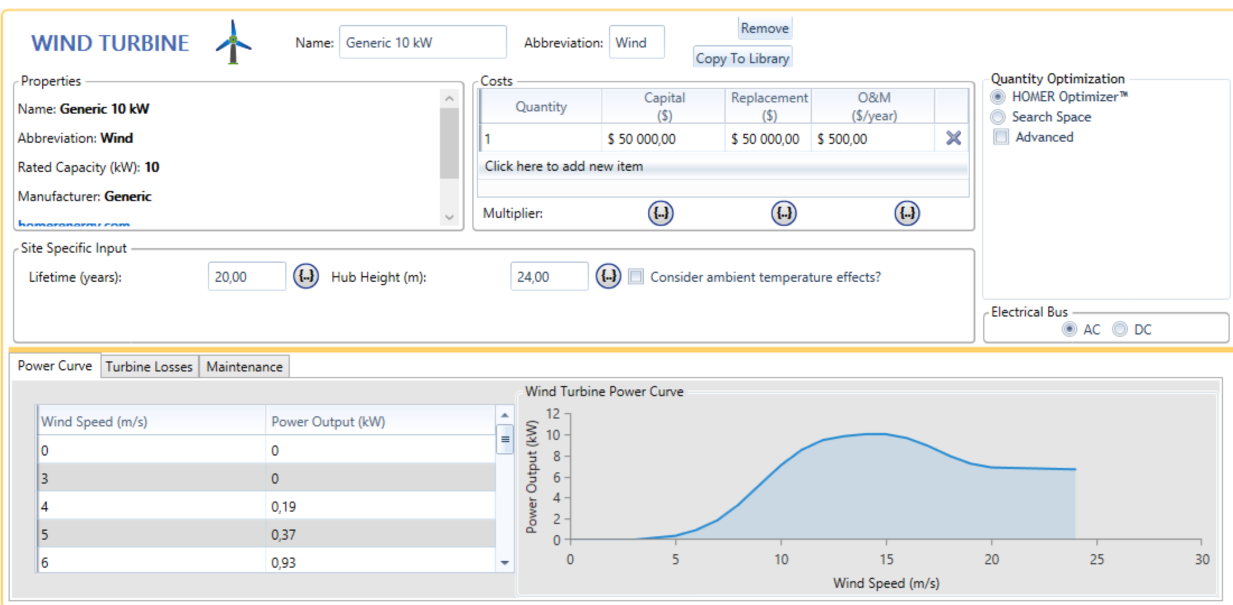

Figure B.65: Data 10kW wind turbine

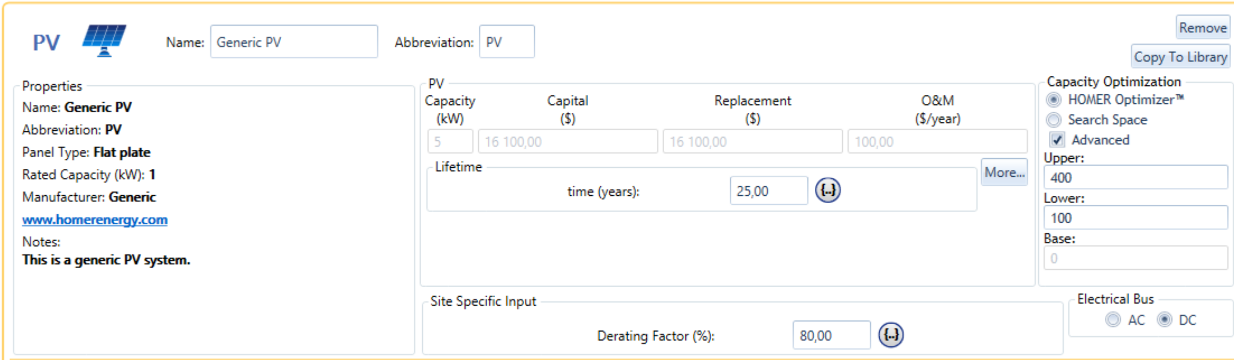

Figure B.66: Data PV system

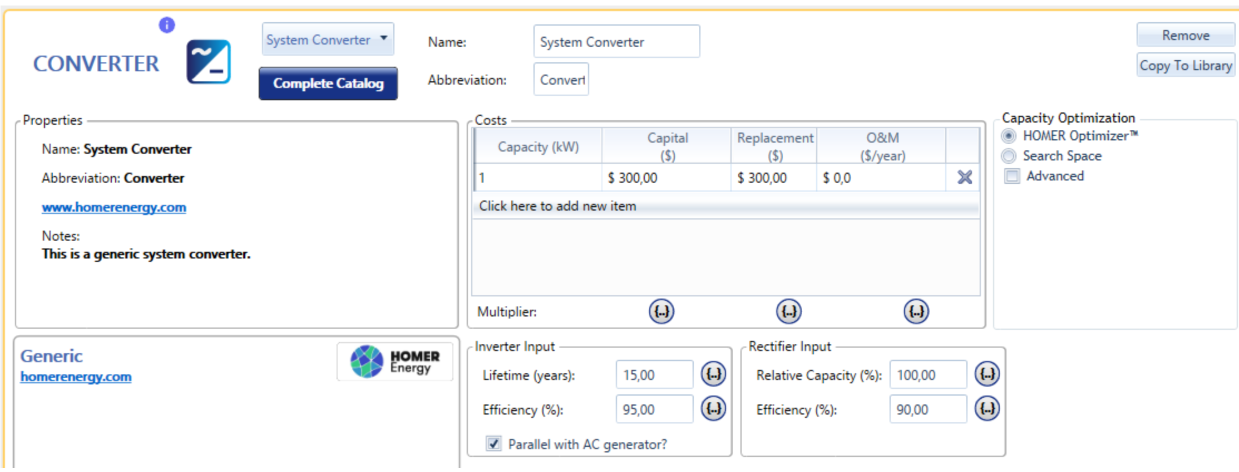

Figure B.67: Data converter

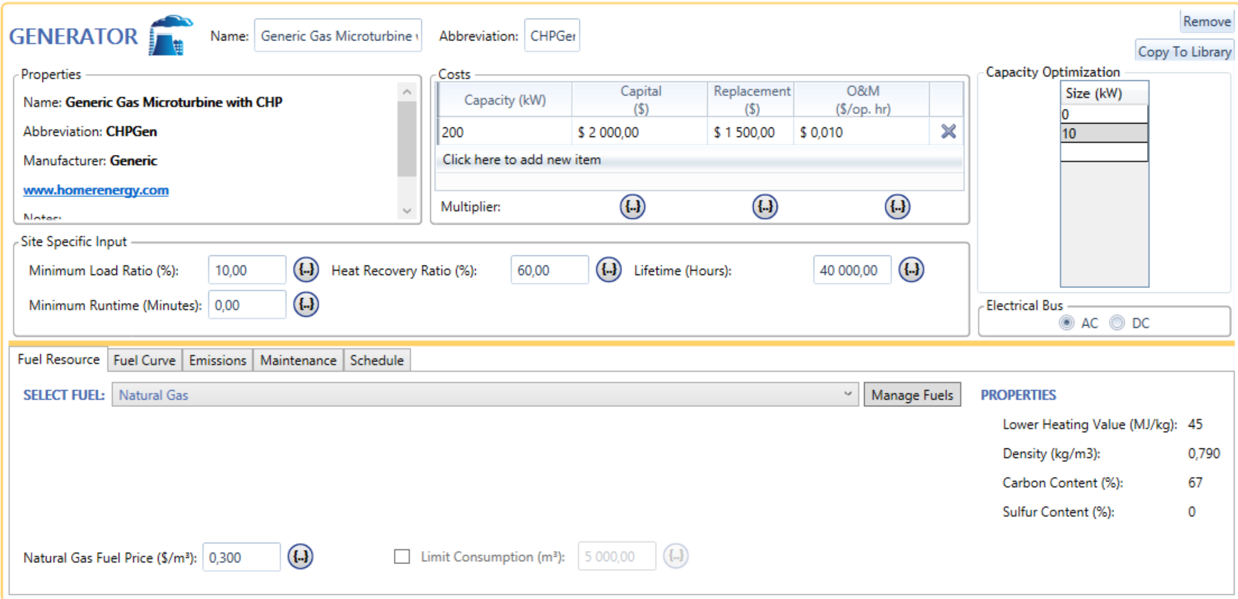

Figure B.68: Data CHP micro-gas turbine

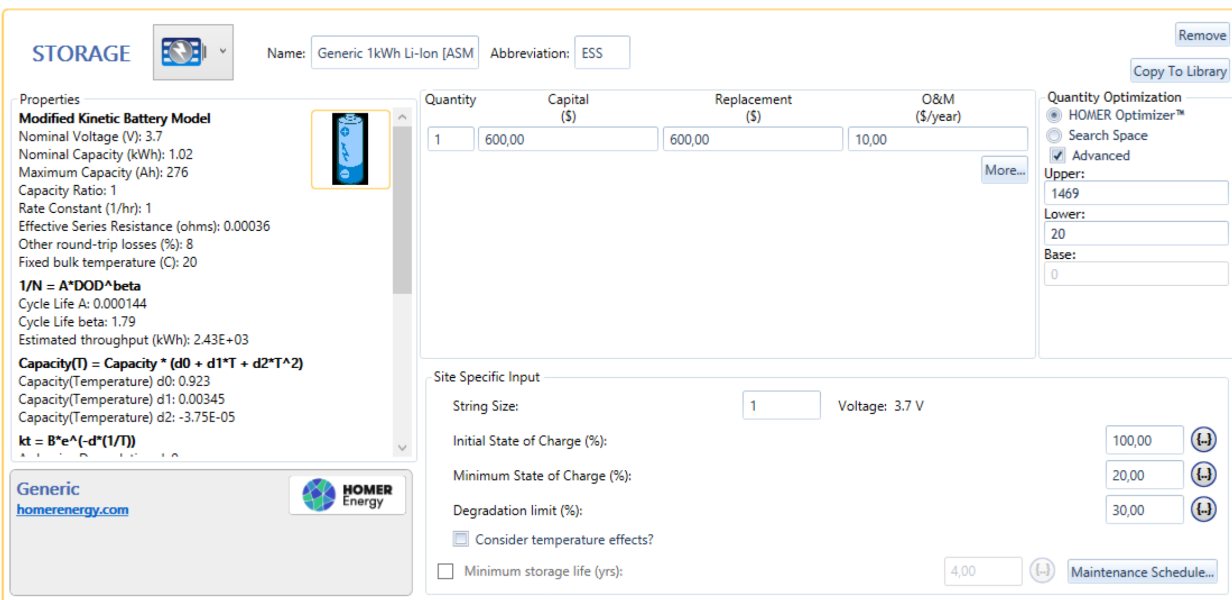

Figure B.69: Data ESS

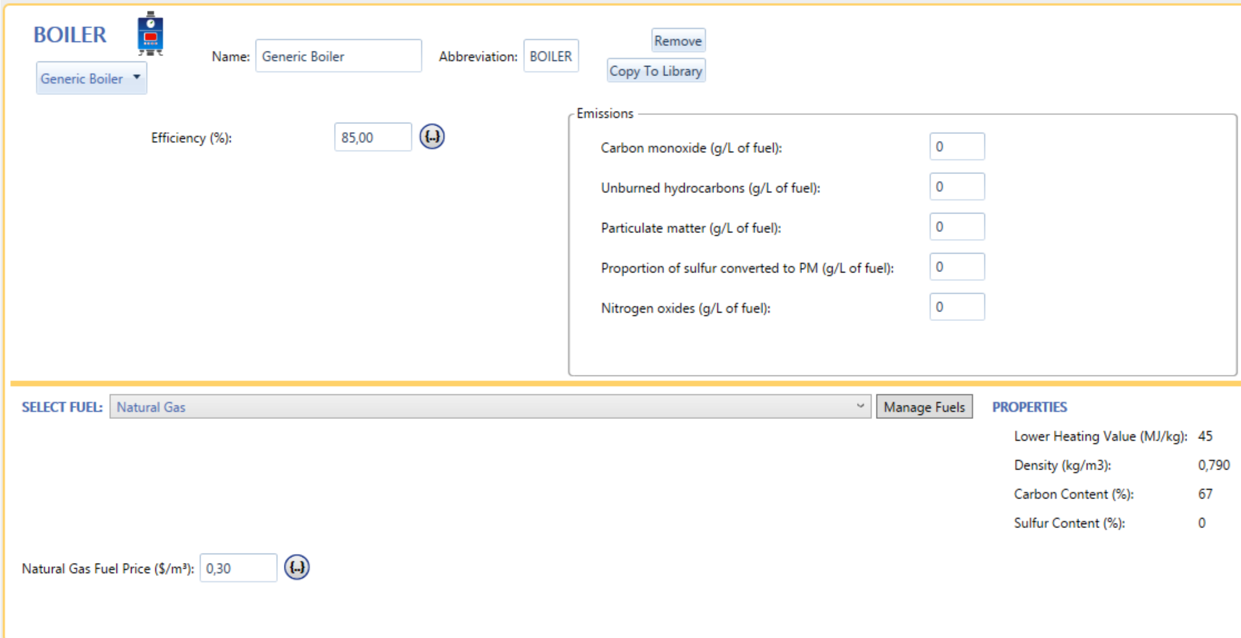

Figure B.70: Data boiler

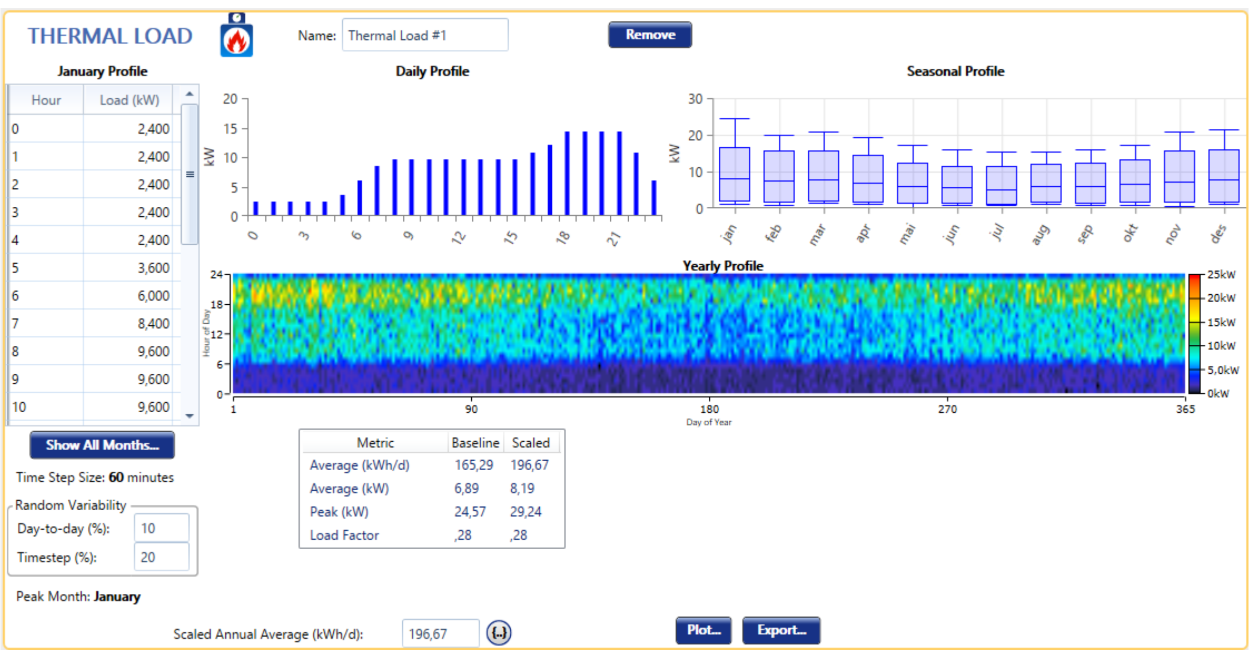

Figure B.71: Data thermal load

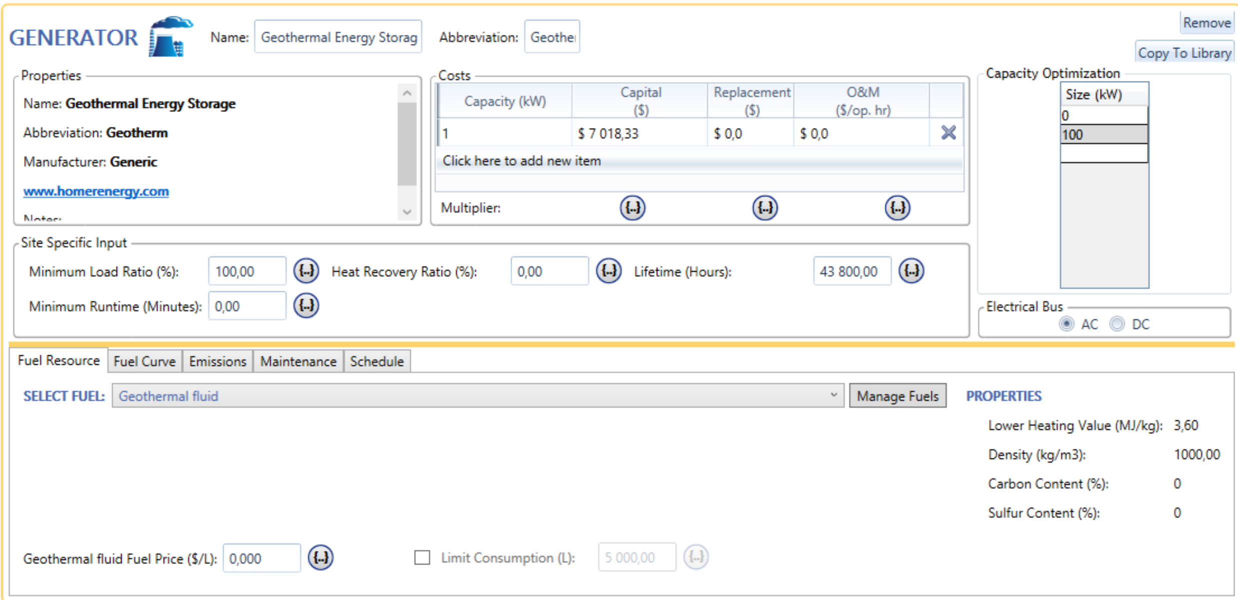

Figure B.72: Data geothermal energy storage

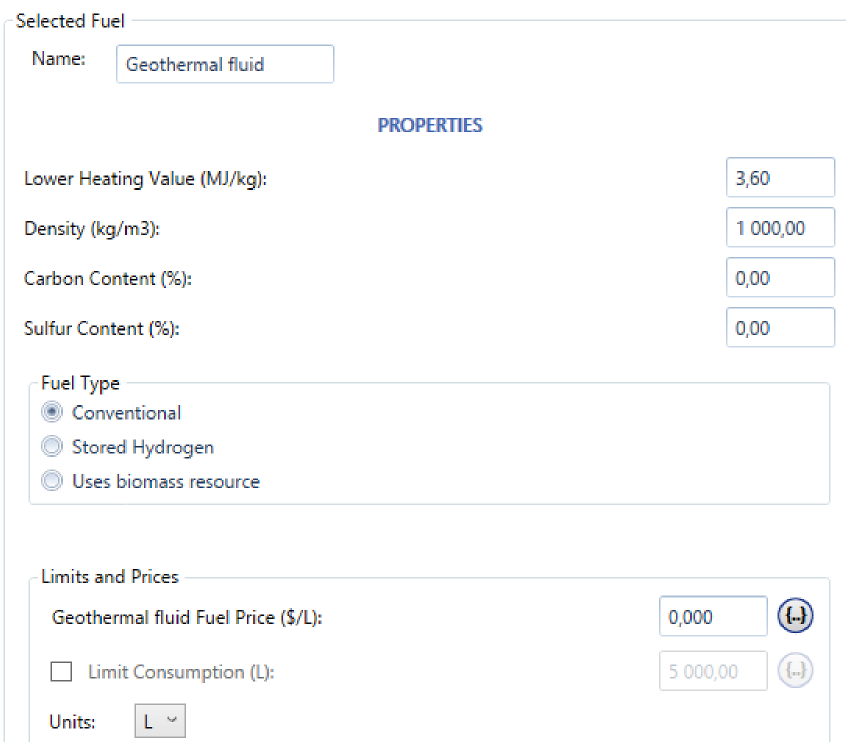

Figure B.73: Data geothermal fluid

C Microgrid Planning Systematic from Sintef

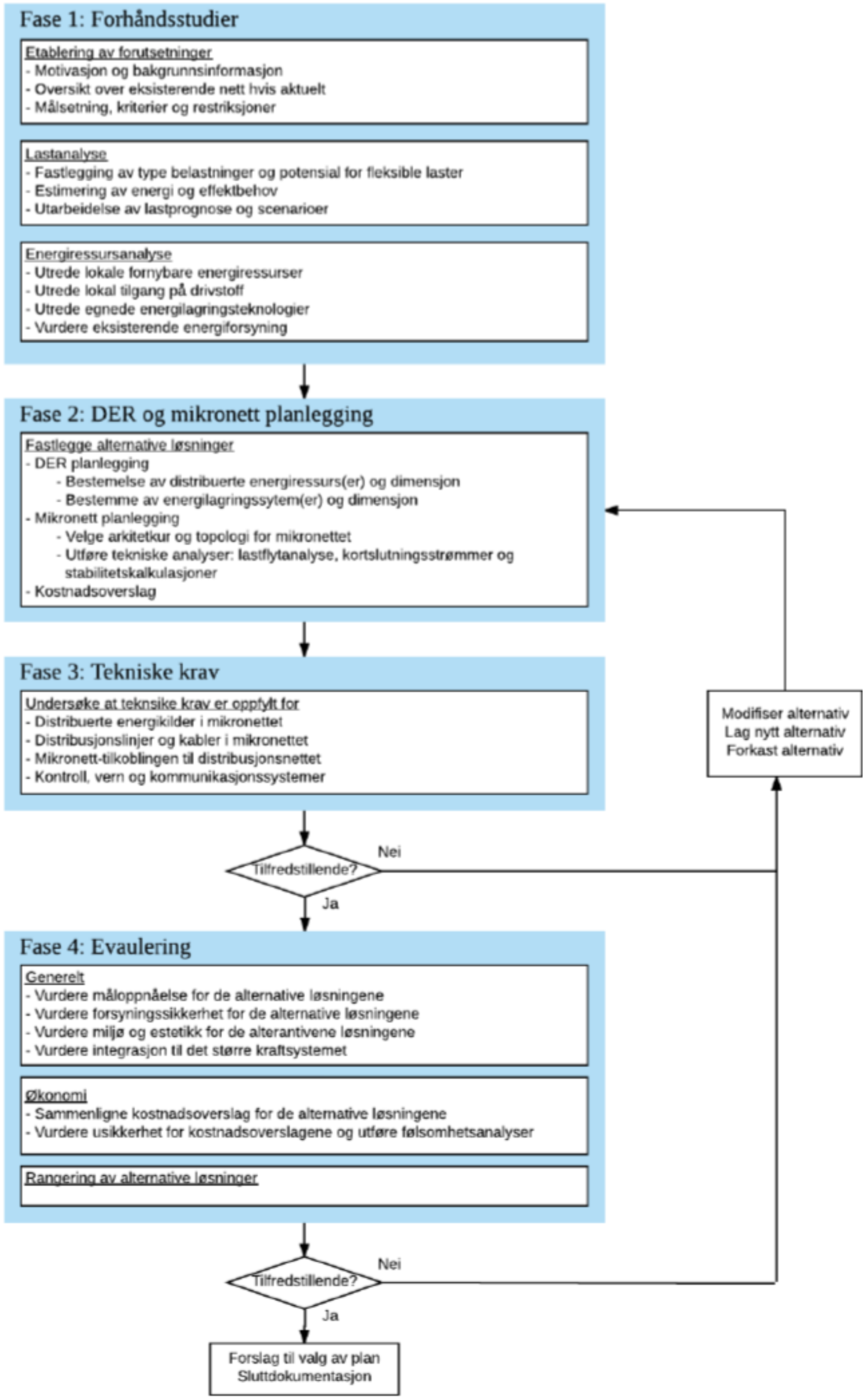

Figure C.74: Microgrid planning systematic [13]

D Planning Map Linnheia Nord

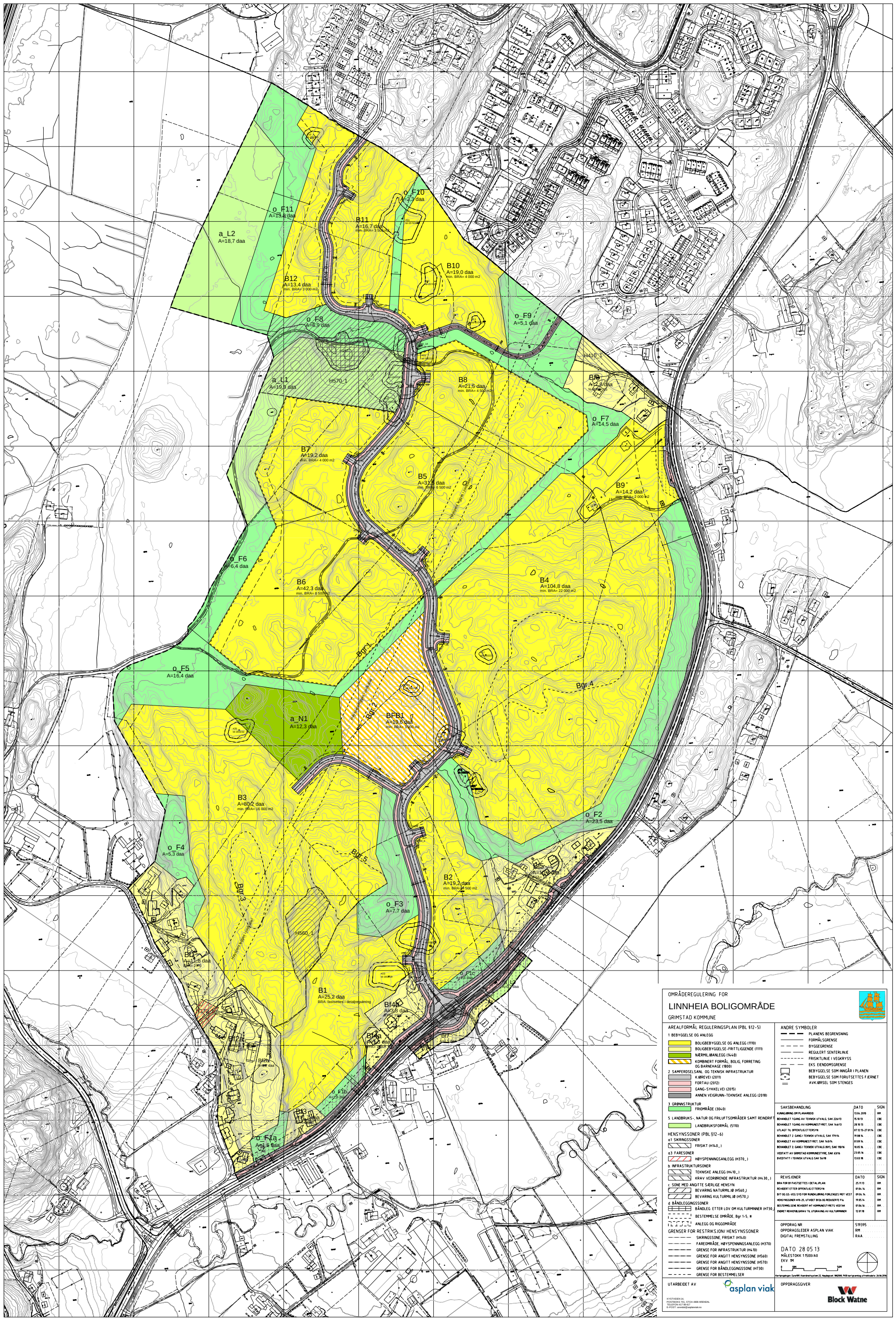

Figure D.75: Planning map Linnheia