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A hybrid wind-diesel stand-alone system for fish farming applications

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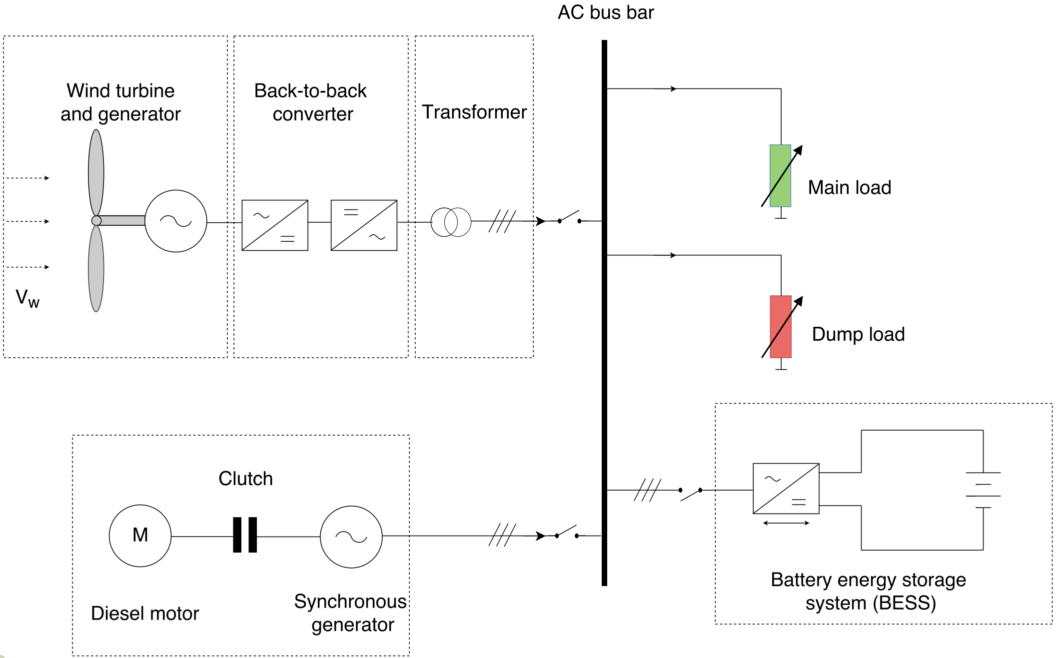

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A hybrid wind-diesel stand-alone system for fish farming applications

Marius Holt

Project thesis

Submission date:	December 2016
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Abstract

Many Norwegian fish farming facilities are located in remote areas along the Norwegian coastline. For these facilities, grid-connection often involves either very high costs or an unacceptably high grid loss. A consequence of this is that diesel generators currently solely power most of the facilities. In order to reduce CO_2 emissions, hence contribute to a more sustainable fish farming industry, it would be desirable to replace as much as possible of the diesel with energy from local renewable sources. A natural solution might be integrating wind power to utilize the excellent wind resources along the coast.

As a starting point, the project provides a clear and perspicuous overview of both the Norwegian fish farming industry and hybrid wind-diesel systems in general – mainly linked to their component technologies. This constitutes the basis for implementing a suitable long-term performance model in MATLAB, which is further used in several simulations. The purpose of the simulations is to give the reader an intuitive feeling on the different components' impact on system performance.

A wind profile is obtained from long time series between 1994 and 2014, with actual wind data collected at a measuring site close to the proposed location. The consumption profile has been made from scratch and consists of one deterministic and one stochastic part, in order to reflect a realistic load pattern. Together, these prognoses have been utilized to analyse system behaviour for each half-hour during one year.

The main results show that the yearly diesel fuel can be reduced from 170 000 litres/year to about 25 000 litres/year, solely by including a wind turbine together with the diesel generators. This implies a reduction in diesel fuel purchase cost of more than 1.5 million NOK. Including a battery will reduce the diesel fuel further, and thus increase the renewable penetration of the system. However, including a storage element involves a substantial cost. Lastly, it is seen tha the dump load should be able to consume about the same power as the wind turbine rating, in order to utilize the available energy as much as possible.

Acknowledgements

I would like to thank my supervisor, professor Kjetil Uhlen for great counselling and valuable advices throughout the semester. Your expertise and availability is highly appreciated. Further, a special thank you is aimed to my external contact, Pål Preede Revheim at NVES. He has provided me with all the necessary information, and then some. This project would not have been possible without your excellent help and fast responses.

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Glossary

NVES	✣	Nasjonalt Vindenergisenter Smøla
WFF	✣	Welfare Fish Farming
TN-S	✣	Terra-Neutral Split
PE	✣	Protective Earth (conductor)
N	✣	Neutral (conductor)
PV	✣	Photovoltaic
WT	✣	Wind turbine
HAWT	✣	Horizontal Axis Wind Turbine
DFIG	✣	Doubly-fed Induction Generator
DA	✣	Diesel aggregate
DE	✣	Diesel engine
DG	✣	Diesel generator
BESS	✣	Battery Energy Storage System
DoD	✣	Depth of Discharge
SOC	✣	State of Charge
VRLA	✣	Valve-regulated lead-acid
AGM	✣	Absorbed glass matrix
NiCd	✣	Nickel cadmium
NiMH	✣	Nickel metal hydride

VRFB	✣	Vanadium redox flow battery
MOSFET	✣	Metal Oxide Semiconductor Field-Effect Transistor
IGBT	✣	Insulated Gate Bipolar Transistor
DC	✣	Direct current
AC	✣	Alternating current
PWM	✣	Pulse-width modulation
VSC	✣	Voltage source converter
RSC	✣	Rotor side converter
GSC	✣	Grid side converter
WO	✣	Wind Only
DO	✣	Diesel Only
WD	✣	Wind-Diesel
BC	✣	Base Case

Nomenclature

P_{WT}	✣	Wind turbine power [kW]
ρ	✣	Air density [kg/m^3]
A	✣	Area swept by rotor blades [m^2]
C_p	✣	Power coefficient
λ	✣	Tip-speed ratio
β	✣	Pitching angle [°]
V_W	✣	Wind speed [m/s]
ωr	✣	Rotor rotational speed [rad/s]
R	✣	Rotor blade radius [m]
n_m	✣	Turbine generator rotational speed [rpm]
f_s	✣	System frequency [Hz]
P	✣	Number of poles in the generator stator
D_f	✣	Diesel fuel [l/hr]
A	✣	First diesel fuel constant [l/kWh]
B	✣	Second diesel fuel constant [l/kWh]
P_D	✣	Diesel generator power [kW]
$P_{D,nom}$	✣	Diesel engine nominal power [kW]
c	✣	Weibull scale factor
k	✣	Weibull shape factor

P_{CONV}	✣	Battery converter power [kW]
P_{LOAD}	✣	Main load power [kW]
P_{DUMP}	✣	Dump load power [kW]
V_B	✣	Battery nominal voltage [V]
A_B	✣	Battery current capacity [Ah]
DoD	✣	Battery depth of discharge
$W_{B,max}$	✣	Maximum battery state of charge [kWh]
$W_{B,min}$	✣	Minimum battery state of charge [kWh]
$P_{B,max}$	✣	Maximum power to/from battery [kW]
$P_{CONV,max}$	✣	Maximum battery through converter [kW]
$P_{DUMP,max}$	✣	Maximum limit for dump load [kW]
$P_{DUMP,min}$	✣	Minimum limit for dump load [kW]

1 | Introduction

1.1 Background and objective

Many Norwegian fish farming facilities are located in remote areas along the Norwegian coastline. For these facilities, grid-connection often involves either very high investment costs or an unacceptably high grid loss. A consequence of this is that diesel fueled generators currently power most of the facilities, as they are considered both robust and accessible. The diesel engines are also flexible in response to a variable demand. However, they are often over-dimensioned to meet the peak demand. This results in long periods where the engines are operated at low output power compared to nominal power, thus yielding high CO_2 emissions and a very low efficiency. Another drawback with diesel engines is the constant need for importation of diesel fuel, which is both expensive and a possible threat to the fragile surrounding ecosystem, if not handled properly.

In order to reduce CO_2 emissions, hence contribute to a more sustainable fish farming industry, it would be desirable to replace as much as possible of the diesel with energy from local renewable sources. A natural solution might be integrating wind power to utilize the excellent wind resources along the coast.

An initiative actuated by Pure Farming AS named «Welfare Fish Farming» (WFF), in cooperation with the Norwegian Wind Energy Center AS (NVES) aims to facilitate environmentally friendly fish farming through a new concept of fish farming. A core part of this concept is a wind-diesel-battery hybrid energy system.

The main purpose of this study is to shed some light on the possibilities of implementing such a hybrid system solution to an intended fish farming fleet. A special focus is given to the system components in order to gain a more extensive understanding of the important working principles. Furthermore, the components' influence on the renewable penetration - particularly how diesel fuel consumption can be reduced - is also discussed.

1.2 Scope of work

The workings of this project are confined to an introduction to hybrid wind-diesel systems, mainly linked to its components and their impact on the system performance. Based on historical wind data and a predicted consumption profile, various compositions of component types and sizes are investigated. A few simulations have been carried out using self-made MATLAB scripts. These scripts describes the system control logic on a steady-state basis. This implies analyses of diesel fuel consumption and which components that are delivering or consuming power for each half-hour during one year.

In order to not gap too wide economical analyses have been omitted in this project. This might be of interest in the successive master thesis, together with dynamic simulations. Other aspects that could be further inspected are discussed in section 6.1 «Shortcomings and further work».

1.3 Project outline

The structure of this thesis aims to present the motivation, theoretical background and working principles of a hybrid wind-diesel-battery system in a clear and perspicuous way. Another goal is to explain the technical terms on a basic level, so that little or no previous knowledge of subjects presented is needed to extract the essence.

Chapter 2, *The Norwegian fish farming industry*, gives an introduction to the Norwegian fish farming industry. Here key features of the industry today, development possibilities and challenges are discussed.

Chapter 3, *Hybrid wind-diesel systems*, describes possible hybrid system topologies. It goes thoroughly through each of the system's components and their features.

Chapter 4, *System modelling in MATLAB®*, presents the procedure of modelling each component in MATLAB, together with a control strategy for the system.

Chapter 5, *Case study results*, constitutes of the results from sensitivity analysis and other special cases.

Chapter 6, *Conclusions*, summarises the main features of this project thesis.

2 | The Norwegian fish farming industry

2.1 A typical offshore fish farm

Norway has an long coastline which spans over more than 100 000 km in total [8], bringing with it many excellent locations for offshore fish farming. As seen from Figure 2.1, a lot of these locations are already being exploited.

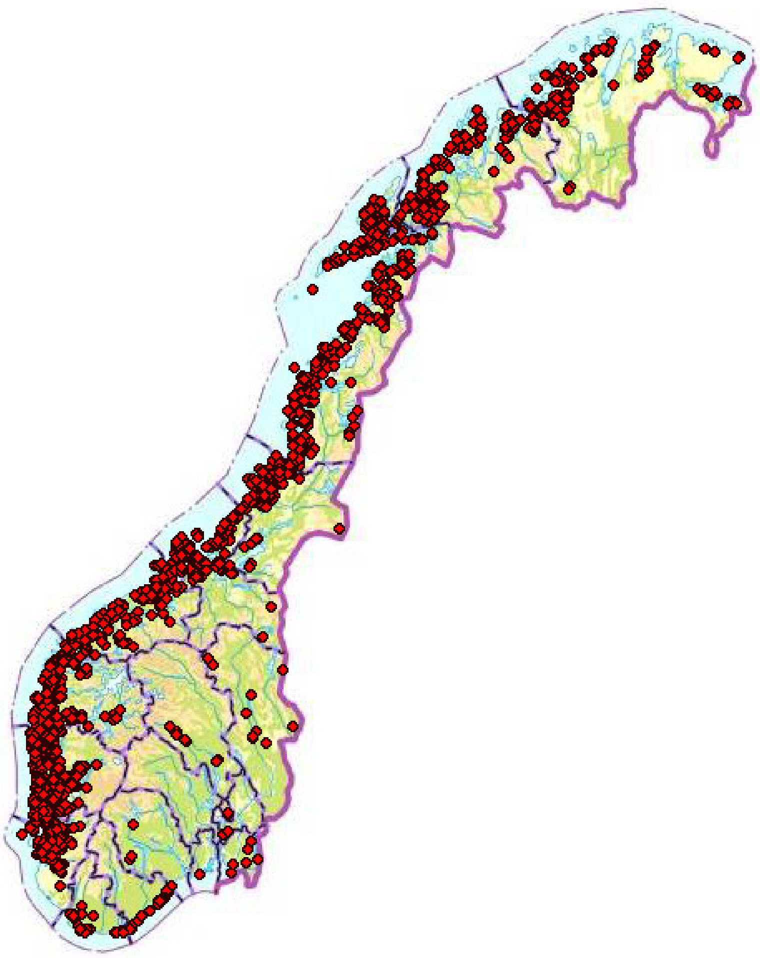


Figure 2.1: Map with locations of Norwegian aquaculture [1]

To get a better understanding of these farms, a conceptual contemplation of a typical offshore fish farm layout is carried out in this section. Looking from the outside, the most conspicuous features of a fish farm are the feed barge and the surrounding sea pens of which the barge is connected to, as seen from Figure 2.2.

In rough terms, the feed barge consists of a control system, working facilities for the employees, a machine room for the diesel engines and feeder blowers, and storage solutions for feedstock (silos) and diesel fuel. It is the base station for the fish farm's employees. From the sea barge, feed lines stretches out to each of the cages. These cages are typically made of steel or plastic, depending on the surrounding environment and application. It should be clarified that the terms «sea pen» and «cages» are used interchangeably, but they are the same.

The plastic cages are usually circular and can be up to approximately 200 m in diameter. They can either be placed separately from each other - and thus be accessed by boat - or clustered together with bridges between them. The steel cages on the other hand are usually rectangular and situated together in a grid as shown in Figure 2.2. They have a walkway between them which makes them easy to inspect. Irrespective of the cage material, each cage has a net connected to it. This is the only barrier which keeps the fish inside, thus their robustness plays a crucial role in preventing fish from escape. The sea pens are also equipped with lightning modules, which are used at nighttime to simulate daylight and by this stimulate of growth.

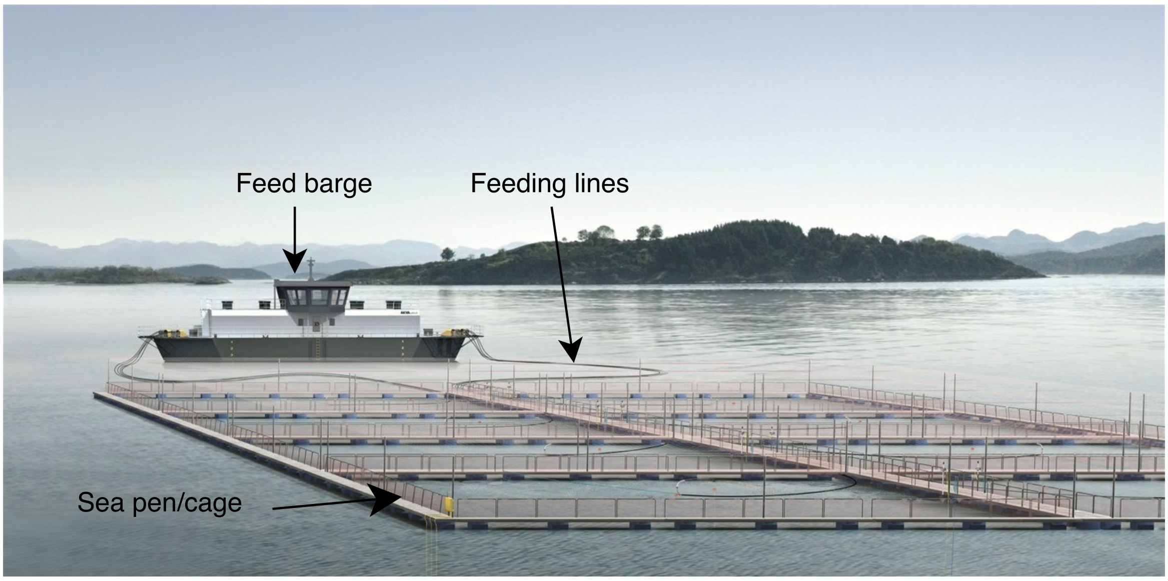


Figure 2.2: Typical offshore fish farm layout [2]

One of the main features inside the barge is the feeding system. This consists of several components to make sure that the fish gets the right amount of food at the right time. It starts with the electrically driven feed blowers, which provides the desired air flow speed in the feeding pipes. These blowers are normally three phase electrical motors, running at a nominal voltage of 400 V. Situated after these blowers there are dosage regulators to ensure that the right amount of feed from the silos are fed into the pipes. If there are several sea pens on the fleet that needs supply of food, selective valves can be installed after the dosage regulators to disperse the pellets. All of these features are normally situated at the feed barge. Stretching out from the barge, there are feeding pipes leading to each of the sea pens. At the end of each pipe a spreader is connected. This is usually a curved metallic tube situated in the middle of the sea pen that rotates with a flexible speed and spreads the feed evenly within the pen.

2.2 The industry today

Aquaculture plays an important role in the Norwegian industry. In 2015 Norwegian aquaculture had an export value of approximately 47 billion Norwegian Crowns [3], which makes Norway the second largest exporter of fish products in the world after China [9]. Each day products from Norwegian aquaculture industry constitutes millions of meals all over the world, and the demand is continuously growing. Export of Atlantic salmon and rainbow trout are by far the most dominant in Norway, but also mackerel, halibut, cod, common mussel and other mollusc are being bred.

2.2.1 Key statistics and trends

As seen from Figure 2.3, the growth in both income and tonnes exported have been rather extreme the the last ten years, contributing to new employment and improved infrastructure in many coastal communities. The total number of 6727 employees in the industry (per June 2015) has almost been doubled from 2005, and solely from 2014 to 2015 it increased by nearly 500 [10]. The main reasons for this radical growth can be explained by an increasing world population combined with a highly successful marketing strategy from Norway - especially to Japan where Norwegian salmon are commonly used in sushi. Most of the Norwegian fish is exported within the European Union, but new vast market opportunities are emerging i.e. in India [11]. One result of the boom in demand is increased development and research on the biological impacts on the fish. Norway is one of the world leading countries, within this field. Research on farming new species are also emerging.

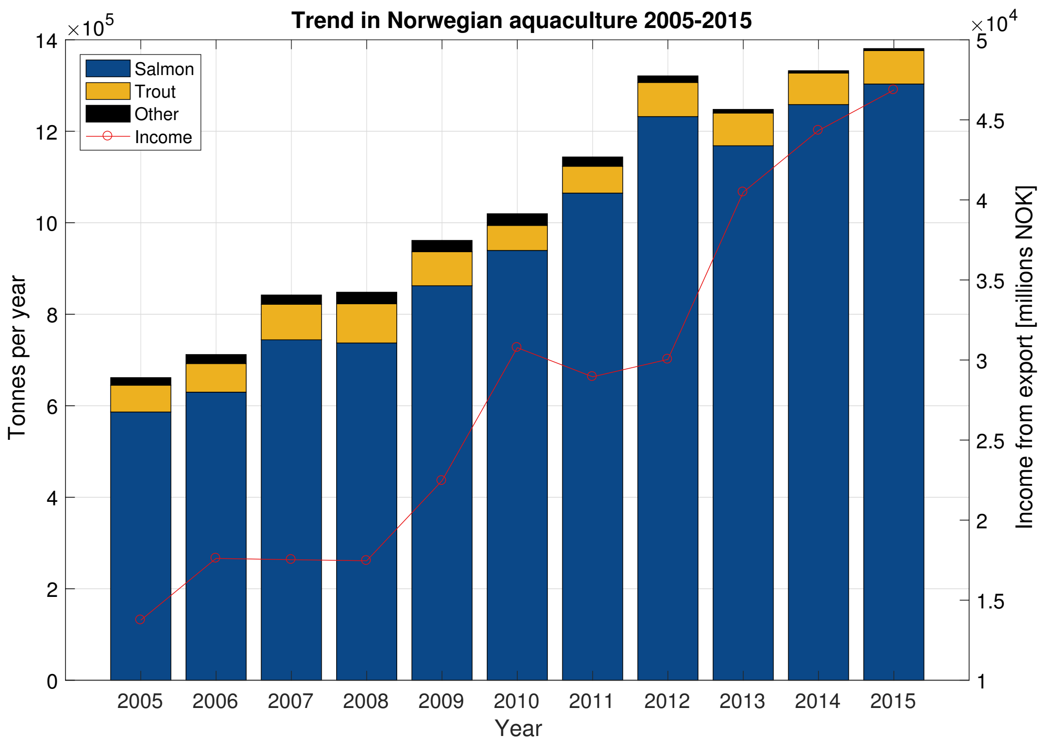


Figure 2.3: Trends in export of Norwegian aquaculture, based on [3]

2.3 Challenges

Another result of the growth in the industry is the need for improved knowledge on the environmental impacts of aquaculture, in order to secure both fish health and surrounding environmental sustainability. One of the major challenges in the industry today is the problem with sea lice [12]. This is a naturally existing parasite that has been present in the ecosystem for as long as we know. Clusters of lice clings to the fish and starts eating. This causes infections and open wounds, distorting the fish's salt balance which ultimately may kill it. Even though this is a naturally occurring parasite, the introduction of aquaculture industry has increased the total number of salmon in the maritime environment by many times the naturally occurring wild salmon. This makes the number of possible lice carriers much higher.

Several different treatments are used. Amongst those, one possibility is fallowing of the farm which involves that after the fish is killed, several weeks should pass before new fish is installed in the cages. Another treatment is usage of wrasse. This is a fish that eats the lice and can be placed in the cages. Removing the lice by using high pressure washers is also possible. Several other treatments are also in use. [13],[14]

Other challenges the industry faces includes escaping of farmed fish and excessive biological waste for the bottom fauna to handle. A survey performed by the Office of the Auditor General in Norway from 2012 [15], shows that escaped farmed fish can pose a significant environmental threat through genetic interaction with wild fish, and that this may affect the wild fish's ability of survival. The production of farmed fish emit organic matter, nutrients and chemicals. The survey [15] concludes with the following: «Both the industry itself and the management has major challenges that must be solved and it is difficult to envisage any radical growth in Norwegian aquaculture before challenge and others point to is resolved».

2.4 The proposed fish farm

The fish farm to be discussed and analyzed in this project does not exist at present, but it's design and structure is mainly similar to conventional offshore fish farms, explained in the previous sections. The location of the proposed farm is at the North-Western coast of Norway, close to Smøla, as depicted in Figure 2.5. This geographical area has excellent wind conditions, making it ideal for hybrid wind-diesel purposes. Concerning size, a total number of six feed blowers should supply 12 sea pens. Furthermore, the fleet's yearly energy consumption is expected to be around 470 000 kWh [16].

The electrical system of the fleet is a TN-S configuration, shown in Figure 2.4. TN-S stands for «Terra Neutral-Split» implying that the protective earth conductor (PE) and the neutral wire (N) are separated. In such a configuration the line-to-line voltage is 400 V, while the voltage between one phase and the neutral is 230 V. This makes it possible to connect both single-phase loads (230 V) and three phase loads (400 V line-to-line) to the network. Examples of single phase loads may be heating and lightning of the barge, while three phase loads can be the feed blowers.

A thorough explanation of the fleet's consumption profile is found in section 4.3.

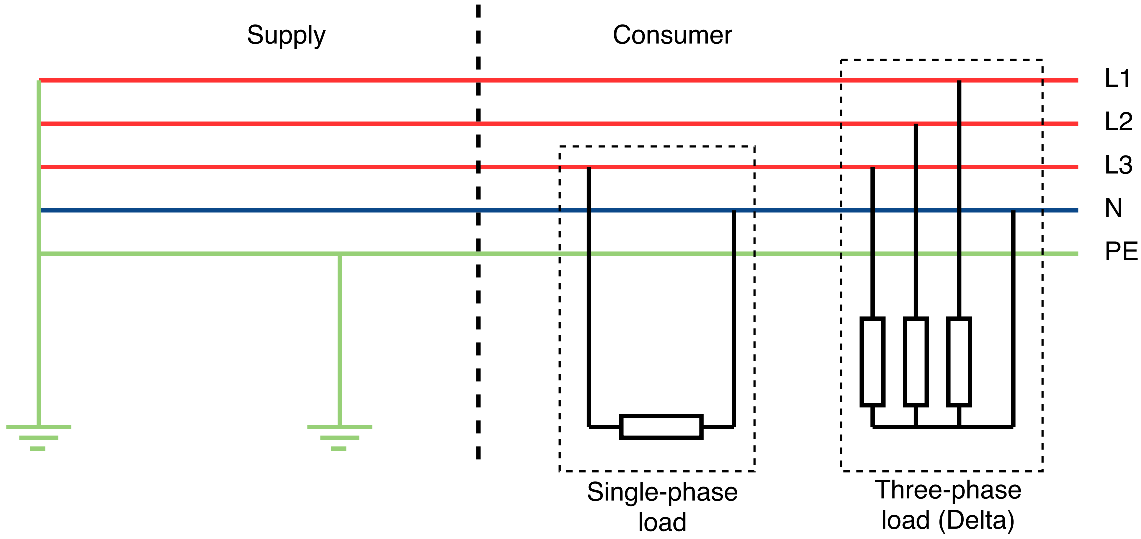


Figure 2.4: TN-S configuration schematic

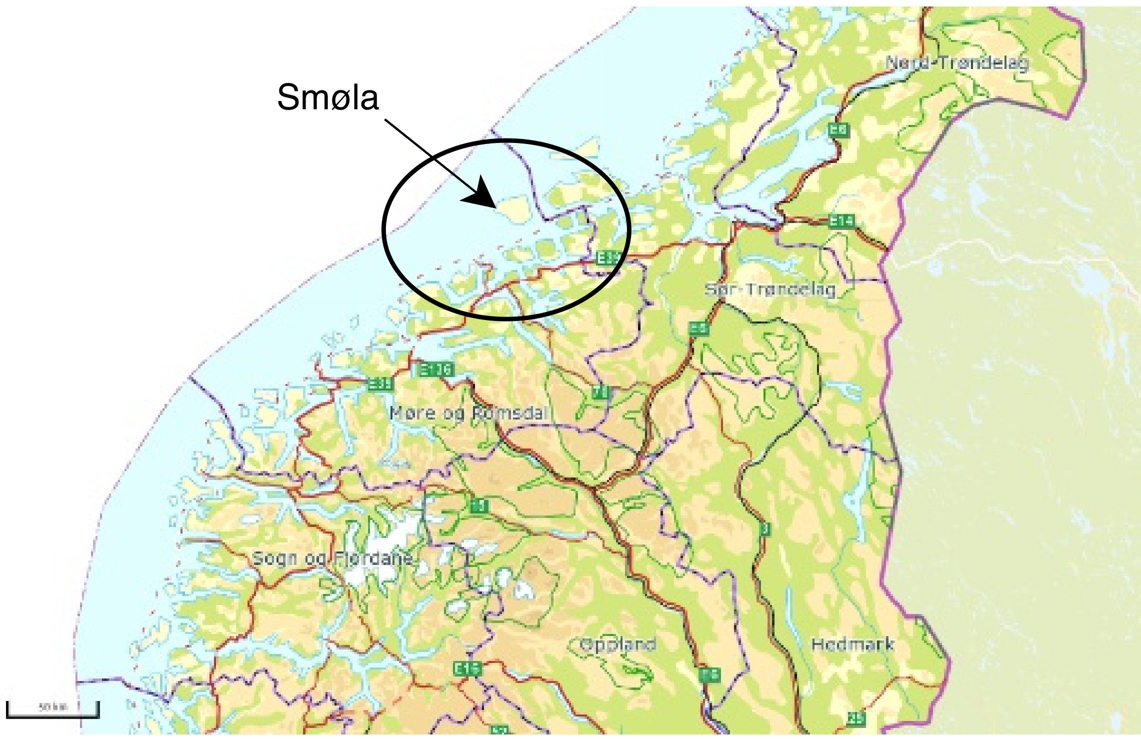


Figure 2.5: The proposed fish farm location

3 | Hybrid wind-diesel systems

3.1 Hybrid systems in general

Hybrid systems are often used in rural areas or islands where connection to a grid is found to be either uneconomical or involves unacceptably high grid losses to carry out. As a consequence, most of these areas are powered solely by diesel aggregates.

The hybrid system utilizes local renewable energy sources in combination with existing diesel aggregates in order to supply an electric load. The main purpose of this is to reduce emissions and cost of diesel fuel.

There are several different hybrid system topologies existing today. Examples can be wind energy and diesel together (wind-diesel), solar energy from photovoltaic cells (PV) and diesel (PV-diesel) or both of them together with diesel (wind-PV-diesel). Regardless of which renewable combination that are used, most of the hybrid systems have in common that they incorporate an energy storing system. Examples of energy storage can be batteries, flywheels, large capacitors and compressed air.

The reason for this is based on the intermittent nature of wind and solar power. Therefore it would be undesirable to implement a system solely based on wind energy and diesel aggregates (DA), as this will lead to a small renewable penetration[1]. Another problem this brings with it is the undesirable way of operating the DAs. Wind and sun conditions are hard to predict, thus unforeseen shortfall of the renewable resources leads to frequent and aperiodic starting- and stopping of the DAs. This way of operating them causes increased wear and tear which ultimately reduces their lifetime. The energy storing unit can smooth these mismatches between renewable generation and load. Hence, starting and stopping of the DAs can be optimized with respect to wear and tear and cost.

[1]Renewable penetration: How much of the load is covered by renewable sources

3.2 The hybrid wind-diesel system for fish farming applications

The hybrid system discussed in this project is a wind-diesel topology with a battery as the storage unit. The reason for using wind energy is based on the excellent wind resources that is present along the Norwegian coast. The choice of using battery as energy storage, is linked to it's scalability regarding energy capacity, good efficiency and affordability. Batteries are applicable for both long-term and short-term, making them ideal for use in small-scale electrical grids with renewable penetration. Improved focus on research and development of new battery technology, has led to higher competition in the market and also reduction in cost.

A simplified single-line diagram of the proposed system is shown in Figure 3.1. In the next sections, an introduction to the different components of the studied system are given. This is done to give the reader a more extensive understanding of the system's working principles.

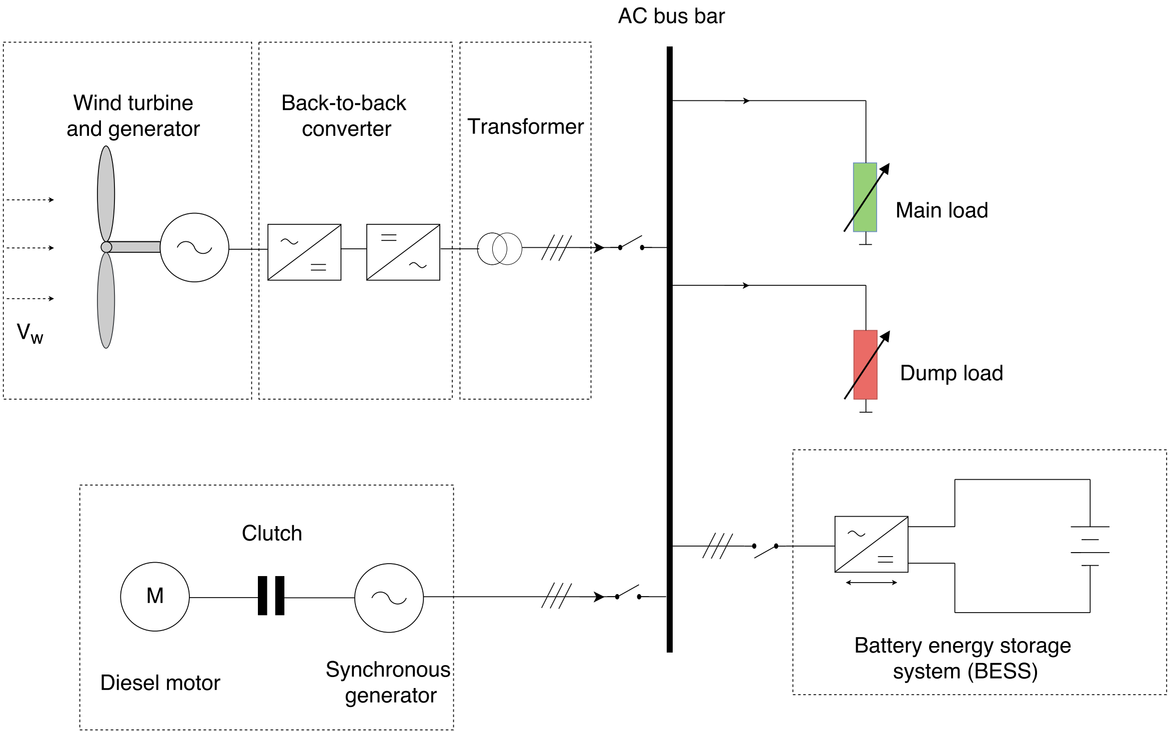


Figure 3.1: Simple schematic of the system layout

3.3 System components

3.3.1 Wind turbine (WT)

The type of turbine investigated in this project, and also the most common wind turbine design today, is the three bladed horizontal axis wind turbine (HAWT) [17]. In this kind of turbine the axis of rotation is parallel to the ground. There are several reasons why three blades are the most used [18]:

- From an aerodynamic perspective, the efficiency of using more than three blades is minimal
- Three blades gives a symmetrical moment of inertia
- More blades yields increased component costs
- Three blades are often considered more aesthetic than one and two bladed turbines

In order to get an overview of the main working principles of the wind turbine, it is important to define some terms. *Cut-in speed* and *cut-out speed* are such terms that is unavoidable when studying a wind turbine. Cut-in speed describes the minimum wind speed that has to occur before the wind turbine starts to operate. This can typically be 2-4 m/s. On the other hand, cut-out speed denotes the maximum wind speed that can occur before the the turbine will stop producing. The turbine is shut down at too high wind speeds to prevent structural damage due to high mechanical stress.

Other important aspects that have to be mentioned is *pitch control* and *stall control* of the turbine. Both these are mechanisms present to control the output power of the turbine.

Pitch control is an active form of control which involves rotating each of the rotor blades around their longitudinal axis, in order to manipulate the drag, lift and thrust forces acting on the blades. This is the most used form of control in modern wind turbines.

Stall control can either be an active or passive form of control. The active stall control is very similar to the regular pitch control. Turbines that uses passive stall control have rotor blades that are designed such that they prevent laminar flow for too high wind speeds. This implies that for sufficiently high wind speeds, the thrust on the blades will no longer increase anymore, yielding constant rotational speed and nominal output power until the cut-off speed is reached.

A wind turbine's output power can be described by equation (3.1) [19].

$$P_{WT} = \frac{1}{2} \cdot \rho \cdot A \cdot C_p(\lambda, \beta) \cdot V_W^3 \tag{3.1}$$

Here ρ is the air density (normally 1.225 $\frac{\text{kg}}{\text{m}^3}$ at 15°C and sea level [20]), A is the area swept by the rotor blades, C_p is the power coefficient and V_W is the wind speed in m/s. The area swept by the rotor blades can be represented by $A = \pi \cdot R^2$ when is R is the rotor blade radius. The power coefficient describes how much power that actually is extracted from the air to the theoretically maximum power extracted [21]. It is a function of λ and β, where λ denotes the tip-speed ratio and β denotes the pitch angle of the turbine blades.

The tip-speed ratio is further a function of the wind speed, rotor radius and rotational speed of the rotor shaft which is seen from equation (3.2).

$$\lambda = \frac{\omega_r \cdot R}{V_W} \tag{3.2}$$

The power coefficient has a theoretical maximum limit of $C_p \approx 0.593$, called the Betz' limit [21]. However, modern turbines typically have C_p between 0.45-0.5. The aim of discussing these factors is to show that turbine output power can be manipulated in many ways. It also facilitates why variable-speed turbines are desirable. By using a variable-speed turbine it is possible to adjust the rotational speed of the turbine in order to optimize the tip-speed ratio. Further, the power coefficient depends only on the tip-speed ratio (for a give pitch angle) and the turbine output power depends on the power coefficient. Thus by changing the rotational speed, the output power can be adjusted.

The principal features of an onshore HAWT are shown in Figure 3.2. A brief explanation of each feature is also given.

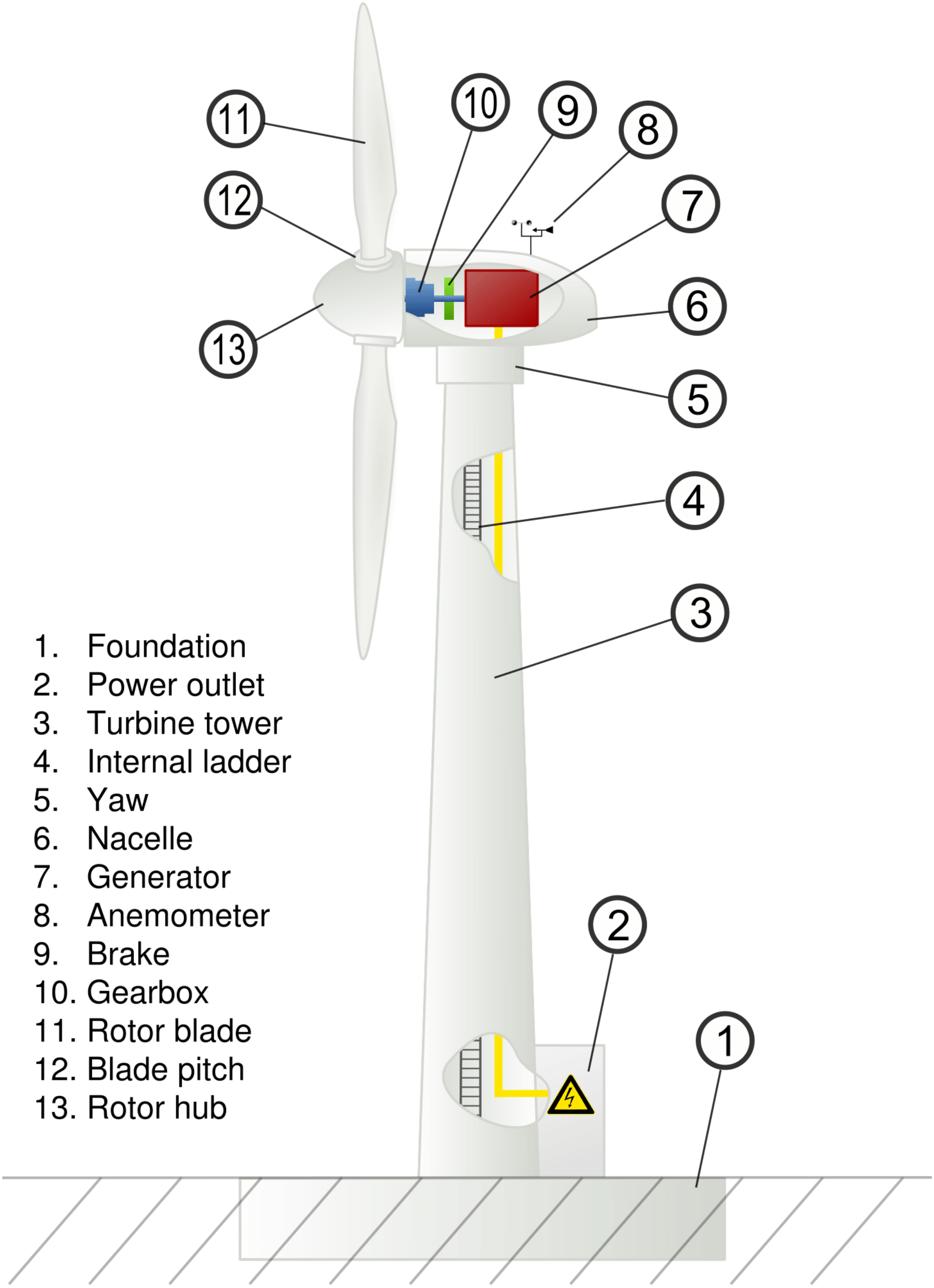


Figure 3.2: Wind turbine schematic [4]

1. **Foundation:** This is most often made of reinforced concrete. The weight of the foundation depends mainly on the hub height. The foundation is the tower's connection point to ground and has to ensure that the turbine stays upright and stable under any conditions.

2. **Electrical power outlet:** The connection point to the electrical grid. Many of the new turbines on the market comes with a back-to-back ac-dc-ac electrical power converter included. This converter can adjust the output voltage and phase angle to ensure the desired turbine output.

3. **Turbine tower:** There are two main types of turbine towers: Shell and lattice. The shell towers are typically made of steel, concrete or a hybrid with both - depending on decision variables such as costs, weight and turbine height.

4. **Internal ladder:** Used for access to the nacelle.

5. **Yaw:** This is an electric or hydraulic drive which makes it possible to rotate the whole nacelle with rotor blades around the vertical axis. Most modern turbines has an electric yaw drive as this removes the problem with hydraulic leaks. The yaw mechanism makes it possible to adjust the output power by changing the angle between the rotor blade sand the incoming wind. If maximum power output is desired they should be perpendicular, as this will maximise the effective blade area.

6. **Nacelle:** The housing of the generator, gearbox, drive train, brake and main bearing.

7. **Generator:** There are four main types of turbine generators according to IEC 61400-27 [22]:

    - Type 1: Asynchronous generator (usually squirrel cage) directly connected to the grid.

    - Type 2: Wounded asynchronous generator with variable rotor resistance directly connected to the grid

    - Type 3: Doubly-fed induction generator (DFIG). This is a wound asynchronous generator, where the rotor is excitated via slip rings and carbon brushes. The rotor circuit is decoupled from th grid through a power electronic converter system.

- Type 4: Full-converter generators. This can be either synchronous or asynchronous generators that are decoupled from the grid by a power electronic converter.

During the last years, most of the new turbines on the market are either Type 3 or Type 4. The reason for this may be that both Type 3 and Type 4 generators facilitates variable-speed operation of the turbine, which is desirable as discussed above.

8. **Anemometer:** Often placed at the top of the nacelle together with a wind vane. The anemometer measures the instantaneous wind speed while the wind vane measures the direction of the incoming wind.

9. **Mechanical brake:** The purpose of the break is to either stop the turbine if the aerodynamic braking fails or prevent the rotor from moving i.e. during maintenance.

10. **Gearbox:** Wind turbines can either have or not have a gearbox. Depending on the size, the turbine blades typically rotates between 20-60 rounds per minute (rpm). Further, most of the generators have only 4-6 poles in the stator while the desired output frequency is around 50 Hz. With so few poles the generator has to rotate much faster than the rotor to acquire the desired output voltage frequency. This is seen from equation, where n_m is the rotational speed of the generator rotor to maintain a turbine output voltage frequency of f_s, with P poles in the stator. E.g. if $f_s = 50$ Hz and $P = 4$ poles, then the generator rotor has to rotate at $n_m = 1500$ rpm. Thus, a turbine generator with few poles will need a gearbox to convert the slow rotation of the rotor to a high-speed shaft driving the generator rotor.

$$n_m = \frac{120 \cdot f_s}{P} \text{ [rpm]} \tag{3.3}$$

However, some turbine manufacturers chooses to avoid the gearbox, by using larger and heavier multipole generators. These are called direct-driven generators. Here the generator rotor rotates at the same speed as the turbine blades. The advantage of this is the increased reliability of supply, as the need of gearbox repair and maintenance of the gearbox is eliminated. Malfunctions in the gearbox have traditionally been the most frequent problem in wind turbines [23].

11. **Rotor blade:** Most of the blades used today are glass fibre reinforced plastic, but other composites such as laminated wood are also tested [21].

12. **Blade pitch bearing:** The connection point of the blades to the pitch drive. The pitch drive are usually electric in modern turbines.

13. **Rotor hub:** This is the connection point of the rotor blades.

3.3.2 Diesel aggregate (DA)

The diesel aggregates in a hybrid system normally consists of diesel engines (DE) connected to synchronous generators (DG) through a mechanical clutch. Thus the term DE will be used for the motor side, DG will be used to the generator side and DA will be used for the whole diesel system. The clutch can either be engaged or disengaged depending on whether the aggregate should produce electrical power or not. When the clutch is engaged, the mechanical shaft of the engine and the alternator's rotor are mechanically coupled, and rotates with the same speed. The frequency of the generator output voltage and current is adjusted by a governor control on the engine. The output voltage, active and reactive power are adjusted by controlling the excitation of the rotor circuit by means of a voltage regulator.

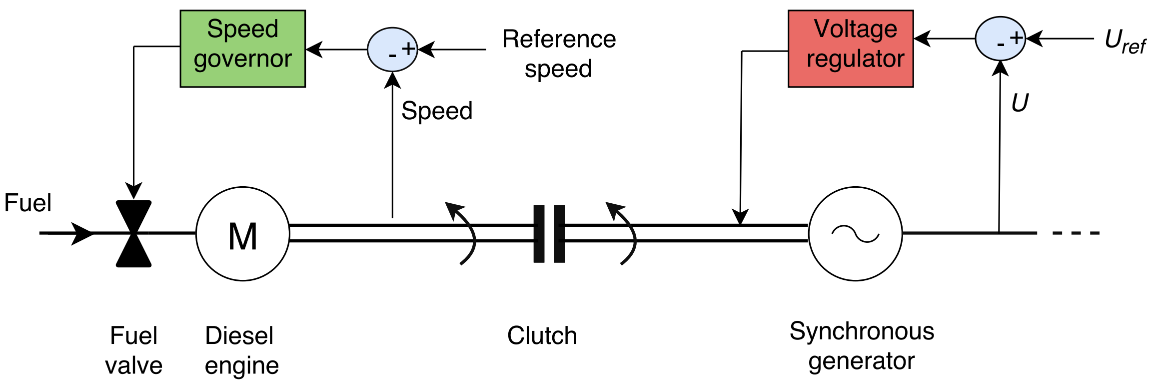


Figure 3.3: Diesel aggregate schematic

If the engines are run at low power compared to their rated power, the efficiency of the machine will be very low. Therefore it is often desirable to use several diesel aggregates with different power rating. E.g. at low load a small generator can operate at decent efficiency instead of a large generator serving the load at a very bad efficiency.

The fuel consumption of a DE (D_f) depends on the output power (P_D) and the engine's nominal power ($P_{D,nom}$), and can be approximated by a simple linear equation [24]:

$$D_f = A \cdot P_D + B \cdot P_{D,nom} \tag{3.4}$$

Here A and B are constants depending on the size and type of DE.

3.3.3 Battery energy storing system (BESS)

The battery energy storage system (BESS) plays a major role in the hybrid system. As wind is an unpredictable source of power, solely using wind-diesel without an energy storage device will lead to a lower renewable penetration than with and energy storage. This is because the diesel generators have to run much more in this situation, due to the increased risk of inadequate generated power. Incorporating a BESS enables the opportunity of smoothing the short-term fluctuations in wind energy as well as long-term variations in the load. This results in better utilization of the available wind resources [25].

Activated by the increased focus on renewable energy, the battery industry are going through a rapid development, leading to continuously cheaper and better batteries. Multiple technologies are available on the market, and all have their own strengths and weaknesses. The capacities ranges from kWhs to MWhs, while their discharge time varies from seconds to several hours. Other important features are the desired depth of discharge (DoD), voltage level and maintenance frequency. Together, these factors affects the lifetime of the diesel engines. Starting and stopping the engines too frequent causes increased wear and tear, and eventually a shorter operational lifetime before needing maintenance.

A BESS is not only a battery, it is a composite system consisting of several other components as well, including cooling, monitoring and control solutions, DC switch, AC breaker and usually a power converter. A battery stores and delivers DC current, while the wind turbine and the loads are connected to an AC bus. Therefore a switch-mode power converter must be included. Even though the converter usually is included in the BESS, its functionality and purpose will be described in more detail in the next section.

Altogether, a BESS is an expensive component [26], requiring special transportation, regularly maintenance and complex installation. Their useful lifetime is generally limited to around two decades. Thus, to choose the appropriate battery for this application requires an thorough overview of fundamental battery concepts, and the various technologies' distinct features. Some fundamental battery concepts are shown in Table 3.1 below.

Table 3.1: Fundamental battery concepts

Term	Unit	Description
Battery capacity	Ah, kWh, MWh	The maximum energy that can be stored in and extracted from the battery under specified conditions.
State of charge (SOC)	Ah, kWh, MWh, %	The energy stored in the battery at a given time.
Power capability	kW, MW	The maximum power that can flow to and from the battery.
Depth of discharge (DoD)	%	Describes the fraction of energy which can be drawn from the battery. It is expressed as a percentage of the nominal battery capacity. The larger the DoD, the shorter the cycle life [27].
Cycle life	Cycles	The number of charge and discharge cycles before losing considerable performance. Often specified at a certain temperature and DoD.
Calendar life	Years	The number of years before losing considerable performance.
Energy density	Wh/kg	The energy stored per kilogram.

3.3.3.1 General introduction to battery operation

A battery is a device which converts chemical energy directly into electrical energy and the other way around. It consists of one or more galvanic cells with a specific cell voltage. Each of these galvanic cells contains the following important elements:

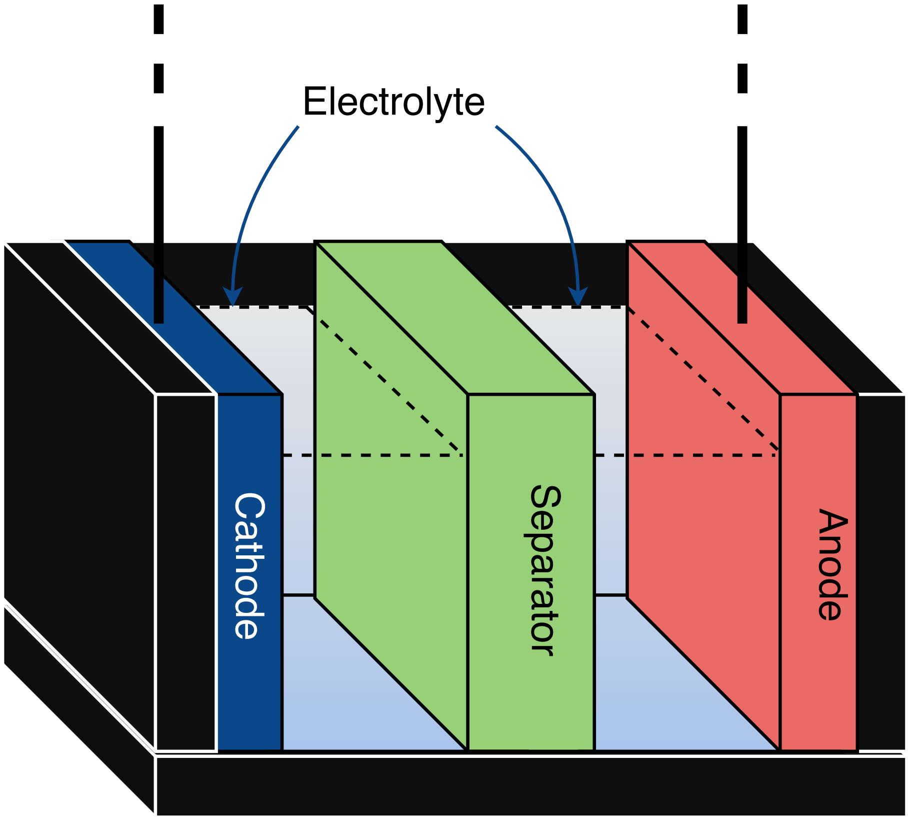
- Two electrodes, called the cathode and the anode

- An electrolyte
- A separator

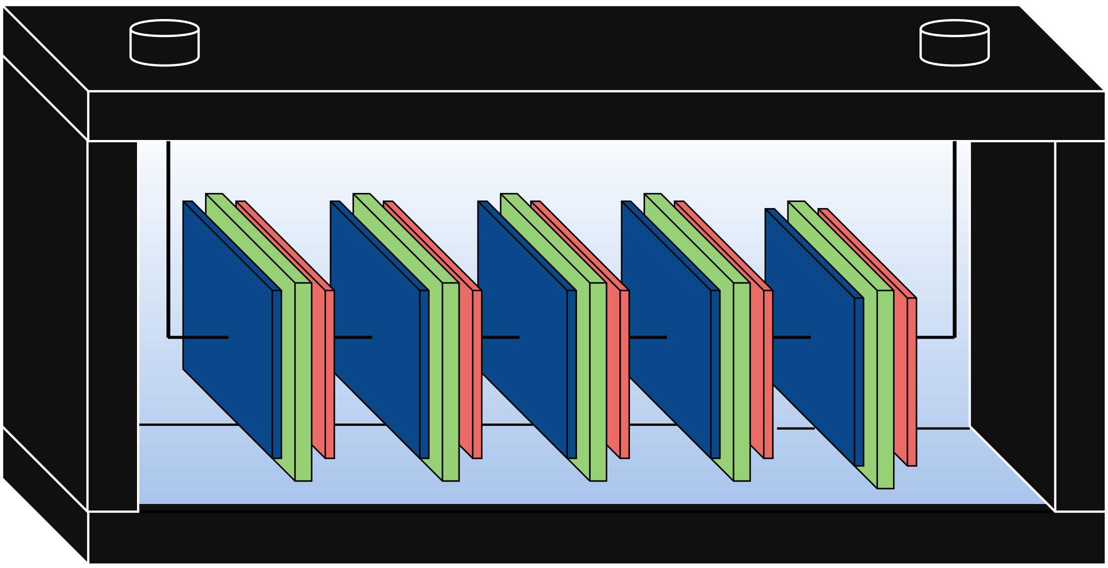
The cathode and the anode are usually both made of metal, but other materials are also used today. The anode is made of a material that easily oxidizes, which means that it is willing to give up electrons in order to obtain a stable number of electrons in the outer shell. Examples of common anode materials can be zinc and lead. The cathode is made of a material that usually reduces, implying that it easily assimilates electrons. The cathode is defined as the electrode where the current leaves, while the anode is the electrode where the current flows into[2]. If the battery is supplying electrical power, then the cathode has a positive polarity and the anode a negative polarity. If the battery charges, then the opposite is the case.

As depicted in Figure 3.4a and 3.4b, the cathode and anode are both immersed in an electrolyte, and are situated in separate cells. An electrolyte can be described as an aquatic solution of a chemical compound, where positive and negative ions are dissolved and therefore easily can interact with the electrodes. The cells are separated by a separator. This is an electrically insulating membrane, that prevents direct physical contact between electrodes, but yet allows electrolytic ions to flow freely between them [28].

[2] The direction of current is normally defined as the direction where *positive ions* (cations) travel.



(a) Simple schematic of basic battery configuration



(b) Multiple single battery cells in series

Figure 3.4: Battery basics

In each of the cells a reaction takes place between the electrode and the electrolyte. For example, when the battery produces electric power, the chemical reaction at the anode will be in the form of oxidation, while corresponding reduction takes place at the cathode. These are called *redox reactions*. The bi-product of the oxidation process is free electrons, which are captured in the reduction process. This results in a potential difference between the electrodes, making it possible for a current to flow. This potential difference depends on what kind of electrode materials that is used. Some chemistries have a higher standard electrode potential than others.

3.3.3.2 Considerations when choosing a battery technology

Since batteries are electrochemical components, the manner and conditions under which they are used affects their performance, cost and cycle life [27]. There are several factors that has to be taken into consideration when choosing the right battery technology. Three of most important factors will be discussed here:

The first important factor is the location where the battery will be situated. Each battery technology has its own temperature range, for which the battery will work properly within. Some batteries can operate over a wide span of temperatures, without affecting the performance significantly, while others are highly sensitive even to small temperature changes. The location also decides the accessibility of the battery. Another important aspect is the surrounding environment. If the ambient conditions are fragile to emissions, then maybe a battery without toxic elements, or the battery with the smallest expectation of leakage, should be considered.

Questions associated with the application of the battery is also an important factor. Is the battery going to work mainly as a long-term storage or as a short-term (frequency regulating) storage? DoD, battery capacity and battery capability depends all on the size of the load and the consumption pattern. Does the load require frequent, high-power charging/discharging of the battery or will longer and less power intensive charging/discharging cover the load in the best way?

Lastly, cost is yet another crucial factor in most projects. This can be split into two parts: Investment cost and operating cost. Usually there is a positive correlation between investment cost and performance, implying that a more expensive battery will most likely have better characteristics and longer cycle life batteries with lower cost. However, it all depends on both the application and location of the storage system.

Operating cost are mainly linked to transportation and maintenance of the battery. Some technologies need frequent maintenance of the electrolytes, while others do not. Another cost which should be mentioned is the transportation cost. This depends mainly on the location and less on the battery technology.

3.3.3.3 Important criteria for the actual system

A list of the most important criteria regarding the actual system is shown below.

- The system is placed in a fragile, maritime environment. Thus, the battery should either contain a small amount of toxic components or have a safety system preventing a potential effluent to the surroundings.
- The remote location makes transportation complex and costly, as it most likely will have to be transported by ship. Hence, a long battery cycle life is desirable.
- As the temperatures at the location may vary between -30°C and +30°C, the battery must be able to withstand these temperature changes. If not, it must come with a cooling/heating system.
- Superior reliability and low maintenance should be a priority because of the defiant accessibility.
- Off-grid hybrid systems are typically subject to highly variable charging powers, deep cycling, partial cycling and infrequent full charge [29], [30]. Thus, the appropriate battery has to endure these challenges.

Now, that the important criteria are stated, we will take a closer look at the relevant battery technologies used in BESS. There are five major types of batteries: Lead-based, Nickel-based, Sodium-based, Lithium-based and flow batteries. All of these, except for the Sodium-based are discussed in the following sections. The Sodium based batteries have been widely used earlier, but the market is now shifting towards other chemistries. Therefore, due to the limited amount of time, these will be omitted in this project.

3.3.3.4 Lead-acid batteries

Lead-acid batteries is a mature technology that have been commercially available for many year already. It's low cost compared to other battery technologies and broad base of manufacturers has made it a popular solution in many applications. The working cell voltage is normally between 2.2-2.5V. There are mainly two types of lead-acid batteries relevant for use in hybrid systems:

- Flooded/vented
- Sealed/valve-regulated lead-acid (VRLA)

Irrespective of which of the two types, the chemical materials used are the same. One electrode is made of pure lead (Pb), the other is made of solid lead-dioxide (PbO_2) and the electrolyte is a solution of sulphuric acid (H_2SO_4). This is shown i Figure 3.5. The first commercially available battery was the flooded lead-acid battery [31]. This type is not sealed, so the gases produced in the chemical reactions are vented directly into the surroundings. As a consequence, the oxygen formed in the reaction will flow into the ambient environment. Lacking recombination of oxygen to water, results in frequent maintenance (every 2-4 month) by means of refilling water [32]. This is a major drawback of the flooded lead-acid. Nevertheless, flooded lead-acid are considered to be durable installations, with a relatively long cycle life [31].

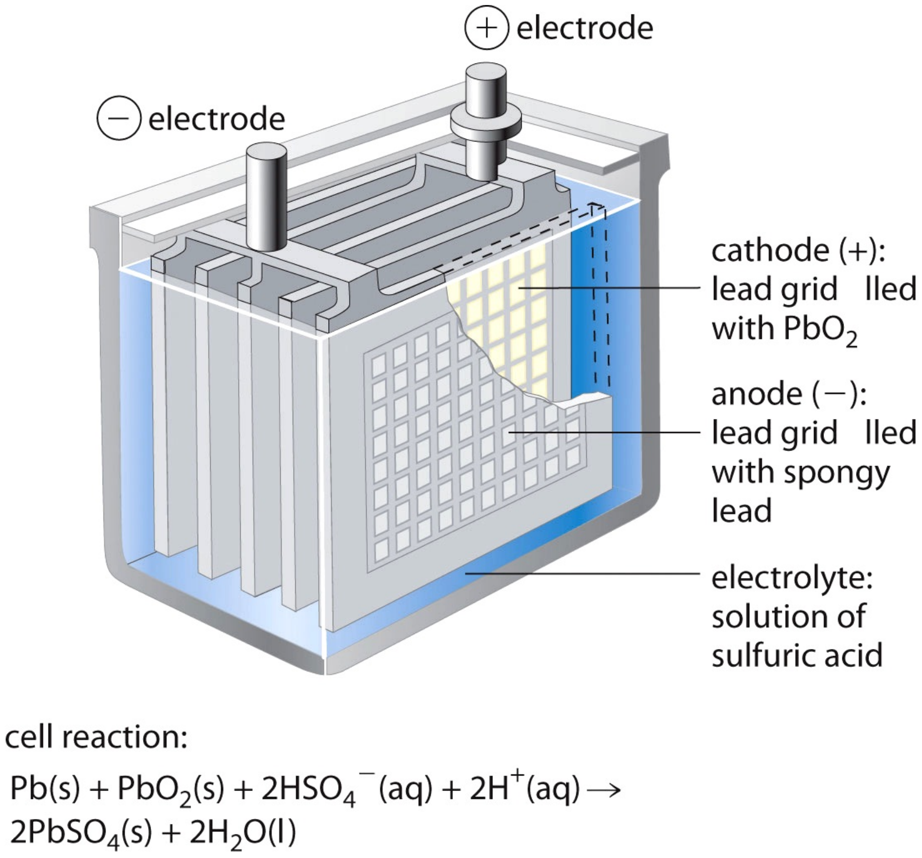


Figure 3.5: Schematic of a single lead acid battery [5]

VRLA batteries consists of the same chemical elements as the flooded, but these are equipped with a pressure-regulating valve, essentially sealing it from the surroundings [33]. The valve only releases gas in the case of an overvoltage. VRLA can further be divided into gel-based VRLA and absorbed glass matrix (AGM) VRLA. In the gel-based type, the electrolyte is a gel instead of a liquid. In the AGM VRLA the electrolyte is enclosed by a fiberglass matrix between the electrodes. Both these configurations have the advantage over flooded lead-acid that they require almost no maintenance. In addition, they are close to leak-proof as the electrolyte is immobilized. This ultimately leads to the possibility of tighter packaging, hence lighter weight. A quick comparison of the advantages and disadvantages between flooded and VRLA is shown in Table 3.2 and 3.3.

Table 3.2: Advantages and disadvantages of flooded lead-acid

Flooded lead-acid	
Advantages	**Disadvantages**
Relatively low cost	Low energy density
Relatively long cycle life (not for deep-cycle)	Must be situated in upright position to avoid leakage
Robust/durable	Needs frequent maintenance

Table 3.3: Advantages and disadvantages of valve-regulated lead-acid

Valve-regulated (VRLA)	
Advantages	**Disadvantages**
Less maintenance than flooded	Less robust
Higher power density (can be packed more tightly)	More costly
Almost leak-proof	Shorter-lived

In today's hybrid systems VRLA batteries are normally selected instead of flooded due to their better endurance in applications with partial cycling at low states of charge [30].

Lead-acid batteries are generally capable of discharging at a very fast rate, but the charging process has to be slow. This is due to a problem with sulfation which occurs at the electrode of pure lead. Simply put, sulfation involves that lead sulfate crystals forms and adheres to the electrode on a permanent basis, reducing the amount of active material on the electrode. Sulfation can occur when the battery is in a low SOC for a longer period, and during partial charging. Ultimately this results in increased internal resistance and reduced battery capacity. To compensate for this problem, the lead electrode can be mixed with activated carbon [27]. Such a structure is seen in what is called «advanced lead-acid batteries». There is extensive ongoing research within the area. Some of the main features of lead-acid in general are listed in Table 3.4.

Table 3.4: Main features of lead-acid batteries

Lead-acid	
Advantages	**Disadvantages**
Large variety of capacities available (approx. 1-16000 Ah)	Efficiency and cycle life is drastically reduced at high temperatures
Recycable	Lead is a heavy material
Mature and well-proven technology	Short cycle life at high DoD
Large matufacturer base	Asymmetrical charging and discharging
VRLA batteries do not need frequent maintenance	Relatively low energy density (approx. 50 kg/m3) Garcia,). [27]
Relatively low internal impedance	Sulfation may occur in partial charging

3.3.3.5 Nickel batteries

In general there are two main types of Nickel-based batteries used in high-power applications today, namely Nickel-Cadmium (NiCd) and Nickel Metal Hydrid (NiMH). Both chemistries use Nickel oxide (NiOOH) on one of the electrodes and potassium hydroxide as electrolyte (KOH). The working cell voltage is usually between 1.1-1.35V, which is rather low compared to other technologies.

Similarly to lead-acid, the NiCd batteries have been used for several decades already. Their ability to operate at extreme temperatures (from -40°C to +60°C) [34], together with a long cycle life (up to 20 years), substantiate their reputation of being robust solutions. They have relatively low internal resistance and the battery voltage remains rather constant during charging and discharging. One of the main drawbacks is the electrode made of Cadmium, which is highly toxic. The requires careful handling of the battery and its recycling process. An overview of the advantages and disadvantages of NiCd batteries are given in Table 3.5.

Table 3.5: Main features of nickel-cadmium batteries

Nickel-Cadmium	
Advantages	**Disadvantages**
Robust	Memory-effect
Long cycle life	Cadmium is highly toxic
Very low cost per charging cycle	Low energy density
Mature technology	High self-discharge rate
Low internal resistance	Low cell voltage

NiMH batteries has emerged as a result of a substantial governmental effort to remove the use of hazardous heavy metals (e.g. lead, mercury and cadmium) from batteries [35]. They possess several of the same features as NiCd, but are considered superior in many ways. The main advantage is the lack of toxic materials, making them easy to recycle. An overview of advantages and drawbacks with NiMH is shown in Table 3.6 below, based on [34] and [28].

Table 3.6: Main features of nickel metal hydrid batteries

Nickel Metal Hydrid	
Advantages	**Disadvantages**
Robust	High self-discharge rate
Not significant memory effect	Relatively high cost
High energy density	
No toxic materials	
Can handle deep-cycling	
Maintenance free	
Long cycle life	

3.3.3.6 Lithium-ion batteries

Lithium-ion batteries have been widely used in consumer electronics for the last couple of decades [36]. Now, due to extensive research and reduced cost, this technology is also becoming cost-effective in larger systems [37]. There are multiple compositions of lithium-ion batteries, which all have different characteristics. Their nominal voltage may vary from approximately 2.4-4 V depending on the chemistry. Similar for all is that during charging lithium ions flows from the positive cathode and to the negative anode. Examples of different types and some of their features are shown in Table 3.7, based on [27].

Table 3.7: Lithium-ion based battery types

Name	Cathode material	Anode material	Electrolyte	Energy density [Wh/kg]
Lithium iron phosphate	Lithium ferrophosphate (LFP)	Graphite	Lithium carbonate	200-2000
Lithium manganese spinel	Lithium manganese dioxide (LMO)	Graphite	Lithium carbonate	800-2000
Lithium titanate	Lithium manganese dioxide (LMO)	Lithium titanate	Lithium carbonate	2000-25000
Lithium cobalt oxide	Lithium cobalt oxide (LCO)	Graphite	Lithium polymer	300-800
Lithium nickel cobalt aluminium	Nickel cobalt aluminium (NCA)	Graphite	Lithium carbonate	800-5000
Lithium nickel manganese cobalt	Nickel manganese cobalt (NMC)	Graphite and silicone	Lithium carbonate	800-2000

From this table it is observed that almost all the chemistries use graphite as anode material, while the cathode material varies. There are so many different types to choose between, but the technology is still relatively young, hence, there is still a lack of knowledge considering long-term performance in hybrid systems. Regardless of the chemistry, lithium-ion batteries have many features that makes them attractive for hybrid system applications:

- They have a high energy and power density, which means that they use less physical space than other batteries.
- Charging and discharging ratings are relatively high, making it capable of covering large load fluctuations.

- They are practically maintenance-free.
- They have excellent charging and discharging efficiency (80% to almost 100% [27],[31], even at very high DoD.
- They can handle the stress connected to infrequent full charging, without suffering from significant degradation [29].
- They have relatively long cycle life even at high DoD (around 3000 cycles at 80% DoD [31])

Even though lithium-ion batteries appear as well-suited for hybrid wind-diesel systems, there are some challenges to overcome. High investment cost compared to other solutions is still a barrier. But the price is continuously decreasing, leading to increased deployment all over the world. High investment cost may also compensate for no maintenance cost, long lifespan and high energy density. Another obstacle concerns safety. Lithium-ion batteries requires sophisticated monitoring and control, in order to avoid overcharging/overdischarging [38]. If this is not handled properly, internal heat may develop, and in the worst case scenario a thermal runaway can occur, leading to fire and complete damage of the system.

3.3.3.7 Flow batteries

Flow batteries have shown promising development during the during the last years [39]. Amongst several other technologies the vanadium redox flow battery (VRFB), have caught increasing interest. As seen from Figure 3.6 a flow battery cell consists of two electrodes, separated by a separator. This is equivalent to the conventional cell-cased batteries. What makes it different is that there are two electrolytic solutions, which circulates through the reaction stack. The electrolytes are stored in separate external tanks and pumped through the system [40]. According to [39], each VRFB cell has a working voltage of about 1.25V. The electrodes are made of carbon-based material. The electrolytes are liquids and are usually made of vanadium pentoxide (V_2O_5) dissolved in a sulfuric solution. A summary of advantages and drawback of VRFBs are seen from Table 3.8. This is based on [40].

Table 3.8: Main features of vanadium redox flow batteries

Vanadium redox flow	
Advantages	**Disadvantages**
Power and energy rating are independent (no trade-off needed)	Operating cost may be substantial, due to maintenance of pumps
Long cycle life	Very high investment cost
High energy efficiency	Complex installations
Little sensitive to overvoltage and undercharge	More likely to leak, thus needs safe containment
Shows little degradation when subjected to partial charging	
Electrolytes can be controlled on a system level and not only on cell level	
Low self-discharge	
Low response time	

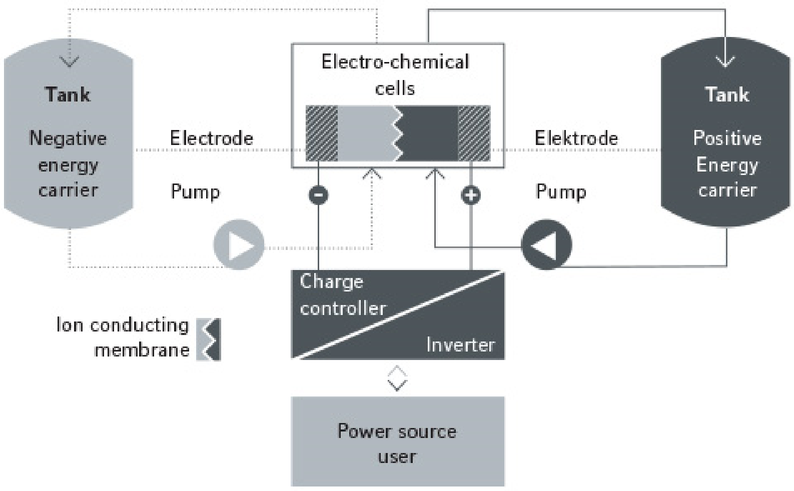


Figure 3.6: A conceptual flow battery [6]

3.3.3.8 Market trends

The market trend is evidently shifting from traditional sodium sulphur, lead-acid and nickel cadmium chemistries to more advanced technologies such as lithium-ion, nickel metal hydride, flow-based and advanced lead-acid. This is a result of both governmental regulations and increased focus on renewable systems, which have driven the cost down. Several pilot projects are now testing these new technologies [37]. Nevertheless, cost are still an entry barrier preventing from extensive commercial success in large hybrid systems. Furthermore, as shown in the previous sections, batteries have very different characteristics, making them suitable for different applications. Even though some chemistries seems superior on a general basis, it all comes down to the decision variables for each project and application. Thus, it is expected that a broad spectrum of battery technologies will be available on the market in the future as well.

3.3.4 Power electronic converters

Two power electronic converters are needed in this system: One between the wind turbine and the AC bus and one between the AC bus and the battery. Both of the converters are based on three-phase application. A power electronic converter is in its simples manner an electrical circuit consisting of different passive elements (inductor, capacitor, diode, thyristor), composed in a way which results in converting or controlling the electric circuit characteristics within desired values. They may also incorporate semiconducting switches (MOSFET, IGBT). There are many different types of power electronic converters. In this paper only the relevant converters used for the WT and the BESS is discussed to give an intuitive understanding of their purpose and mode of operation.

Conventional uncontrolled rectifiers (diodes) and line commutated phase controlled rectifiers (thyristors) have so far dominated the AC to DC power conversion. Such converters have inherent drawbacks such as high harmonics in the input current and output voltage. Therefore, converters with controllable switches have become more prevalent in the last years. Advantages with these are less harmonics, more flexibility connected to output voltage magnitude and phase, and the ability of bi-directional current flow. However, one drawback is the more complex controlling system required.

3.3.4.1 The wind turbine converter

The turbine converter is often a AC-DC-AC back-to-back fully rated converter, which can be delivered as a package together with the wind turbine itself. The most used three-phase converter topology today is a two-level PWM-VSC. PWM stands for Pulse Width Modulation and is a way of controlling the state of the semiconducting switches. The term VSC stands for Voltage Source Converter and implies a converter which uses

IGBT switches. Over the last decade the use of Insulated-gate Bipolar Transistors, or IGBTs, as power electronic switches have increased significantly [17].

By using a power electronic converter, the turbine can be decoupled from the grid, making variable-speed control possible. As explained before, variable-speed turbines are desirable because the turbine can change its operation to acquire the desired amount of output power.

Even though the two-level PWM-VSC is the most used topology today, there are also other solutions used for the rotor side converter (RSC). The RSC, which converts AC to DC, can typically be one of these three configurations (Figure 3.7):

- IGBT-based rectifier
- Thyristor-based rectifier
- Diode-based rectifier

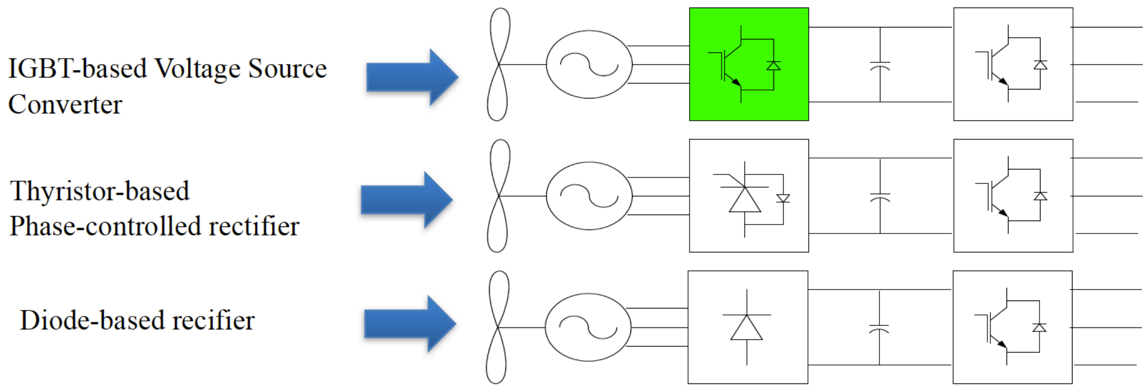


Figure 3.7: Possible RSC configurations [7]

The choice of RSC depends on the type of generator together with the rest of the system's layout. If bi-directional power flow is not required (like for a permanent magnet synchronous generator), then a simple diode-rectifier can be used. However, if bi-directional power flow is inevitable (e.g. in a asynchronous generator which consumes reactive power), then one of the other two must be used. The main objective of the RSC is to control the turbine power and rotational speed, by comparing the actual conditions with the desired conditions provided by the turbine's torque-speed and power curve.

The grid side converter (GSC) is in most occasions a full-bridge, IGBT-based inverter.

This controls the reactive power flow and ensures that the output voltage is withing the specified frequency and magnitude limits.

Between RSC and GSC there may be a DC-link capacitor to smooth the rectifier output voltage ripple, and also a chopper resistor. The chopper resistor protects the converter from overvoltage conditions as it can dissipate excessive energy rapidly. This is a crucial feature as power electronic equipment are highly sensitive to overvoltages.

3.3.4.2 The battery converter

The battery stores and delivers DC current and voltage, while the rest of the hybrid system runs on AC. Therefore a bi-directional power electronic converter is needed between the battery and the AC bus bar. A full-bridge switch-mode DC/AC converter, with controllable switches is a possible solution here.

3.3.5 Main load

The main load of the hybrid wind-diesel system is the collection all energy consuming units needed for covering the basic needs of the system in a desirable manner. The units involved in the main load depends on the hybrid system's application. For usage in rural areas or islands, it may be a village or just a few houses. In the context of an fish farm application, the main load can involve the equipment on the feed barge used in the day-to-day operation.

3.3.6 Dump load

Many hybrid systems are weak grids, meaning that the total inertia present in the grid is relatively small compared to the load. Thus, the system frequency and power quality is more sensitive to variations in load. In the event of excess renewable energy, and the energy storage is fully charged, the surplus of energy will have to be dissipated to avoid a major increase in frequency. This is why a so-called dump load is needed. It may be based on variable resistors or power electronics. Another way of reducing the surplus of energy is by means of pitch control as discussed earlier.

However, all these methods wastes available renewable energy. Using the excessive energy to drive e.g. auxiliary equipment instead may be a better way of utilizing the resources. It should be noted that the complexity of the system will increase by including new equipment, as surplus of energy may arise and vanish in very short time. Hence, sophisticated control strategies has to be implemented to ensure safe operation of the auxiliary equipment.

3.3.7 Three phase transformer

A three phase transformer is to be connected between the GSC of the wind turbine and the switch connected to the AC bus bar. This transformer's function is to convert the wind turbine voltage of 690 V to 400 V line-to-line. It also has other purposes, e.g. act as a filtering component of harmonics and also provide galvanic isolation. This might protect the wind turbine and its converter from potential over-currents and over-voltages.

4 | System modelling in MATLAB®

4.1 Motivation and background

The main motivation behind running simulations in MATLAB is to obtain an intuitive understanding of the different components' impact on the system behaviour. All the simulations have been carried out in steady-state, during one year, and with a time-resolution of 30 minutes. Analysing only the steady-state behaviour, implies that voltage and frequency dynamics are not taken into consideration. Other important aspects such as detailed battery charging techniques and transients occurring when switching from one generating unit to another, are also avoided. Hence, the purpose of these simulations is not to asses the actual practical feasibility of every possible state, but rather give reason for thought concerning the system supervisory control.

MATLAB is a software made by MathWorks and have been used for running the simulations because of its versatility. It is widely used within the university, it possesses excellent graphical tools for curve plotting and it is compatible with other tailormade programs. Simulink is an example of such a software, specialised within multidomain dynamic analyses. Therefore Simulink may be a natural continuation if dynamic properties should be investigated in the consecutive master thesis.

In the following sections, the modular procedure of the wind profile, consumption profile, control strategy and all the system components is explained, accompanied by their limitations and assumptions.

4.2 Wind profile

The wind profile is based on long time series with actual wind data, collected from the measuring station at Veiholmen in the period 1994-2014. This is close to the intended location. The measurements have been performed on an hourly basis, at a height of 10 meters. As the wind turbine hub is expected to be situated at around 50 meters, a wind transformation had to be performed.

In order to acquire this, a software called WAsP have been used to estimate average wind speed at hub height. WAsP is widely used in the industry in applications for vertical and horizontal transformation of wind. Briefly put, it is a set of physical models that combines an atlas of so-called geostrophic wind (wind at high altitude), together with topographic maps, vegetation information, and other parameters to transform wind speeds from one location to another. The disadvantage with WAsP is that it only provide summarized numbers and not time series. Therefore WAsP at the turbine site has been used in combination with actual time series of wind from Veiholmen [41], [42]. Wind speeds can usually be estimated from a Weibull distribution. This is also the case here as Figure 4.1 shows the fitted Weibull distribution at the turbine location. Here a scale factor, c of 9.8 and a shape factor, k, of 1.86 have been used.

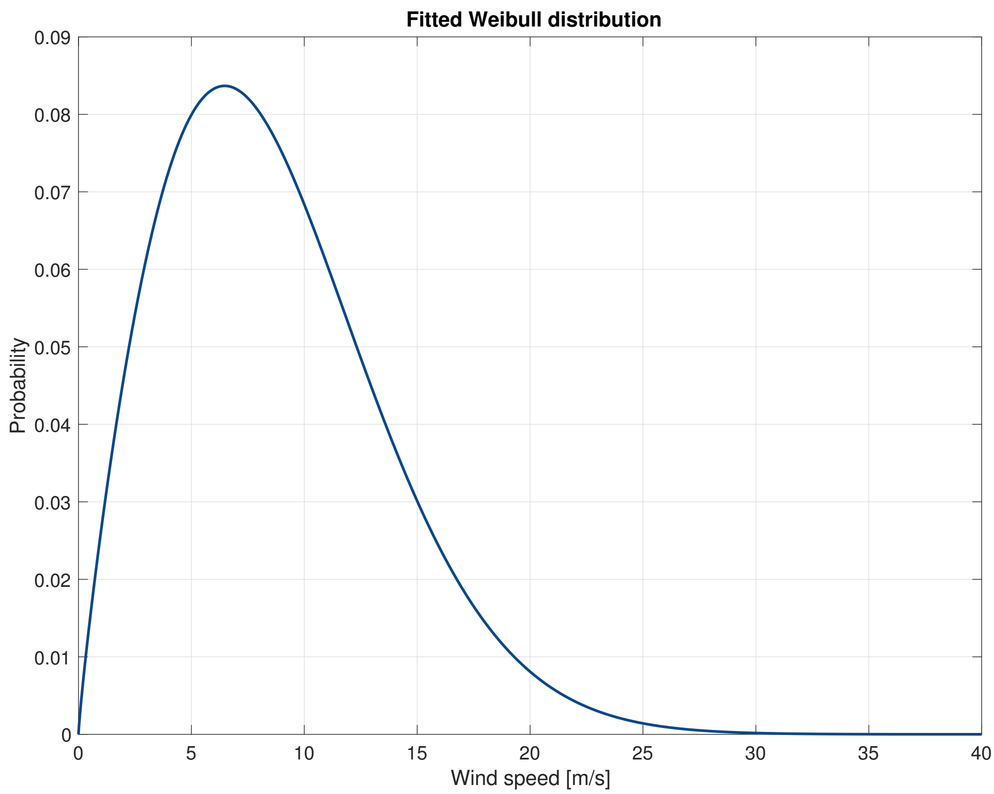


Figure 4.1: Fitted Weibull distribution with $c = 9.8$ and $k = 1.86$

However, drawing random values from this distribution in order to obtain a fictional wind profile, may lead to unrealistic wind conditions. An extreme example just to prove this point is that obviously nothing prevents the wind speeds to fluctuate between 0 and 30 m/s for every hour throughout the year, when using this approach. This is very unlikely to occur in real life. Moreover, this method lacks information concerning seasonal variations, which can be significant. Instead, an actual and representative time series from 2012 have been used, as this is available. Figure 4.2 depict the transformed wind conditions in 2012 at turbine location (50 meters).

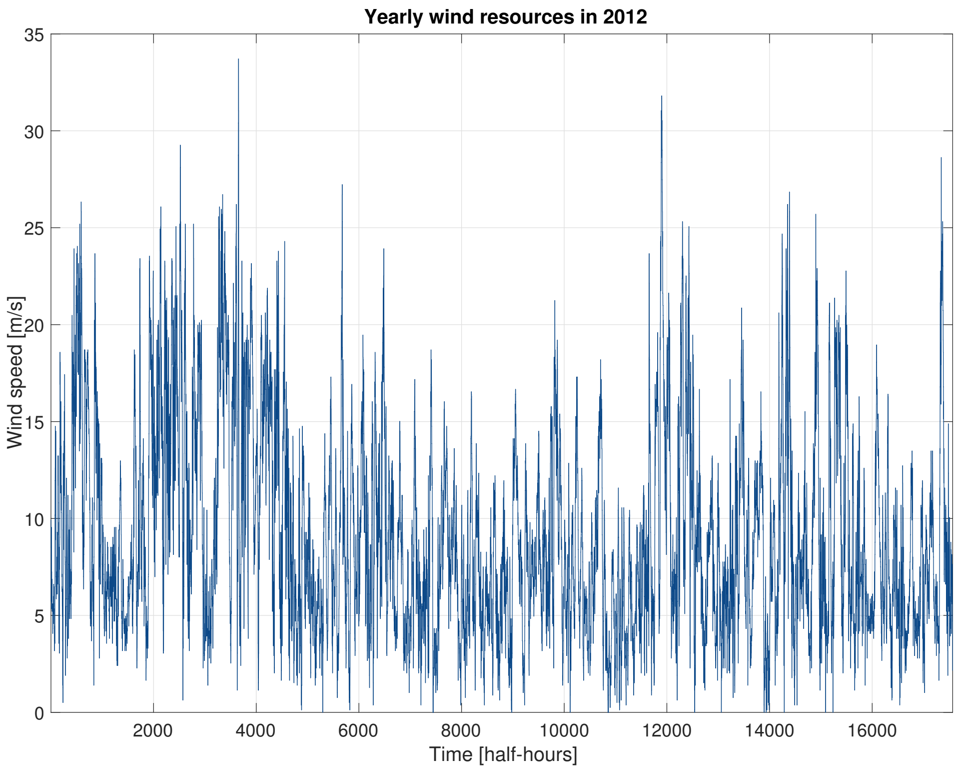


Figure 4.2: Yearly wind resources per hour

During the 21 year period average wind speed has been 8.7 m/s, which is very good. Figure 4.3 shows the mean and standard deviation in wind speed for each moth during this entire period. From this it is clear that seasonal variations are present. In the period from May to about August, the wind speeds are lower and calmer than the rest of the year.

The simulations are carried out on a half-hour basis, while the wind measurements have a resolution of one hour. Hence, an important simplification made in the simulations is treating wind as constant over each hour.

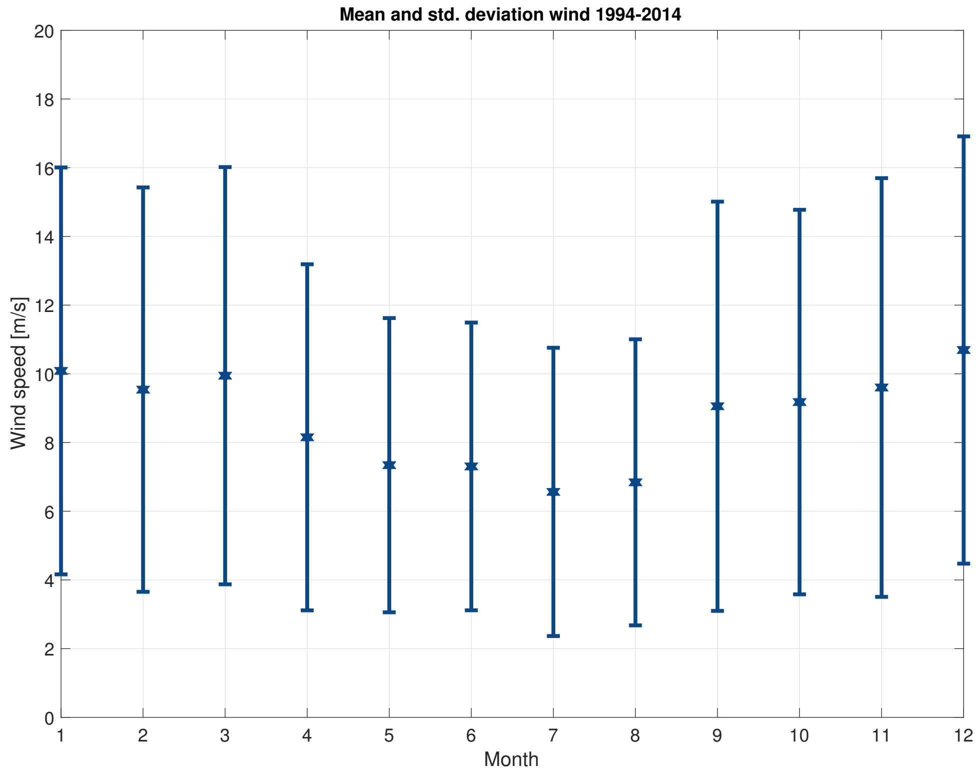


Figure 4.3: Mean wind speed with std. deviation 1994-2014

4.3 Consumption profile

4.3.1 Main load

The yearly energy consumption of the fleet's main load is expected to be around 470 000 kWh. In order to make a suitable consumption profile, the load has been divided into two parts: one deterministic and one stochastic.

4.3.1.1 Deterministic load

The deterministic part constitutes of the feed blowers and sea pen lightning, since there are incorporated routines for operation of these within the industry. Throughout the year, the feed blowers are run at approximately 50% of nominal power as long as there is daylight. An explanation for why the blowers are operated at such sparse rating can be as follows: Fish feed normally consist of marine and vegetable oil that is compressed into pellets [43]. If the feed blower runs at too low power, the air pressure they create will be insufficient, which causes clogging of the feeding pipes. However, if the blowers run at full power, the pellets may break into dust which may lead to clogging and further more frequent cleaning of the pipes. Thus, they are normally operated at approximately half the rated power and only run at 100% during cleaning of the pipes (without any inlet of feed). It should be clarified, that even though the blowers run as long as there is daylight, feed inlet is controlled independently by the dosage regulators to meet the fishes' demand.

As the day-length varies throughout the year, [44] has been used to survey the time for dawn and sunset for each day. Data for the exact location was not available, so data for Trondheim have been used. This should not lead to any major differences, since the two places are almost at the same latitude. There are proposed six feed blowers for the fleet, each with a nominal power rating of 22 kW. Thus, when in operation approximately $0.5 \cdot 6 \cdot 22 = 66$ kW will be drawn by the blowers. It should be noted that in order to satisfy the expected yearly energy consumption of 470 000 kWh, the blowers are assumed to run at 55% (fixed) of rated power.

The other factor included in the deterministic part of the main load is the consumption related to lightning of the cages. When the sun sets, the lights are turned on to simulate daylight and enhance growth. Sets of LED lights which constantly draws 1.2k W each are used. During the last years, many fish farms have shifted from the traditional lightning (with approx. 5kW per set) to LED, and thereby reduced energy consumption related to lightning drastically. All of the 12 cages are equipped with one set of light bulbs, yielding a total power demand of $12 \cdot 1.2 = 14.4$ kW.

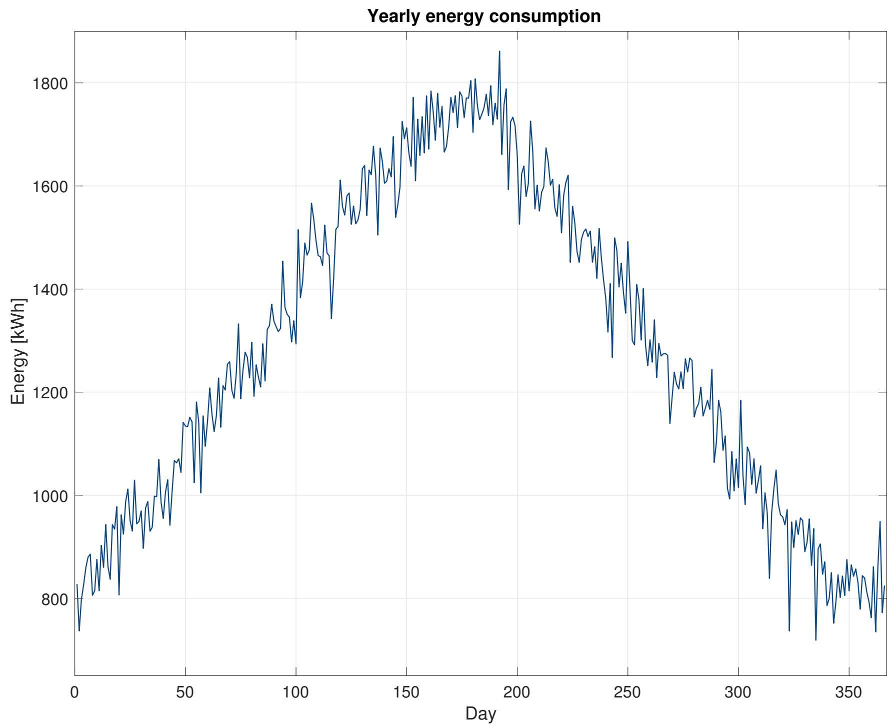
To summarise what has been used in the simulations; During daytime, the feed blowers are run continuously at $0.55 \cdot 6 \cdot 22 = 72.6$ kW. At nighttime the lights are constantly drawing 14.4 kW in total.

4.3.1.2 Stochastic load

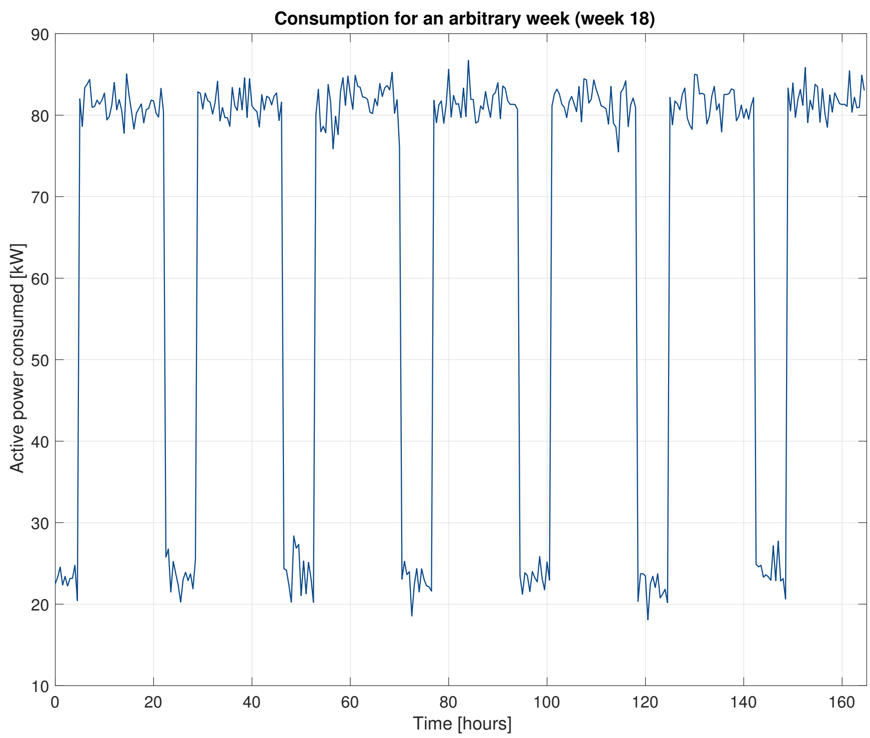
The stochastic load part relates to the feed barge's own consumption. This involves power to heating, lightning, the control system and other electrical facilities, in order for the barge to work on a day-to-day basis. A normal (Gaussian) distribution, with expectation of 9 kW and standard deviation of 2 kW is used in the simulations to represent the barge's own consumption.

4.3.1.3 Total main load

Adding the deterministic and stochastic parts together for every half-hour, every day for one year yields the total main load profile. In Figure 4.4a, the seasonal variations in daily energy consumption is shown to be substantial. During winter, with short periods of daylight the energy per day is approximately 800 kWh. On the other hand, in the summer, when the sun is up for a lot of hours, the energy demand is more than doubled with around 1760 kWh per day. Figure 4.4b shows the active power consumed for one arbitrary week. Daily variations are clearly visible. When the blowers are in operation, the consumption lies around 80 kW ($72.6 + 9 \approx 80$ kW). When the blowers are turned off and the lightning is turned on, demand is around 23 kW ($14.4 + 9 \approx 23$ kW). Lastly, the significant difference in load between wintertime (represented by day 1) and summertime (day 140) are highlighted in Figure 4.5a and 4.5b.

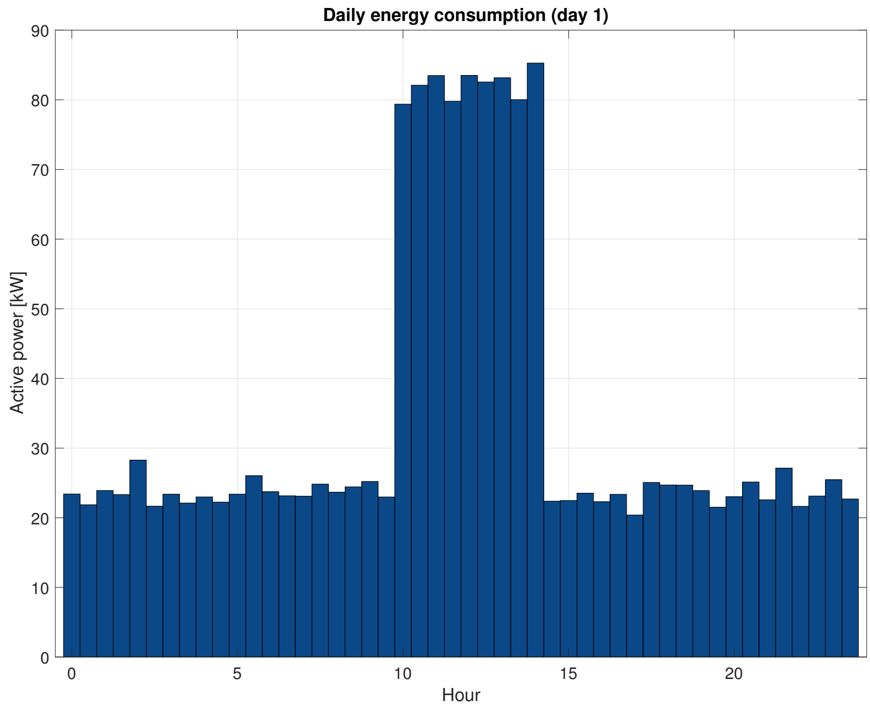


(a) The fleet's yearly variations in daily energy consumption

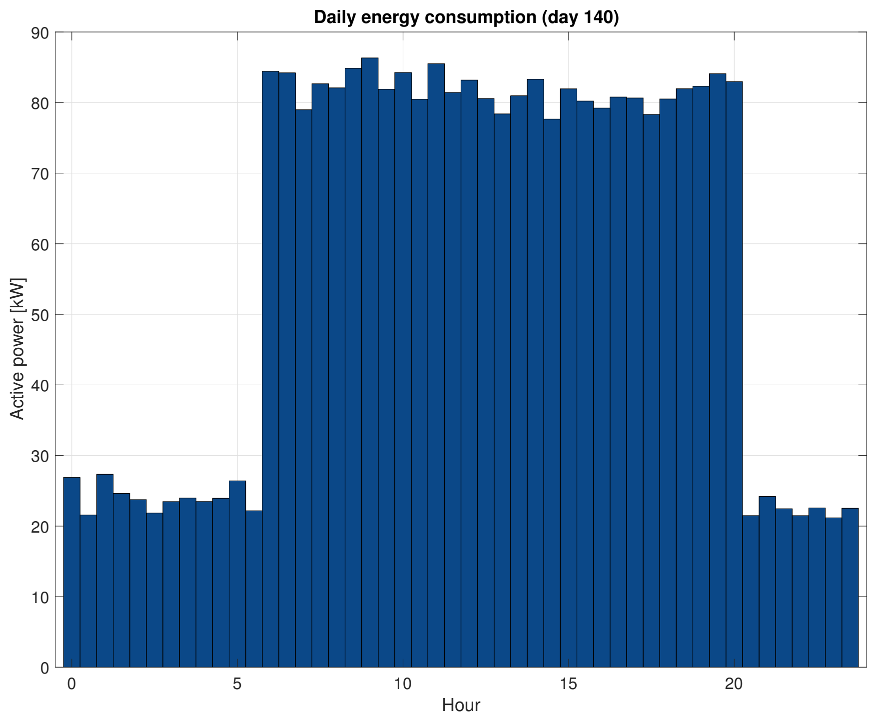


(b) Consumption profile for one arbitrary week

Figure 4.4: Load profile



(a) Load profile for day 1 of the year



(b) Load profile for day 140 of the year

Figure 4.5: Main load profile for two example days

4.3.2 Dump load

In traditional hybrid systems, power electronics or variable resistors have been used as dump load to dissipate the excessive energy in the system, and thereby prevent large frequency fluctuations. Another way of removing surplus of power is by pitching the turbine so that output is reduces. All of these methods wastes accessible renewable energy. Thus to minimize the waste in this particular system, excessive energy is intended to drive production of fresh water, oxygen (O_2) and high pressure washers for removing sea lice.

Profinor have been contacted for information about fresh water production, Storvik Aqua for information about oxygen production and Flatsetsund Engineering regarding high pressure washers. but all have been reluctant to reply on emails. Thus the technological details of these components remains to be solved in the master thesis. Nevertheless, this will have little impact on the steady-state analysis performed here.

In the simulation model, the dump load have been represented by a minimum and a maximum power. If the available power to the dump load is less than the minimum value or larger that the maximum, the turbine output power will be reduced by means of pitching. Otherwise, dump load consumes all the power. The reason for this is based on that there is no point in using the dump load when the accessible power is so low that the equipment won't work properly. And in the opposite case, if the power is too high for the dump load to handle, then some power have to be reduced from the turbine.

4.4 Wind turbine power

A 250 kW EWT wind turbine called EWT DW52250 have been used as background for simulating the wind turbine.

This turbine has a multipole synchronous generator, with wound rotor. The reason why a multipole generator is used, is explained by the turbine's lack of gearbox. Thus, the generator rotor will rotate at the same speed as the rotor blades. As seen from equation (3.3), a higher number of poles have to make up for the slow rotor speed. Furthermore, the turbine is equipped with pitch control and a back-to-back AC-DC-AC power converter. The pitch is driven by electrical motors. A clear advantage of this compared to older pitch control system that uses hydraulic pitch, is the increased reliability as maintenance due to leakage is removed [23]. The fully-rated converter use IGBT-based switches, which facilitates variable speed drive and bi-directional power flow. A list presenting the relevant turbine information is shown below:

- Nominal output power: 250 kW
- Rotor diameter: 52 m
- Tower material: Conical tubular steel
- Variable rotor speed: 12 - 22 rpm
- Possible hub heights: 30, 40 and 50 m
- IEC wind class: IIA
- Cut-in wins speed: 2.5 m/s
- Cut-out wind speed: 25 m/s
- Rated wind speed: 8 m/s
- Power output control: Pitch
- Generator: Synchronous, multipole
- Power converter: Fully rated back-to-back, AC-DC-AC, IGBT-based

Overall, the EWT DW52250 seems like a good solution for the proposed system. During the last 20 years, turbine site has had an annual average wind speed of 8.7 m/s. This corresponds well with the IIA IEC wind class (8.5 m/s annual average wind speed). Other manufacturers, such as Enercon and Vetsas, have been examined as well, but they only provide turbines from 800 kW an upwards. As the maximum power consumption of the fleet lies around 80-90 kW, a turbine of 250 kW should be suitable. The good wind resources at the location entails that the turbine is capable of running at nominal output power for many hours during the year. Hence, even at maximum load there will be extensive periods with $250 - 80 = 170$ kW surplus from wind. This can be used both for charging the batery and driving the dump load. It has clearly been stated earlier in this project that no definite choices will be made regarding specific systems components, however, it is clear that the EWT turbine is of great interest and will be further assessed in the master thesis.

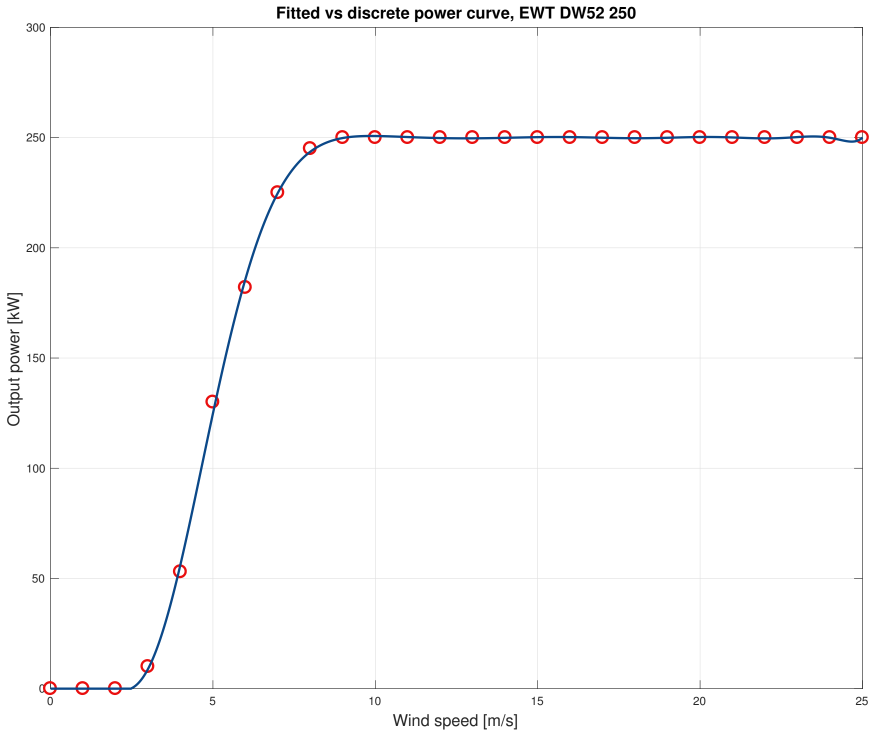


Figure 4.6: Power curve for EWT DW52250

In order to simulate turbine output, the power curve had to be established. The power curve shows the possible turbine output for each wind speed. This is usually provided by the manufacturer, but exact discrete values was not given in the EWT brochure [45]. Thus, discrete values was read manually from the given power curve, and based on these, a 14th order polynomial was used to create a more continuous representation. The resulting power curve used in simulations is shown in Figure 4.6. Cut-in speed and cut-out speed have been included and it is seen that the continuous curve is a good fit of the discrete values. Additionally, nominal power output occurs approximately at rated wind speed (8 m/s) and the pitch control controls the output power to nominal value for higher wind speeds. For wind speeds larger than 25 m/s the turbine will stop to prevent structural damage. Figure 4.7 displays wind turbine output for 100 arbitrary hours. During periods with wind speed lower that 2.5 m/s the turbine produces zero power, while for wind speeds higher than 8 m/s the turbine produces at nominal power.

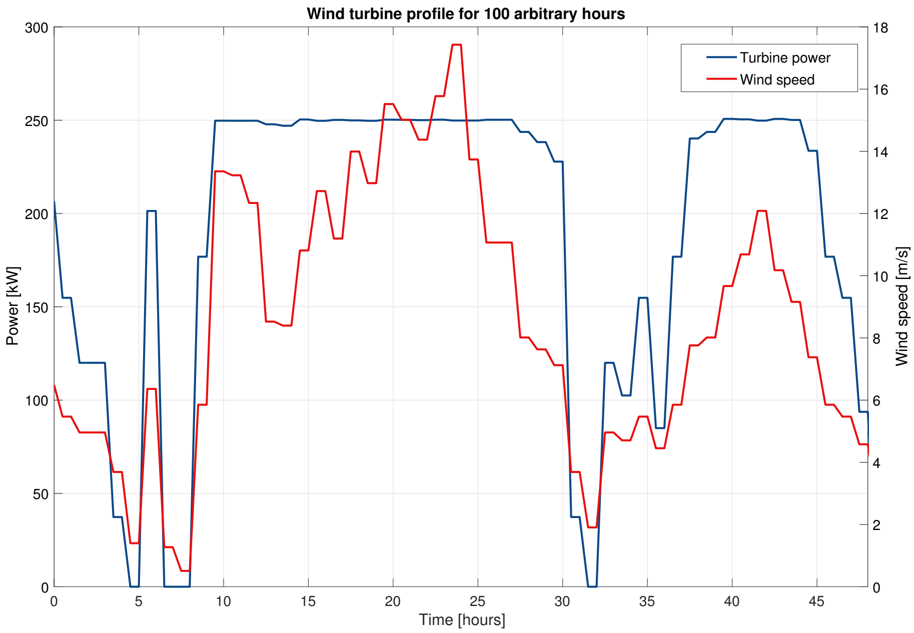


Figure 4.7: Wind speed and turbine output for 100 arbitrary hours

4.5 Modelling the BESS

The battery in the BESS model depends heavily on it's appurtenant power converter. The battery itself is modelled with a constant DC voltage (V_B) of 520 V. This is larger than the 400 V line-to-line because in a three phase inverter, output AC voltage will always be lower than input DC voltage. Further, the battery capacity [Ah] is not fixed. Instead it is varied in the sensitivity analyses performed in chapter 5, to get a better understanding of its impact on the system as a whole. Another sensitivity parameter which is varied is the DoD. For a given battery capacity, changing the DoD will change how much energy that can be drained from the battery. The battery's state of charge (SOC) for each time step is calculated *based on the power flow through the converter*. Because battery energy is simply given by the time integral of power, we may use equation (4.1), with $T = 0.5$ hours.

$$W_B(t) = W_B(0) - \int_0^T P_{CONV}\ \mathrm{d}t \tag{4.1}$$

Here, the polarity of P_{CONV} has been defined as:

$$P_{CONV} = \begin{cases} > 0 & \text{when power is flowing } \textit{from} \text{ the battery} \\ < 0 & \text{when power is flowing } \textit{to} \text{ the battery} \end{cases}$$

To summarise, the fixed, variable, dependent and neglected variables are listed below:

1. **Fixed parameters:**
   - Battery voltage: 520 V
2. **Variable parameters for sensitivity analyses:**
   - Battery capacity [Ah]
   - Depth of discharge
   - Maximum converter power, $P_{CONV,max}$
   - Maximum battery capability, $P_{B,max}$
3. **Dependent variables:**
   - Power through the converter, P_{CONV}, depends on the power balance in the whole system
   - Maximum battery energy level [kWh], for given [Ah]
   - Minimum battery energy level [kWh], depends on [Ah] and DoD
   - State of charge, depends on the power through the converter
4. **Neglected variables**
   - Converter efficiency
   - Battery charge and discharge efficiency
   - Battery self-discharge rate

The efficiencies and the self-discharge rate have been neglected because lack of time. Also as no specified battery chemistry is selected yet, these values would have been approximated anyways. Moreover, they are not expected to have large enough impact on the system as a whole to distort the main characteristics of the simulation results.

4.6 Modelling the diesel aggregate

The diesel aggregates have been treated as the resolving post, since the main goal is to minimise the fuel consumption. «Treated as the resolving post» implies that the diesel is not in operation unless no other option is possible. If the diesel has to run, the diesel power required is calculated. Ultimately the fuel consumed by delivering the power is found by using equation (3.4). There are three possible states for the aggregate: Not in operation, in no-load operation and in operation. No-load operation involves that engines are running, but the clutch is disengaged. It can be considered a standby-mode as the engines are ready to deliver power almost instantaneously.

4.7 The control strategy

In Chapter 5, system performance during different scenarios is investigated. Common for all is that they are special twists of the base case. The base case involves the complete hybrid wind-diesel system with BESS, main load and dump load. To assess this, a control strategy which makes logical decisions based on the system state for each time stem had to be implemented. In order to present this in a pedagogical and perspicuous way, a simplified flowchart showing the main points have been made in Figure 4.8. These are accompanied by an algorithmic explanation which explains the steps in more detail.

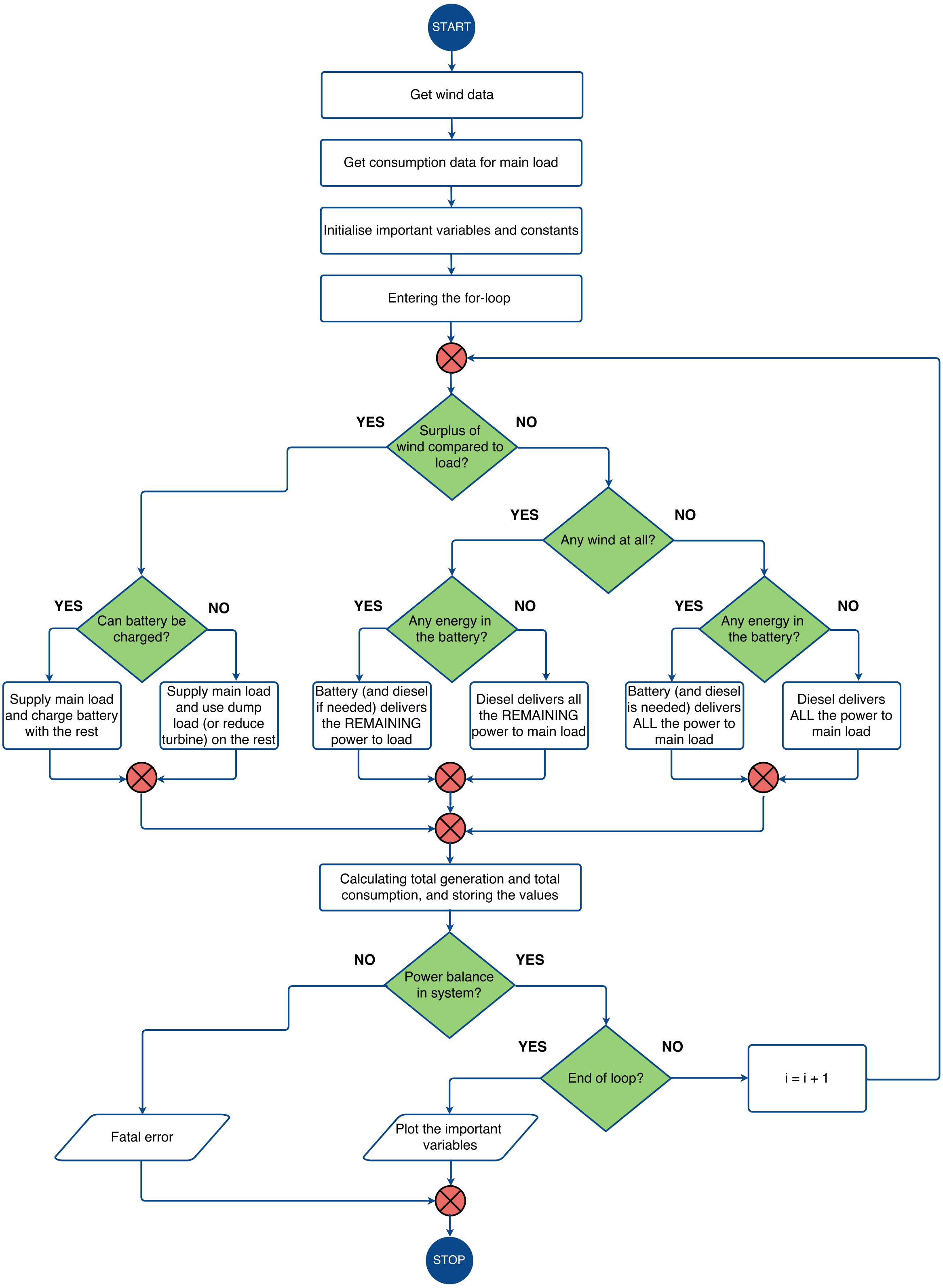


Figure 4.8: Simplified flowchart of the control logic

The scripts made are based on simulations for one year. However, simulations over more years are easily applicable, and the logic will be similar. Thus only behaviour on a yearly basis is described.

- Step one is reading of the wind data. As explained earlier, actual wind conditions with hourly resolution for the period 1994-2014 are used. Further, they are assumed constant over each hour. One year normal year (365 days) is defined as 8760 hours or 17520 half-hours. Thus, leap years have 8784 hours or 17568 half-hours.

- Step two involves generating and obtaining the consumption data for each half-hour throughout the year. The consumption data has been made as explained in an earlier section.

- The the predefined constants are initialised for each component. Other constants are margins used in the logical tests, e.g. margins on battery capacity. These margins specifies how many percent above minimum battery capacity that is sufficient to avoid no-load operation of diesel. E.g. if there is a marginal deficit of wind energy compared to load in the system, then the margin can be *lower* than if there is no wind in the system at all. Obviously the margin have to stricter in the latter case as this is more severe and will drain the battery much faster. Other margins describes the limits which defines what is considered as a comfortable surplus of wind compared to marginal surplus. Similarly, there is a margin which defines what is considered as a clear deficit of wind compared to marginal deficit.

- Now the for-loop is entered. The first thing that happens inside the loop is calculating the difference between maximum possible turbine output and main load for that half-hour.

- Based on this difference, the system state is found. Five main possible states have been defined:

  1. **Clear surplus:** If there is more than 15 kW surplus of wind in the system compared to load

  2. **Marginal surplus:** If there is surplus of wind, but it is less than 15 kW

  3. **No wind:** If the wind turbine produces zero power for that half-hour

4. **Marginal deficit:** If there is a deficit of wind, but it is less than 15 kW

5. **Clear deficit:** If there is more than 15 kW deficit of wind

- Within each state there are a lot of aspects that have to be considered. Therefore a hierarchy of priorities on how to cover the load, is desirable. The hierarchy will depend on whether there is surplus or deficit of wind energy in the system. In the case of surplus, the hierarchy in descending priority is (1) wind turbine, (2) charge the battery, (3) dump load and (4) pitching the wind turbine to reduce output power. In the case of deficit, the priorities are (1) wind turbine, (2) discharging the battery and (3) using the diesel aggregates. In both cases, the top priority in the system is utilizing as much of the wind power as possible. Next comes the battery, which is charged (when possible) during surplus and discharged (when possible) during deficit.

  There are also other challenges. In coarse features, whenever the battery charges or discharges the power to/from the battery cannot be larger than the maximum power allowed by the coherent power converter. Thus, special treatment is needed if this is not satisfied. As an example, consider a situation with surplus of wind. The load is then covered and we wish to charge the battery with the rest. However, the power accessible is too large for the power converter to handle. Thus, the battery will charge with the maximum converter power. But there will still be excessive energy. Then one could check if the dump load can use the power (within the maximum and minimum value as stated earlier). If this is not the case, then ultimately the turbine has to be pitched to reduce output power.

- In this way, which components that generates and consumes are decided for each time step. At all times, power equilibrium as described by equation (4.2) has to be satisfied.

- When the loop is finished, the relevant plots and results can be obtained.

As mentioned above, the cornerstone of this approach is the power equilibrium, which has to be fulfilled at all times. This is shown mathematically in equation (4.2) below.

$$\overbrace{P_{WT} + P_D + P_{CONV}}^{\text{generation}} = \overbrace{P_{LOAD} + P_{DUMP}}^{\text{consumption}} \tag{4.2}$$

Here,

- P_{WT} is the power produced by the wind turbine
- P_D is the power produced by the diesel generator
- P_{CONV} represents the power to or from the battery
- P_{LOAD} is the power consumed by the main load
- P_{DUMP} is the power consumed by the dump load

It is important to be aware of the simplifications and shortcomings of this analyses. Firstly, the analyses are in steady-state, meaning that powers are treated as fixed from one time step to another. Secondly, the number of diesel generators are not taken into consideration. They are only treated as one fuel consuming unit. Thirdly, the type of battery has not been specified. Furthermore, losses and reactive power have been neglected. Even another simplification is linked to the operation of the DA. As mentioned earlier, operating the engines at low power compared to the rated power, results in low efficiency and is not wanted. Thus, one possible improvement of the control logic, may incorporate the following: If the DA is delivering low power to the main load, this can be increased by additional charging of the battery or additional serving of the dump load. In this way one can constrain the DA to run at (e.g.) 50% of nominal value or more.

5 | Case study results

5.1 Introduction to results

In this section results of the simulations are shown. One base case is defined and within this there are five sensitivity analyses. Lastly, three special cases will be investigated. A list with things that are common for most of the cases is summarized in the list below:

1. All the cases simulates over the year of 2012, with a resolution of 30 minutes. As 2012 was a leap year, this involves $2 \cdot 24 \cdot 366 = 17\ 568$ data points. Later results indicates that 2012 is considered a representative year.

2. The same structure is used for all the sensitivity cases BC1-BC5. This includes a brief explanation of the specific case, followed by important figures, a table with summarised values and a brief discussion of the results. The five figures depicts:

   - Energy produced by the diesel generators
   - Diesel fuel consumed by the diesel engines
   - Energy consumed by the dump load
   - Energy lost due to derating of the wind turbine
   - Energy produced by the wind turbine

3. For each sensitivity case, 14 plots are obtained. Five is used in the main report as described above, but the remaining nine plots are placed in the Appendix.

5.2 Base case (BC)

The base case constitutes the foundation for the simulations. Here, all the system components are included and have fixed values. The chosen input values are partly based on [24], [46] and partly on estimates. The main purpose of the base case is not to simulate the actual system as accurate as possible, but rather to provide the reader with an intuitive feeling of the relative sizes of the parameters. A summary of the input data used is given in Table 5.1. The wind and consumption profile is equal for all the simulations and as stated in section 4.2, 4.3 and 4.4.

Table 5.1: Input data for base case

	Name	Parameter	Value	Unit
Diesel	Diesel fuel constant	A	0.246	l/kWh
	Diesel fuel constant	B	0.08415	l/kWh
	Power rating diesel engine	$P_{D,nom}$	100	kW
BESS	Battery voltage	V_B	520	V
	Battery current capacity	A_B	500	Ah
	Battery depth of discharge	DoD	70	%
	Maximum battery state of charge	$W_{B,max}$	260	kWh
	Minimum battery state of charge	$W_{B,min}$	78	kWh
	Maximum power to/from battery	$P_{B,max}$	100	kW
	Maximum battery through converter	$P_{CONV,max}$	150	kW
Dump	Minimum limit for dump load	$P_{DUMP,min}$	10	kW
	Maximum limit for dump load	$P_{DUMP,max}$	120	kW

Output curves for an arbitrary week (42 of 2012) are shown in Figure 5.1, and some of the most relevant output data is summarised in Table 5.2.

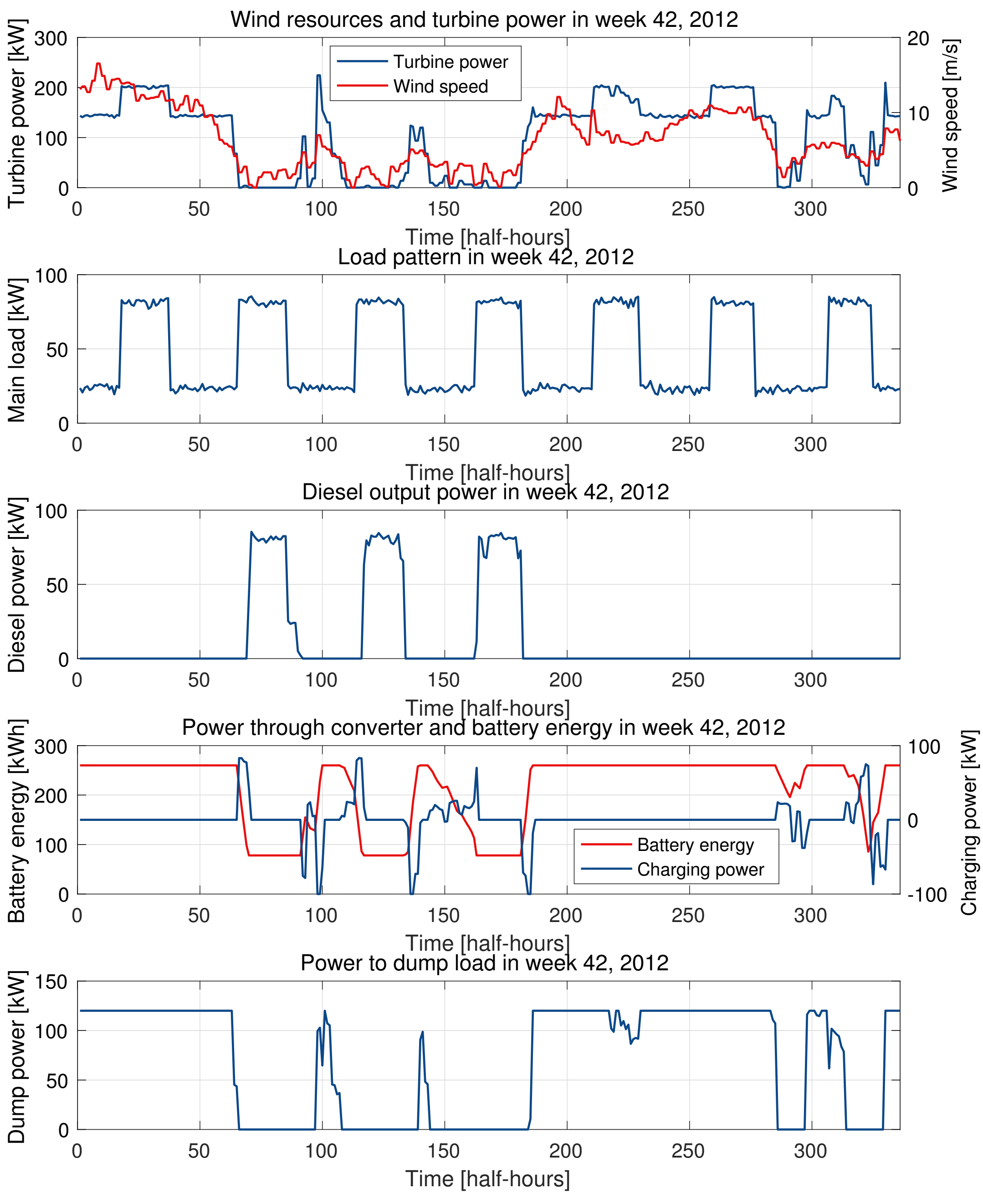


Figure 5.1: Base case, arbitrary week output

Table 5.2: Base case summary

Measure	Value	Unit
Diesel fuel	11 315	litres
Diesel energy delivered	28 480	kWh
Dump load energy consumed	795 199	kWh
Main load energy consumed	470 567	kWh
Wind turbine energy delivered	1 237 262	kWh
Lost energy due to derating	397 367	kWh
Hours with diesel in operation	512	hours
Number of diesel starts	113	times
Number of dump load starts	316	times
DE average power[1]	56	kW

From Table 5.2 it is seen that the energy produced by the WT is more than 40 times the energy produced by DE. The diesel fuel consumption is very low, as [16] reports of a diesel fuel consumption today of approximately 170 000 litres yearly. Thus, a yearly diesel fuel consumption of 11 315 litres is a reduction of about 93 %. With a diesel price of 11.43 NOK/litre [47] per 20.12.2016 , this involves an expenditure cut of 1.81 million NOK only in purchasing cost.

Moreover, the dump load consumes almost the double of the main load. Lost energy due to derating of the WT is almost 400 000 kWh yearly and implies that with the wind sources available, the WT *could* produce $(1237262 + 397367 =)$ 1 634 629 kWh. The number of DE and dump load starts are low and should not cause any trouble. Average DE power indicated how much power the DE delivers on average per hour it is in operation.

5.2.1 Sensitivity on battery capacity (BC1)

In this simulation all the input variables are the same as in base case (Table 5.1), except the sensitivity parameter which is the battery current capacity, A_B [Ah]. A wide range of A_B values have been used to cover most of the possible battery sizes. In specific A_B is varied between 1 Ah and 2000 Ah with an increment of 1 Ah. Thus, for the first increment the maximum battery capacity is $V_B \cdot A_B = 0.52$ kWh and for

[1]calculated as the sum of total diesel power divided by the numbers of hours in operation

$A_B = 2000$ Ah, then $W_{B,max} = 1040$ kWh. For each battery capacity, the system state is simulated over one year.

Five relevant curves are shown in Figure 5.2-5.6. They show energy produced by DE and WT, energy lost, dump load energy and fuel consumption for each battery capacity. Further, some system characteristics are summarised in Table 5.3. A brief explanation of the main trends is also given.

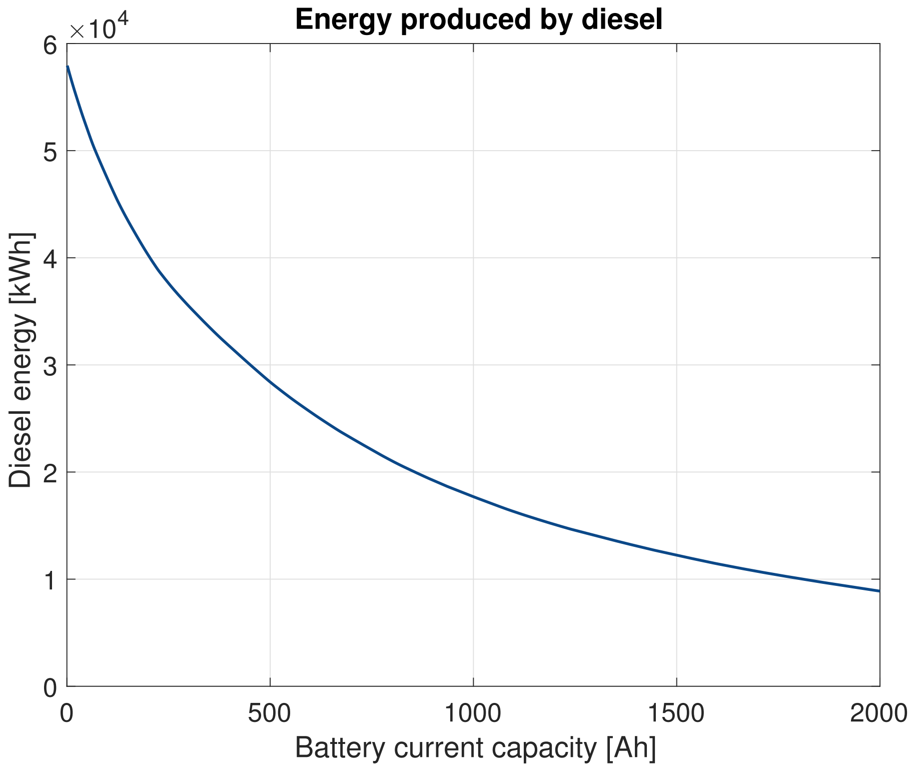


Figure 5.2: BC1, Energy produced by DE

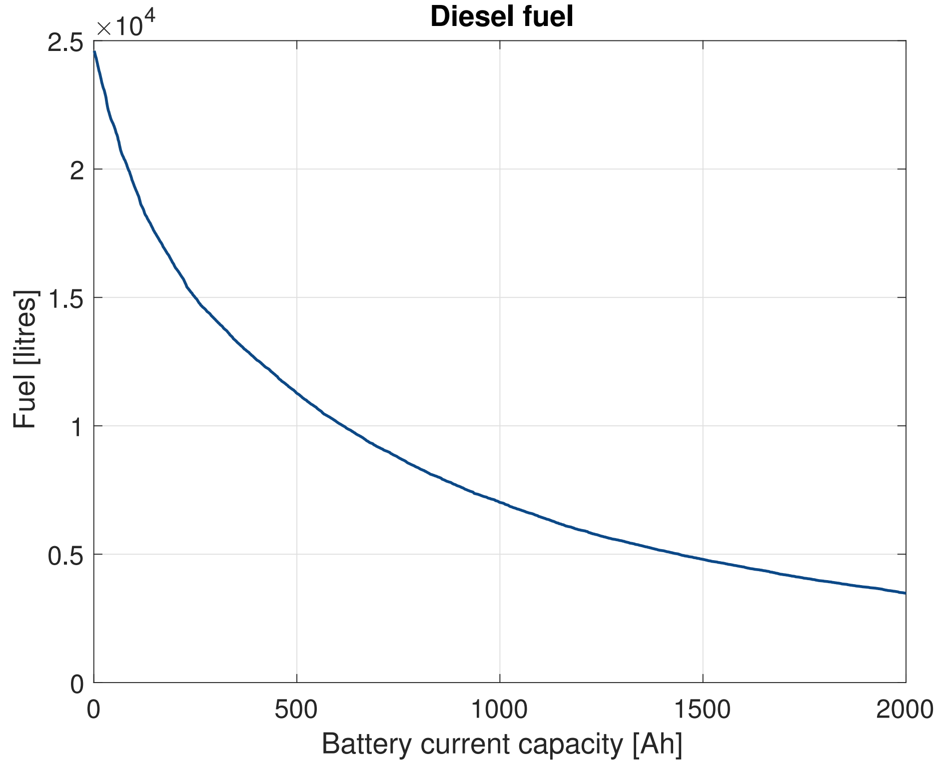


Figure 5.3: BC1, Fuel consumed by by DE

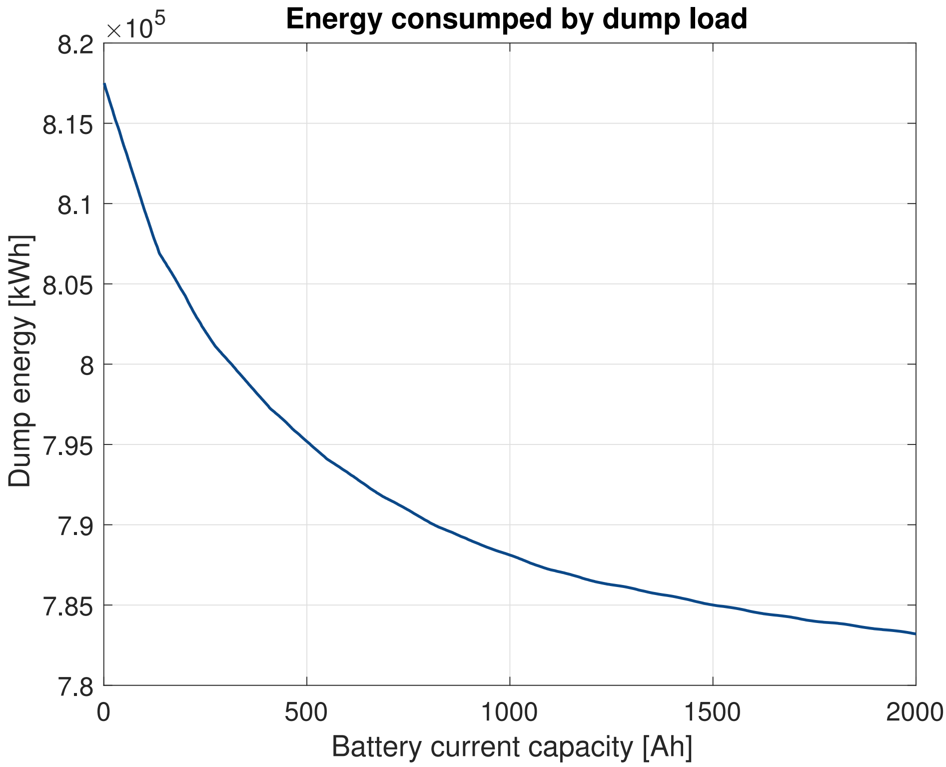


Figure 5.4: BC1, Energy consumed by dump load

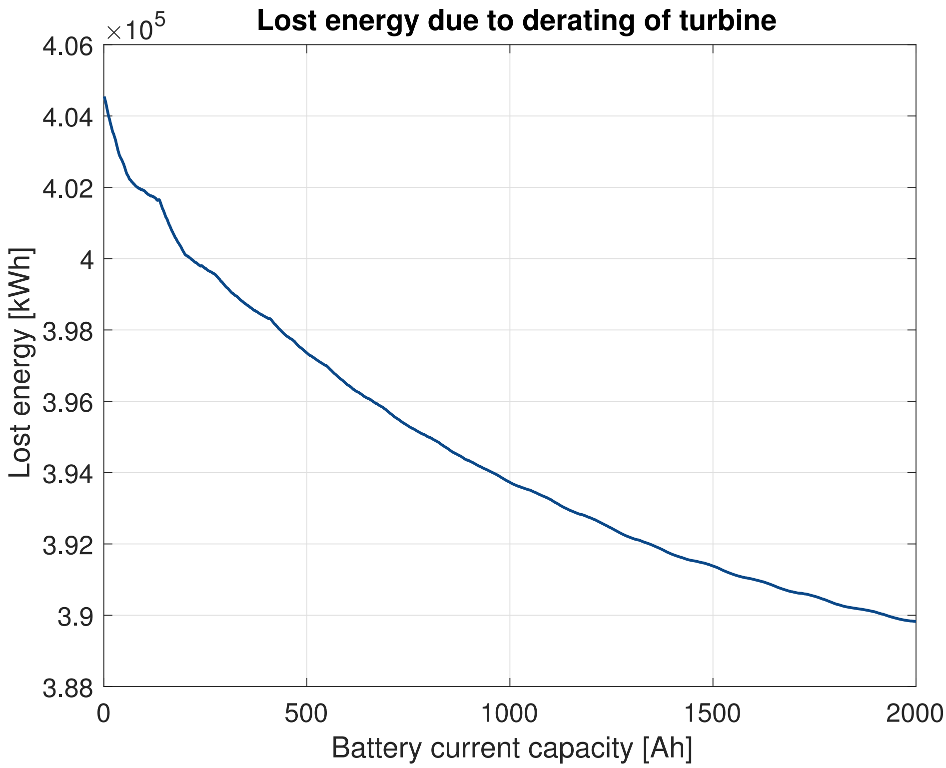


Figure 5.5: BC1, Energy lost due to derating of WT

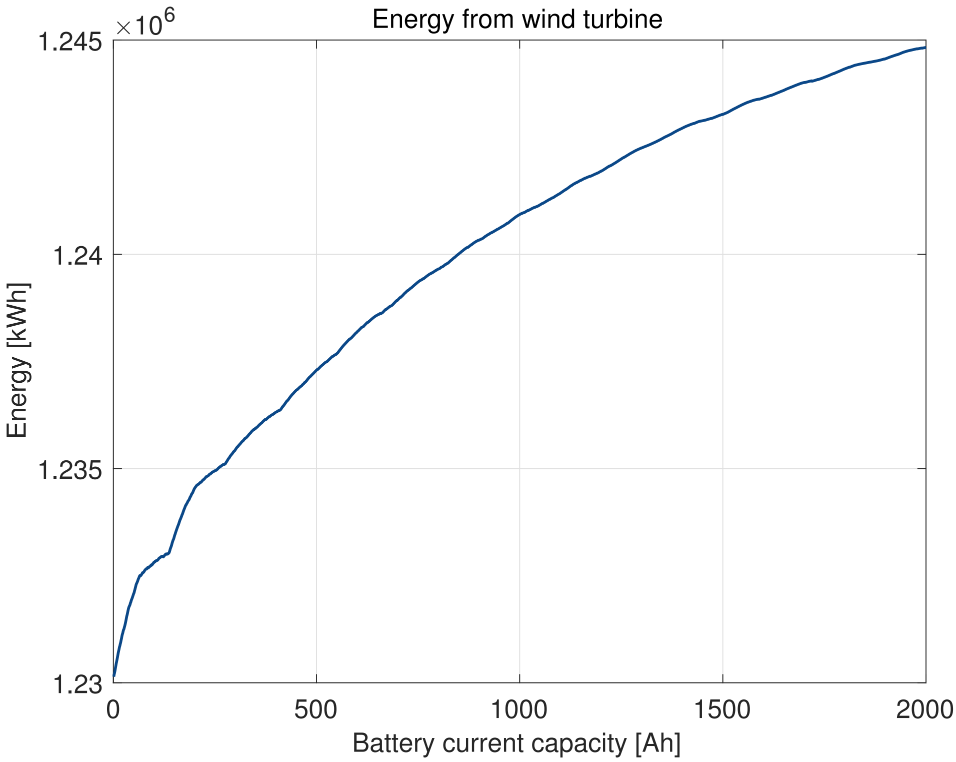


Figure 5.6: BC1, Energy produced by WT

Table 5.3: Summary of battery size sensitivity

	Value A_B [Ah]			
Measure	**1**	**1000**	**2000**	**Unit**
Diesel fuel	24 600	7 017	3 481	litres
Diesel energy delivered	57 940	17 700	8 881	kWh
Dump load energy consumed	817 500	788 100	783 200	kWh
Main load energy consumed	470 370	470 370	470 370	kWh
Wind turbine energy delivered	1 230 142	1 240 928	1 244 828	kWh
Lost energy due to derating	404 500	393 700	389 800	kWh
Hours with diesel in operation	1228	317	154	hours
Number of diesel starts	390	57	24	times
Number of dump load starts	417	370	368	times
Diesel average power	47	56	58	kW

The yellow rows in Table 5.3 depicts the parameters that are most affected by changes in the battery size. Evidently changing the battery capacity has largest impact on the DA. Fuel consumed, energy delivered, number of hours in operation and number of diesel starts can be reduced drastically by increasing the capacity. It should be noted, however, that the reduction is larger when changing A_B from 1 Ah to 1000 Ah, than from 1000 Ah to 2000 Ah. This can be clearly seen from the above figures as well, where the derivative of all the curves is declining. Obviously, at some point (above 2000 Ah) the battery will have sufficient capacity so that the DA is not longer needed. So why will this most likely not be the best solution, even though the diesel can be removed totally? Firstly, the reduction in operation and maintenance (O&M) cost for DE have to be traded off against the O&M cost of battery. Another important aspect is that the DA can most likely not be removed totally. Because in a case of battery and/or turbine failure, one needs redundancy in the system.

5.2.2 Sensitivity on depth of discharge (BC2)

In this sensitivity analysis, DoD varies from 0.05 to 0.9 with an increment of 0.05. The rest of the input values remains as in base case. Hence, maximum battery capacity is fixed at $W_{B,max} = V_B \cdot A_B = 260$ kWh, but minimum battery capacity changes as this depends on the DoD:

$$W_{B,min} = (1 - DoD) \cdot W_{B,max}$$

The five main curves are shown in 5.7-5.11, and a summary is given in Table 5.4.

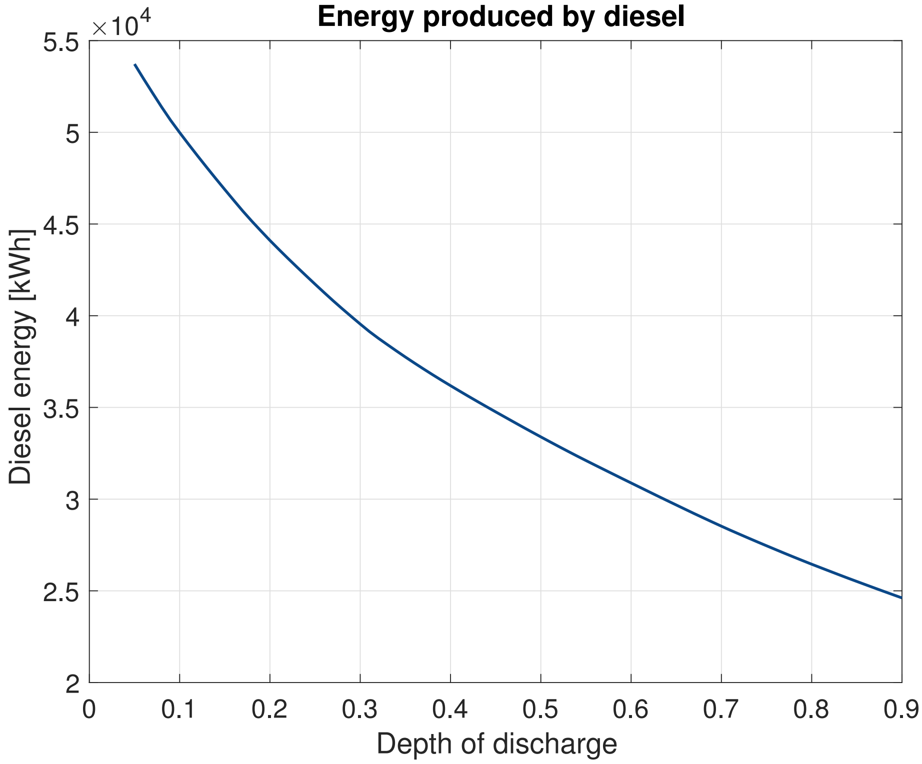


Figure 5.7: BC2, Energy produced by DE

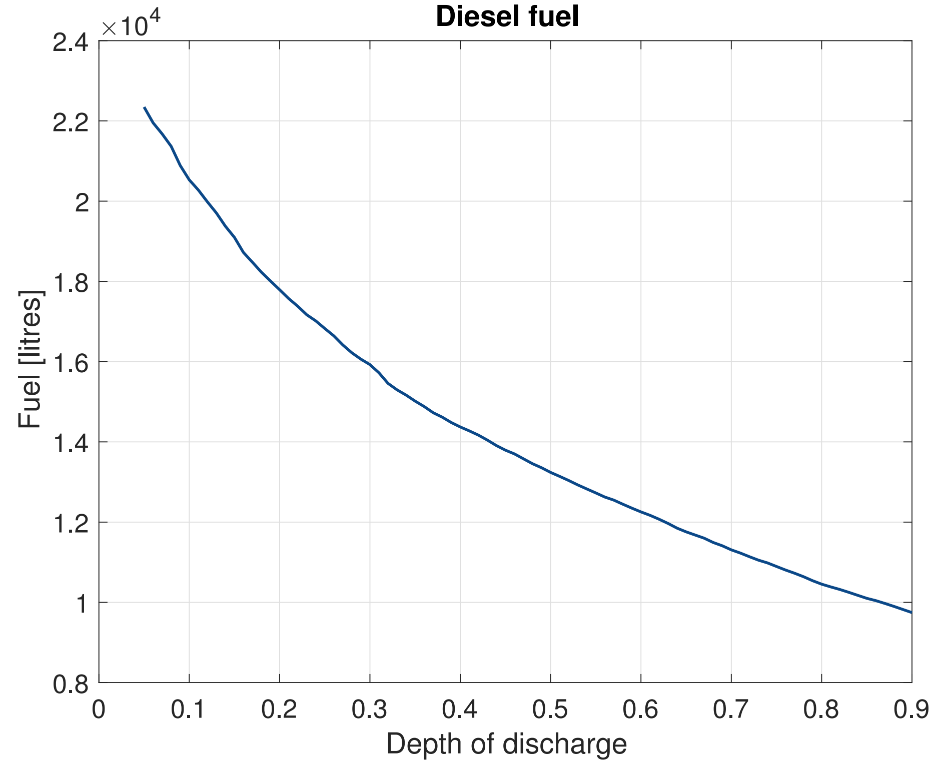


Figure 5.8: BC2, Fuel consumed by by DE

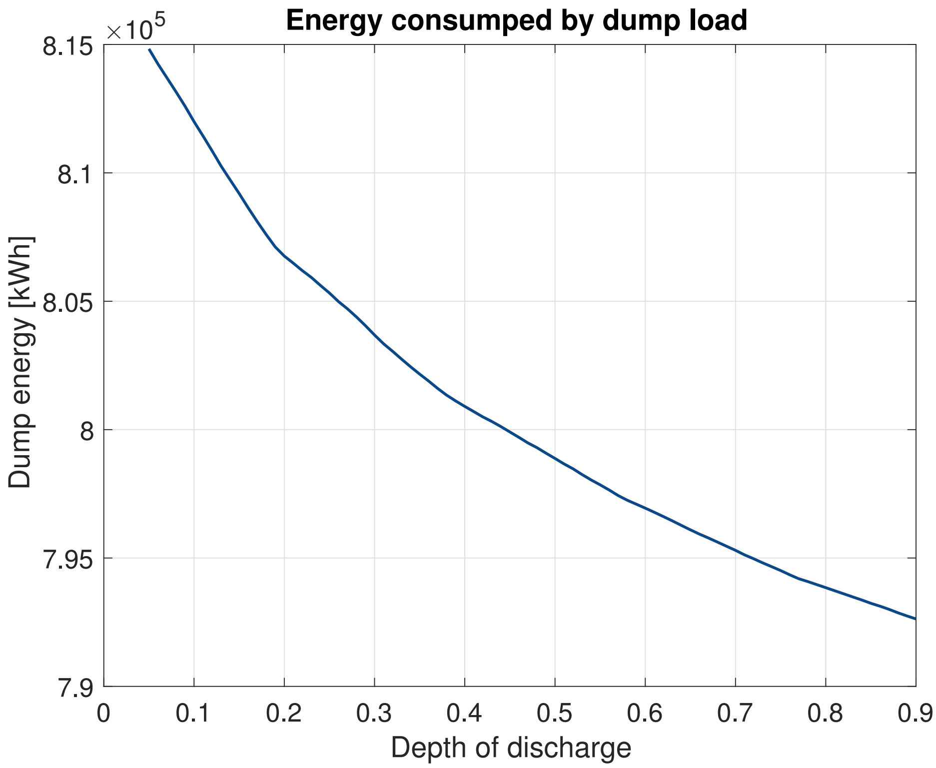


Figure 5.9: BC2, Energy consumed by dump load

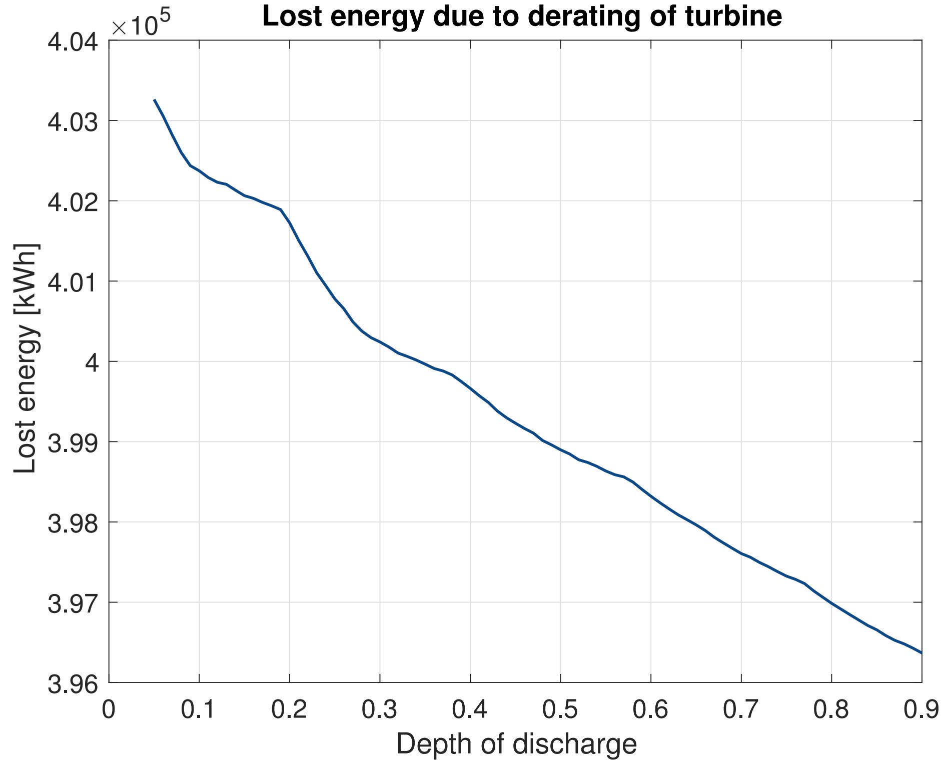


Figure 5.10: BC2, Energy lost due to derating of WT

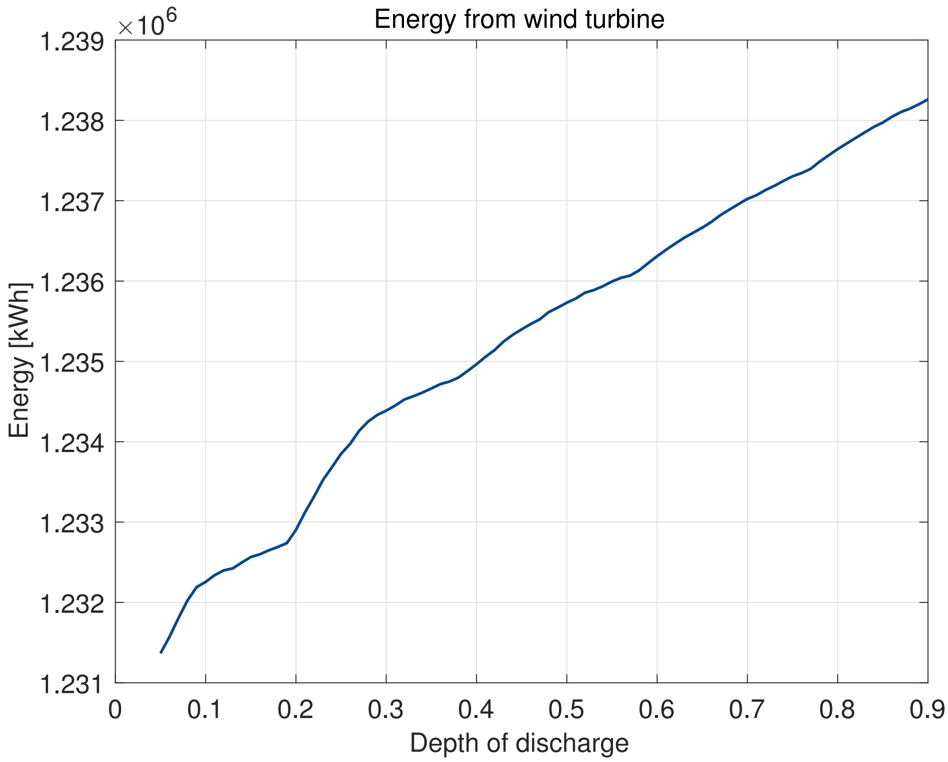


Figure 5.11: BC2, Energy produced by WT

Table 5.4: Summary of DoD sensitivity

	Value *DoD*			
Measure	**0.05**	**0.45**	**0.9**	**Unit**
Diesel fuel	22 350	13 790	9745	litres
Diesel energy delivered	53 720	34 760	24 610	kWh
Dump load energy consumed	814 800	799 990	792 600	kWh
Main load energy consumed	470 370	470 370	470 370	kWh
Wind turbine energy delivered	1 231 365	1 235 399	1 238 261	kWh
Lost energy due to derating	403 300	399 200	396 400	kWh
Hours with diesel in operation	1085	623	439	hours
Number of diesel starts	337	138	86	times
Number of dump load starts	409	364	369	times
Diesel average power	50	56	56	kW

A higher depth of discharge results effectively in more battery capacity and thus reduced use of DA, as expected. Increasing the DoD from 0.05 to 0.9 almost halves the diesel fuel, energy delivered by DE and hours with diesel in operation. But the largest impact is seen from the number of diesel starts. This is reduced by 74% over the sensitivity interval. Thus, increasing the DoD implies more battery storage available, less energy produced by DG, less fuel consumed by DE, more WT power delivered and ultimately slightly less energy lost due to derating.

5.2.3 Sensitivity on maximum power to/from battery (BC3)

This type of sensitivity investigates the impact of maximum power flow to and from the battery. As the battery has a maximum power rating and the coherent power converter also has a maximum power rating, the maximum power to and from the battery will be limited by the smallest value of these two ratings. Therefore, in order to simulate this, $P_{B,max}$ is set to 260 kW (more than max power from turbine and max power to load), and $P_{CONV,max}$ is varied between 5 and 250 kW with an increment of 0.5 kW. Thus, $P_{CONV,max}$ represents the minimum value of max battery power and max converter power in this simulation. The five main curves are shown in 5.12-5.16, and a summary is given in Table 5.5.

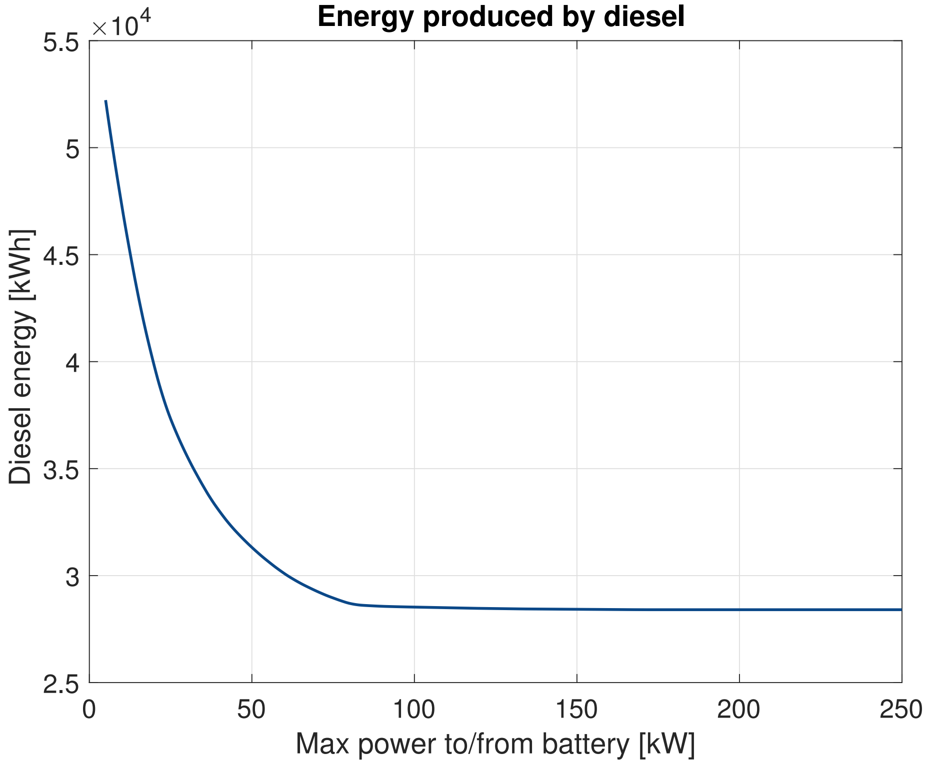


Figure 5.12: BC3, Energy produced by DE

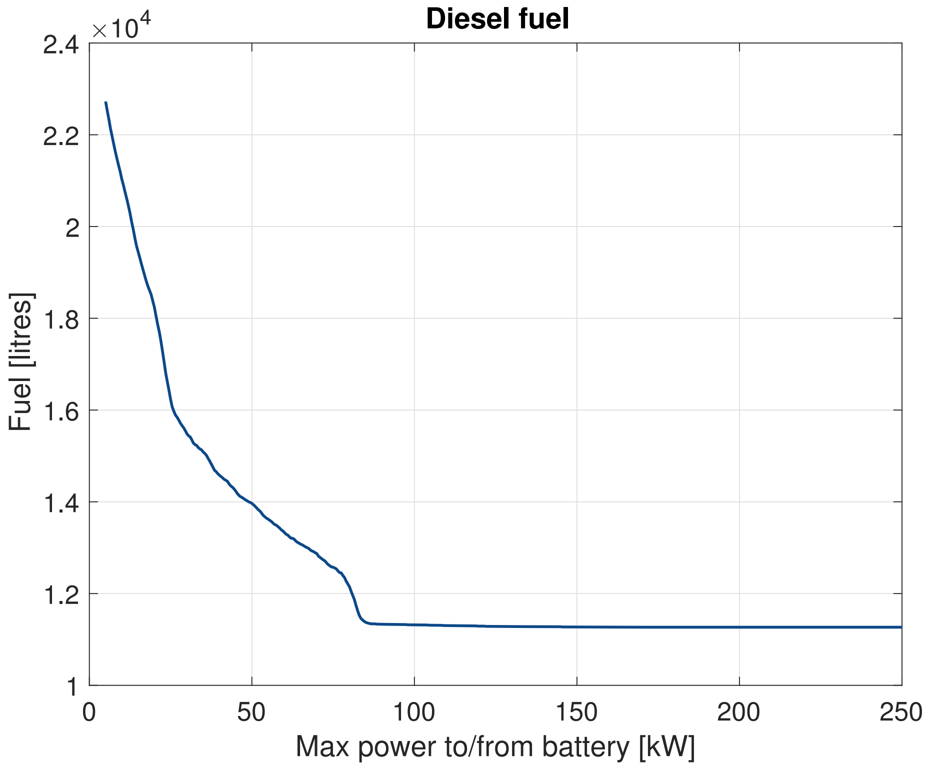


Figure 5.13: BC3, Fuel consumed by by DE

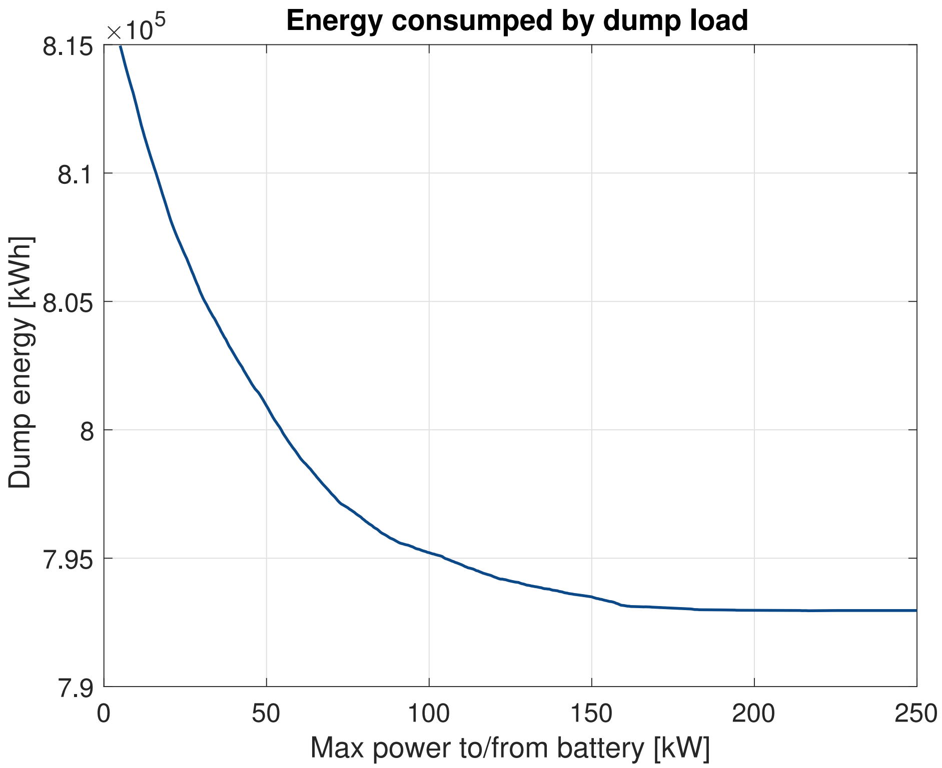


Figure 5.14: BC3, Energy consumed by dump load

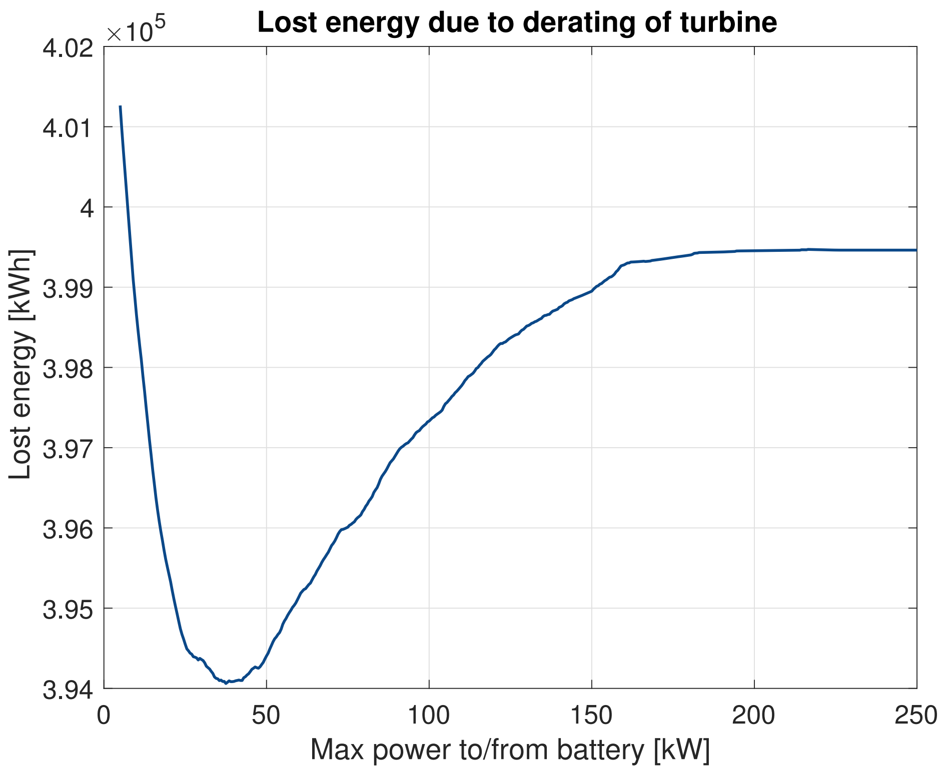


Figure 5.15: BC3, Energy lost due to derating of WT

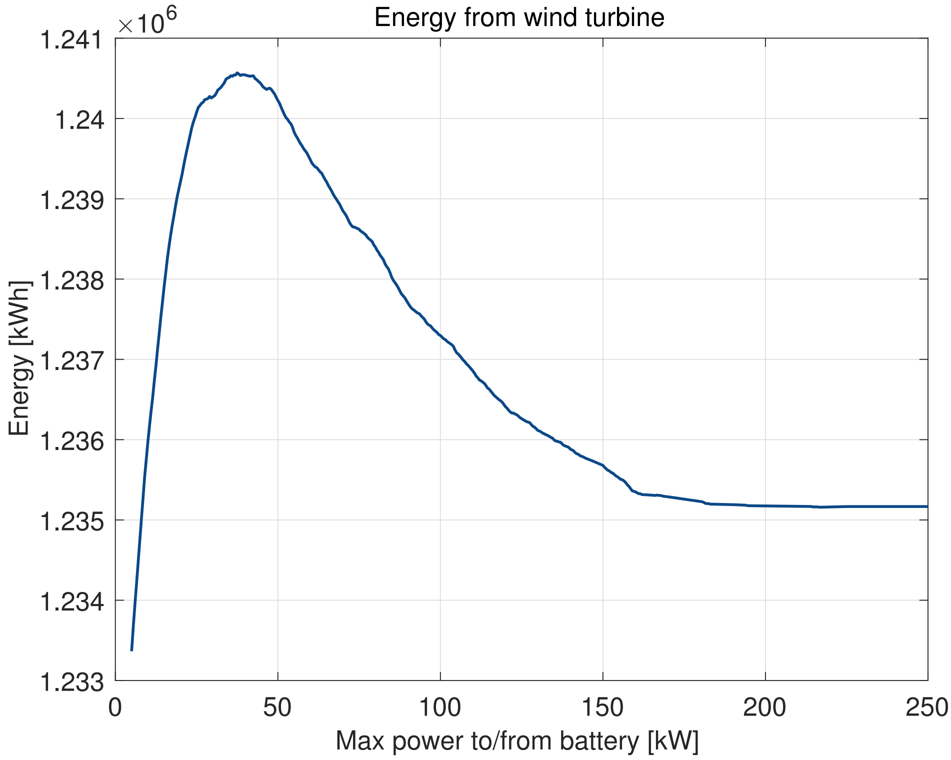


Figure 5.16: BC3, Energy produced by WT

Table 5.5: Summary of battery power sensitivity

	Value $P_{B.max}$ [kW]			
Measure	**5**	**70**	**250**	**Unit**
Diesel fuel	22 730	12 870	11 270	litres
Diesel energy delivered	52 220	29 270	28 410	kWh
Dump load energy consumed	815 000	797 500	793 000	kWh
Main load energy consumed	470 370	470 370	470 370	kWh
Wind turbine energy delivered	1 233 365	1 238 849	1 235 165	kWh
Lost energy due to derating	401 300	395 800	399 500	kWh
Hours with diesel in operation	1174	674	509	hours
Number of diesel starts	393	192	111	times
Number of dump load starts	413	374	342	times
Diesel average power	45	43	56	kW

An increase in power leads to reduced need for diesel, which is similar to the results in BC1 and BC2. However, Figure 5.12 and 5.13 indicates that above approximately 84 kW there is no further impact on fuel consumption and energy from DG. This is because the main load has a peak value of about 84 kW. So, for a max battery power limit of less than ≈84 kW, the battery cannot provide the entire load even if it has sufficient energy to do so. This will cause the diesel to start and deliver power more often. But, for values above 84 kW this will no longer be a constraining factor.

5.2.4 Sensitivity on lower dump load margin (BC4)

A sensitivity analysis on the lower dump load margin is presented in this section. To clarify one more, the lower dump load margin denotes the lowest power that the dump can accept to run. If the surplus power available is less than this limit, dump load will not be used and the turbine is derated instead. In conventional hybrid systems, this limit does not exist, but in this particular system, the dump load is actually electrical machines or drives that should not be operated below a certain power limit. This is what the margin aims to represent. In this analysis, $P_{DUMP,min}$ changes from 1-40 kW with an increment of 0.5 kW. The five main curves are shown in 5.17-5.21, and a summary is given in Table 5.6.

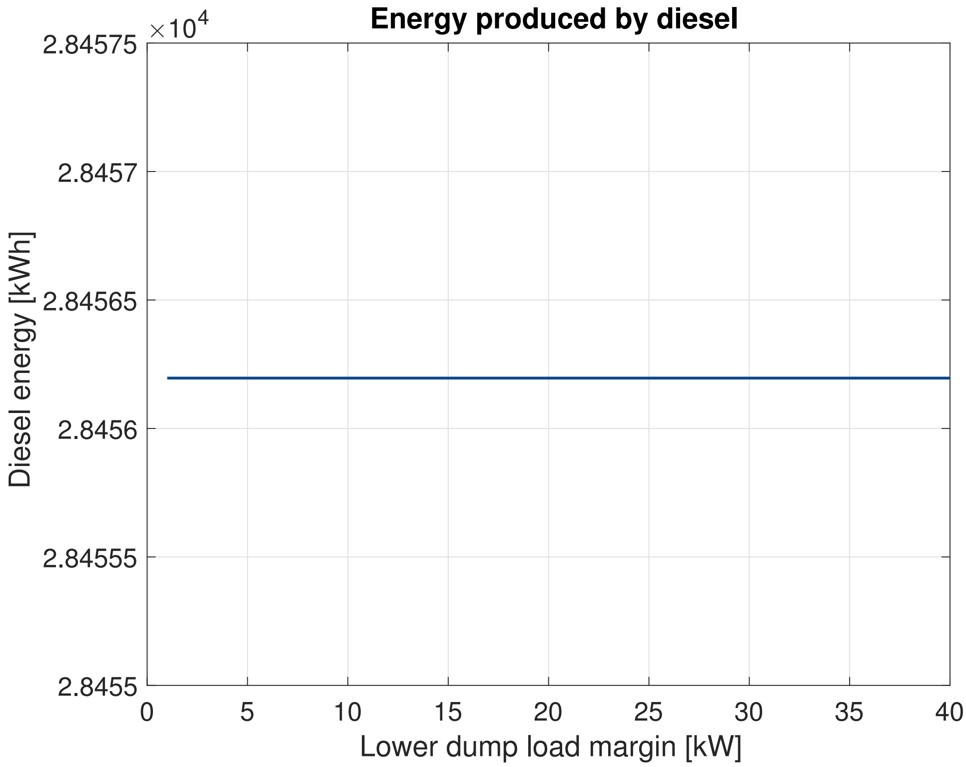


Figure 5.17: BC4, Energy produced by DE

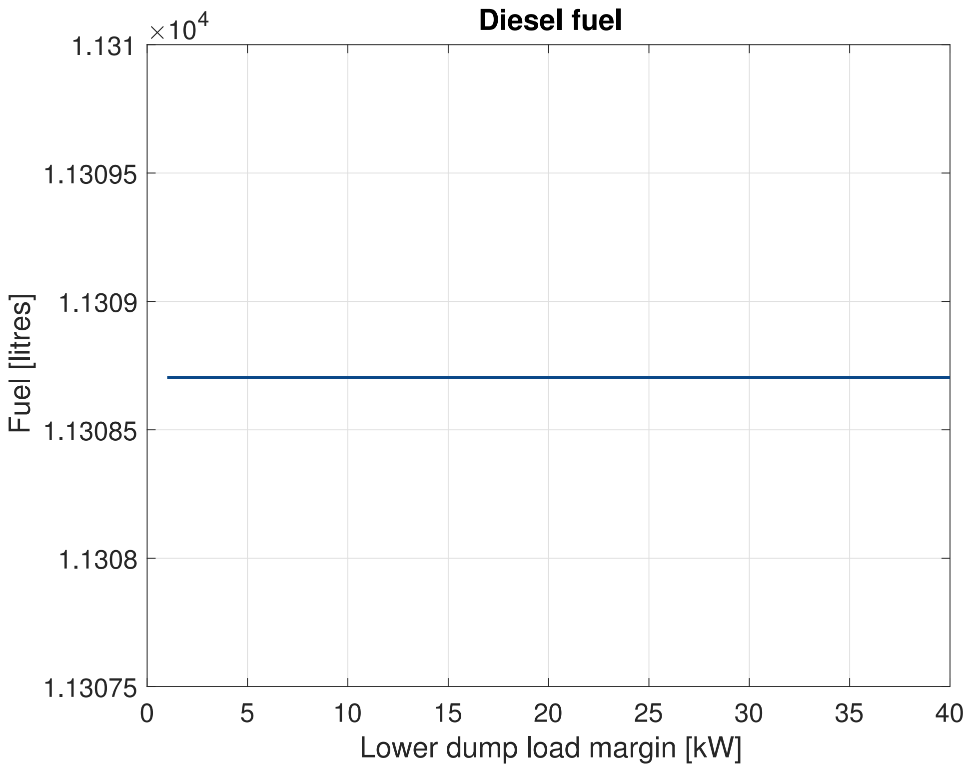


Figure 5.18: BC4, Fuel consumed by by DE

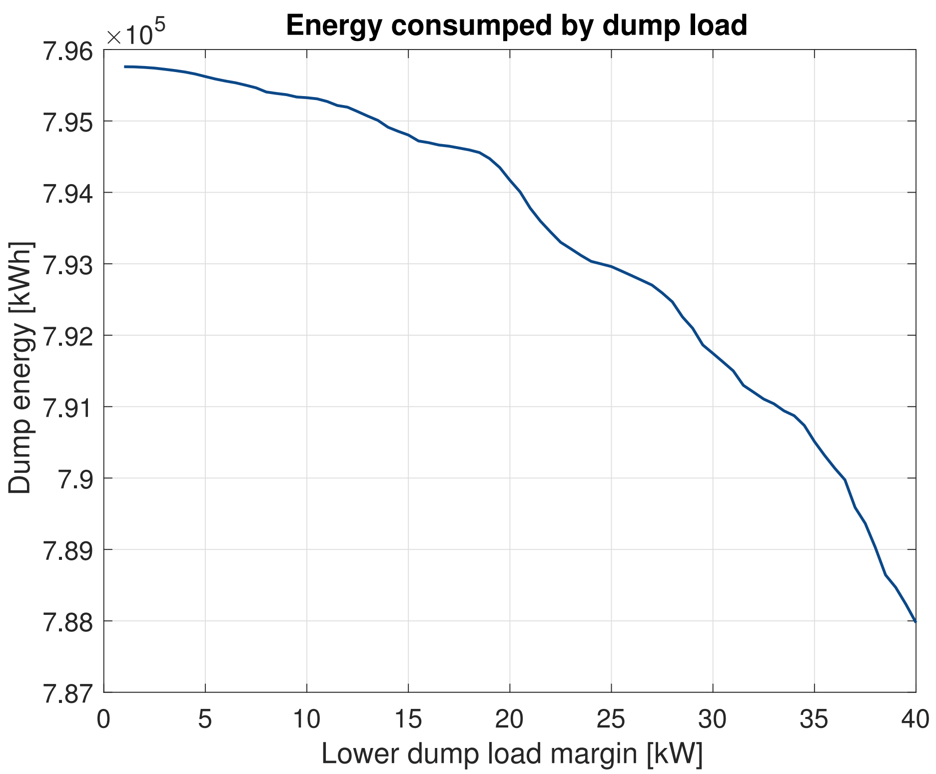


Figure 5.19: BC4, Energy consumed by dump load

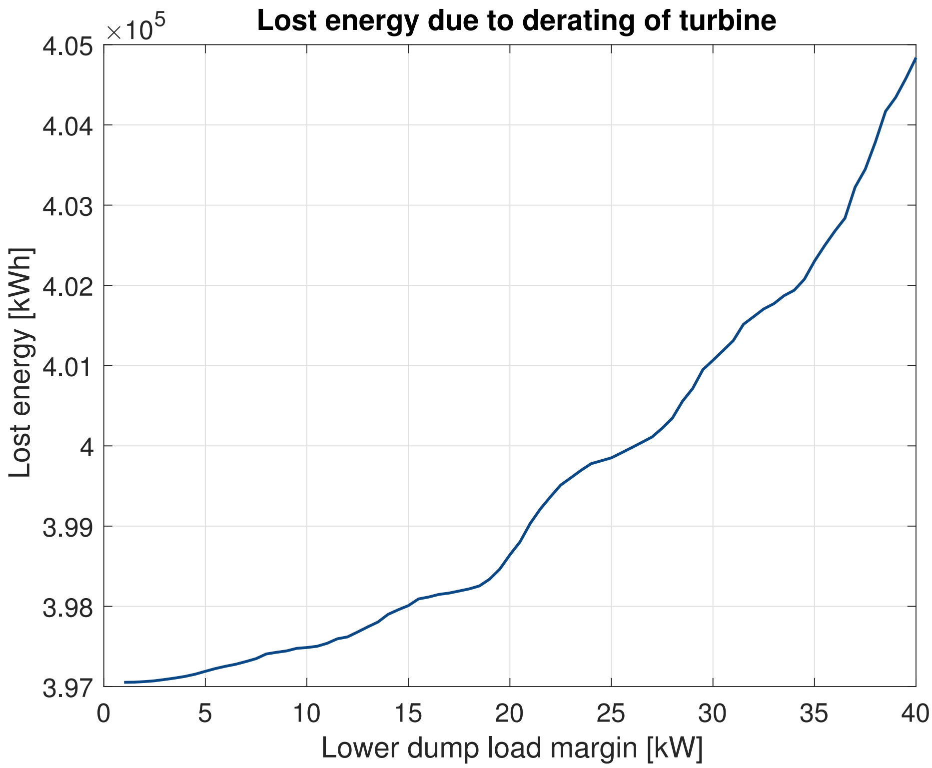


Figure 5.20: BC4, Energy lost due to derating of WT

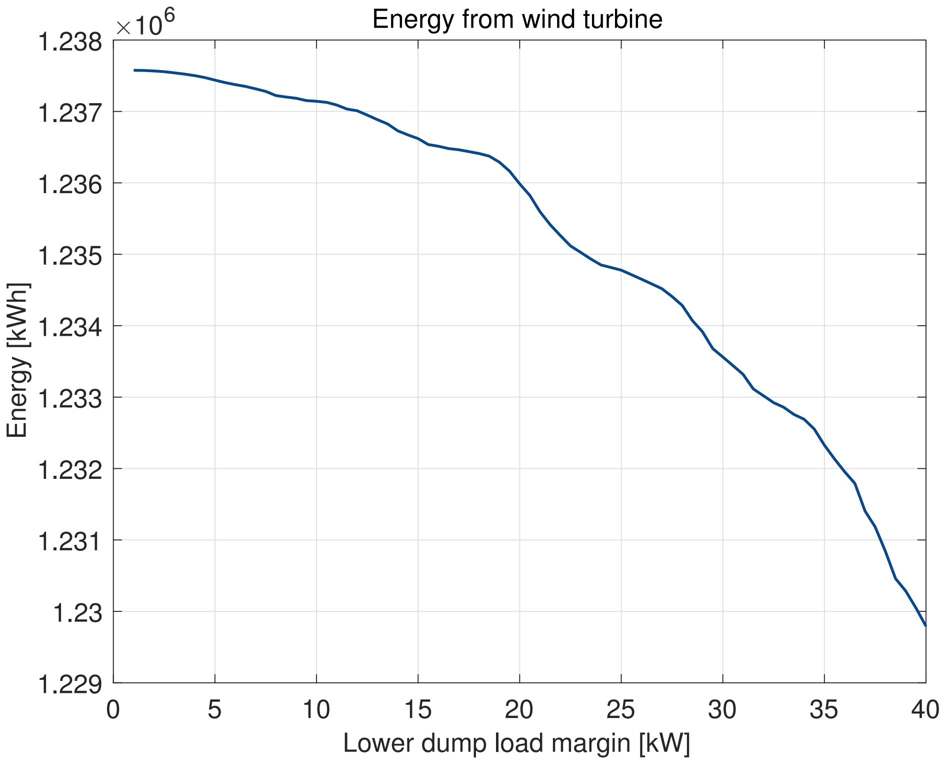


Figure 5.21: BC4, Energy produced by WT

Table 5.6: Lower dump load margin sensitivity

	Value $P_{DUMP,min}$ [kW]			
Measure	**1**	**20**	**40**	**Unit**
Diesel fuel	11 310	11 310	11 310	litres
Diesel energy delivered	28 456	28 456	28 456	kWh
Dump load energy consumed	795 800	794 200	788 000	kWh
Main load energy consumed	470 370	470 370	470 370	kWh
Wind turbine energy delivered	1 237 575	1 235 988	1 229 792	kWh
Lost energy due to derating	397 100	398 600	404 800	kWh
Hours with diesel in operation	512	512	512	hours
Number of diesel starts	114	114	114	times
Number of dump load starts	339	400	425	times
Diesel average power	56	56	56	kW

Opposite to the previous sensitivity cases, changing the dump load margins does not affect the diesel operation at all. This is because dump load is only used whenever there is a surplus of wind energy compared to main load. What is seen from the figures and Table 5.6, is that changing the margin from 1-40 kW does not affect the system significantly. Energy consumed by the dump load decreases slightly, it has to start a little more frequent and the lost energy increases with about 8000 kWh.

5.2.5 Sensitivity on upper dump load margin BC5

The electrical machines constituting the dump load cannot consume an infinite amount of power. This is what the upper dump load margin represents. Here it has been varied from 20 kW to 250 kW with an increment of 1 kW. The five main curves are shown in 5.22-5.26, and a summary is given in Table 5.7.

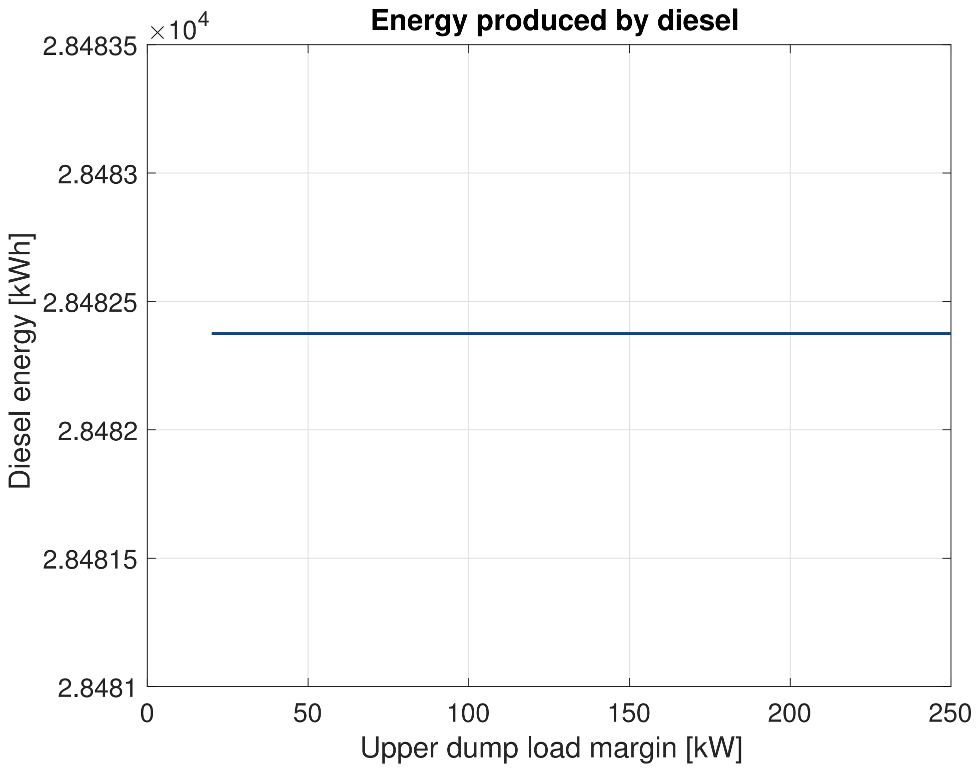


Figure 5.22: BC5, Energy produced by DE

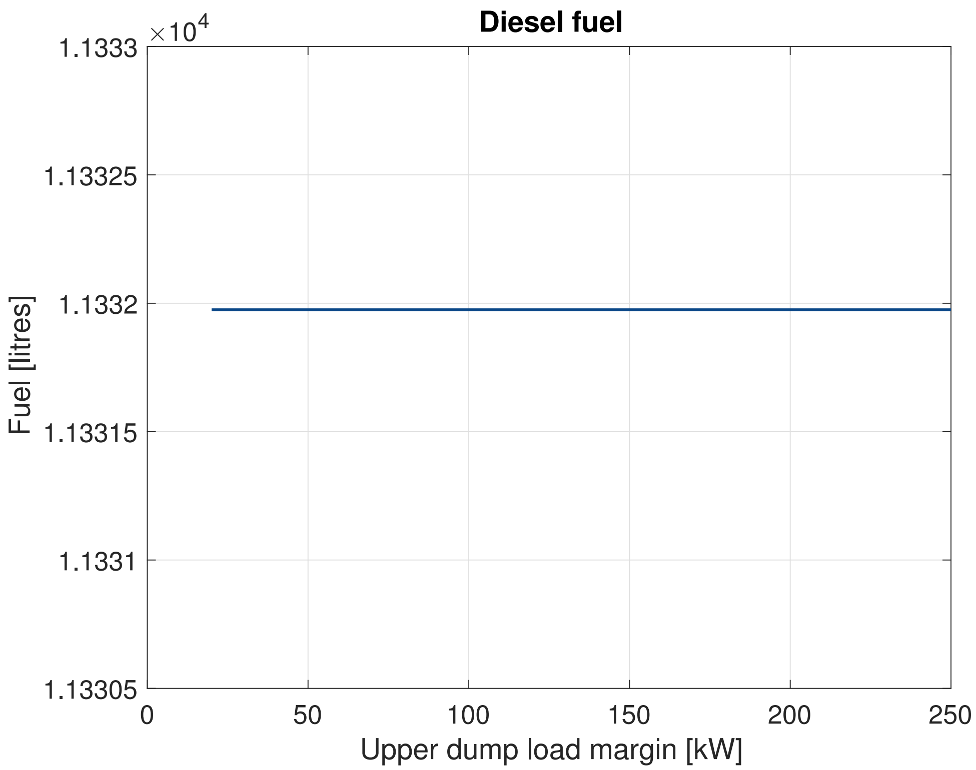


Figure 5.23: BC5, Fuel consumed by by DE

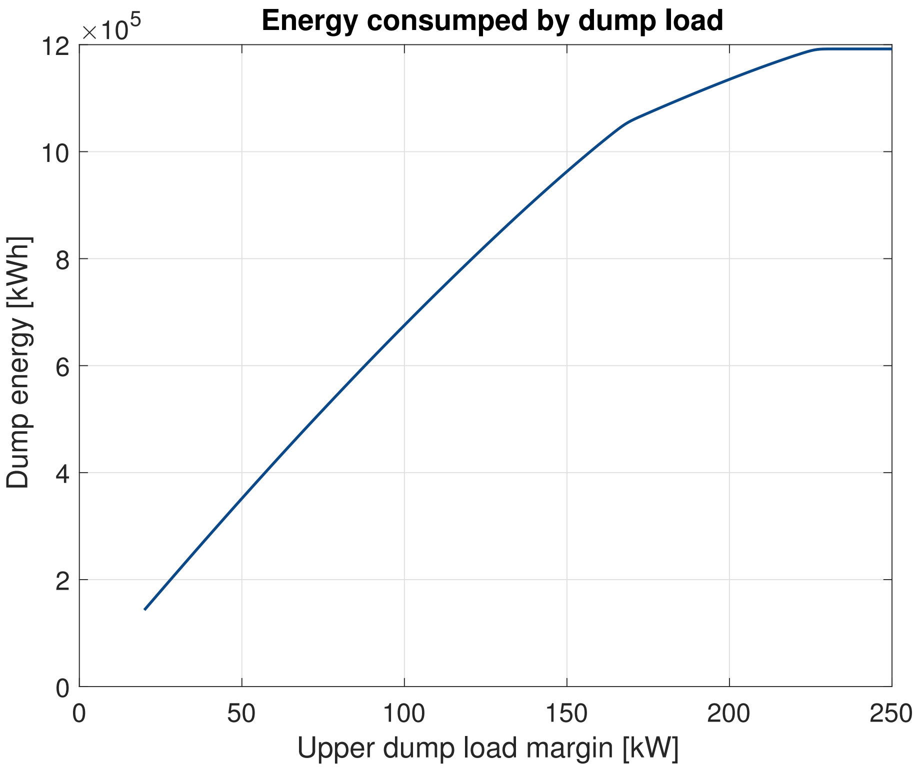


Figure 5.24: BC5, Energy consumed by dump load

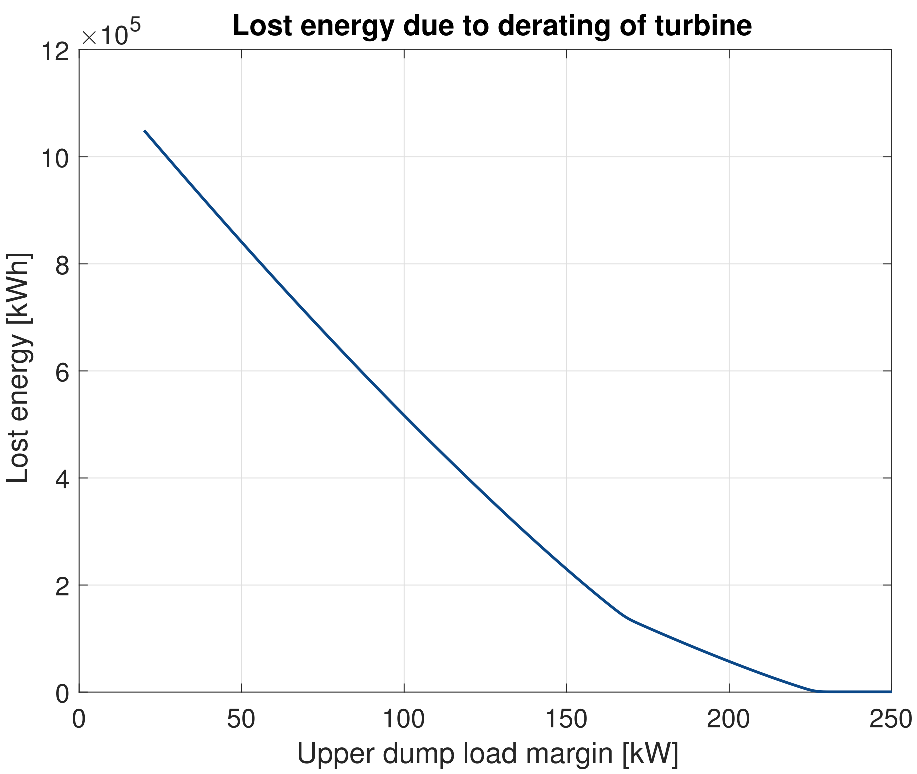


Figure 5.25: BC5, Energy lost due to derating of WT

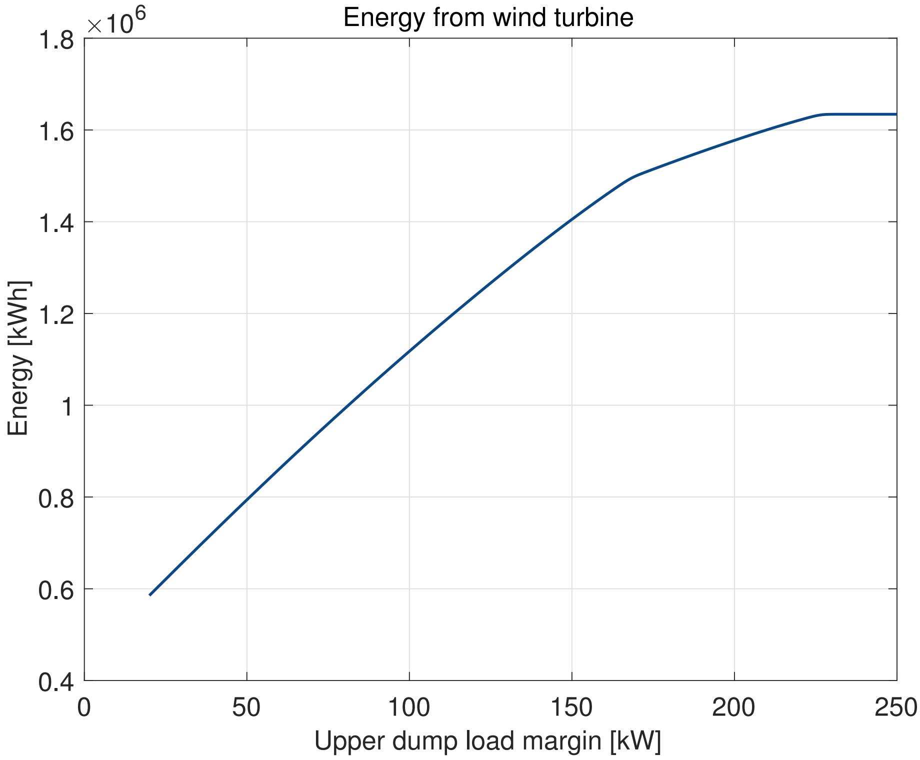


Figure 5.26: BC5, Energy produced by WT

Table 5.7: Upper dump load margin sensitivity

	Value $P_{DUMP,max}$ [kW]			
Measure	**20**	**125**	**250**	**Unit**
Diesel fuel	11 332	11 332	11 332	litres
Diesel energy delivered	28 483	28 483	28 483	kWh
Dump load energy consumed	143 100	824 300	1 192 035	kWh
Main load energy consumed	470 370	470 370	470 370	kWh
Wind turbine energy delivered	585 300	1 266 480	1 634 210	kWh
Lost energy due to derating	1 049 000	368 100	424	kWh
Hours with diesel in operation	514	514	514	hours
Number of diesel starts	112	112	112	times
Number of dump load starts	365	365	365	times
Diesel average power	56	56	56	kW

Changing the upper dump load margin does not affect the diesel operation at all, but it has massive impact on the three factors marked yellow in Table 5.7. The lost energy due to derating can almost be eliminated totally by increasing $P_{DUMP,max}$ to around

250 kW. On the contrary, with a low margin of 20 kW leads to 65% of the available wind energy are lost. Thus, the size of the dump load apparatus heavily influences the energy produced by the WT.

5.3 Special case 1: Wind only (WO)

An analysis of the system with only one EWT DW52250 wind turbine to cover the main load is carried out. The main purpose is to investigate the energy produced by the wind turbine, number of hours with insufficient wind to cover the main load. The simulation for 2012 shows that total energy produced by WT is 1 634 329 kWh, and that the total number of hours with insufficient wind is 1234 - or about 14% of the time.

Furthermore, the average energy produced per year, for all the available wind data points, have been calculated. This resulted in a yearly average of 1 521 183 kWh. Thus, the values for 2012 lies slightly above the average (7% above), and can therefore be considered a representative year. It should be noted that in order to account for the leap years, one year is here defined as 365.25 days or 8766 hours.

The procedure on how the yearly average energy produced have been obtained should be described briefly: All the data from the wind time series have been used. This means 119 277 hours from 1994 to 2014. However, there is a lot of data missing in the time interval due to failure on the measurement equipment. If every hour for every day between 1994 and 2014 had been recorded, the total data set would have $24 \cdot 365.25 \cdot 21 = 184\ 086$. Thus 119 277 indicates a loss of 64 809 hours, or 7.39 years effectively, when using the definition of one year as described above. Therefore, the effective number of years in the wind times series given is $21 - 7.39 = 13.61$ years.

5.4 Special case 2: Diesel only (DO)

This simulation have been carried out, just to verify the validity of the diesel fuel equation (3.4). As mentioned earlier, [16] reports that yearly the diesel fuel on a fleet of similar size is around 170 000 litres/year, when diesel generators is the only source of supply. Simulating over one year gave $D_f = 189\ 699$ litres/year. This is about 10% off, but it also means that the diesel fuel values obtained from the simulations in this project is most likely a slight overestimate.

5.5 Special case 3: Diesel and wind turbine (WD)

The last simulation in this project is similar to the base case, but here the battery is removed. Figure 5.27 illustrates system behaviour for the same week (42, 2012) as was used for the base case. A quick comparison shows a tendency of longer and more frequent diesel aggregate operation. In addition the dump load starts more often. Table 5.8 also shows this tendency.

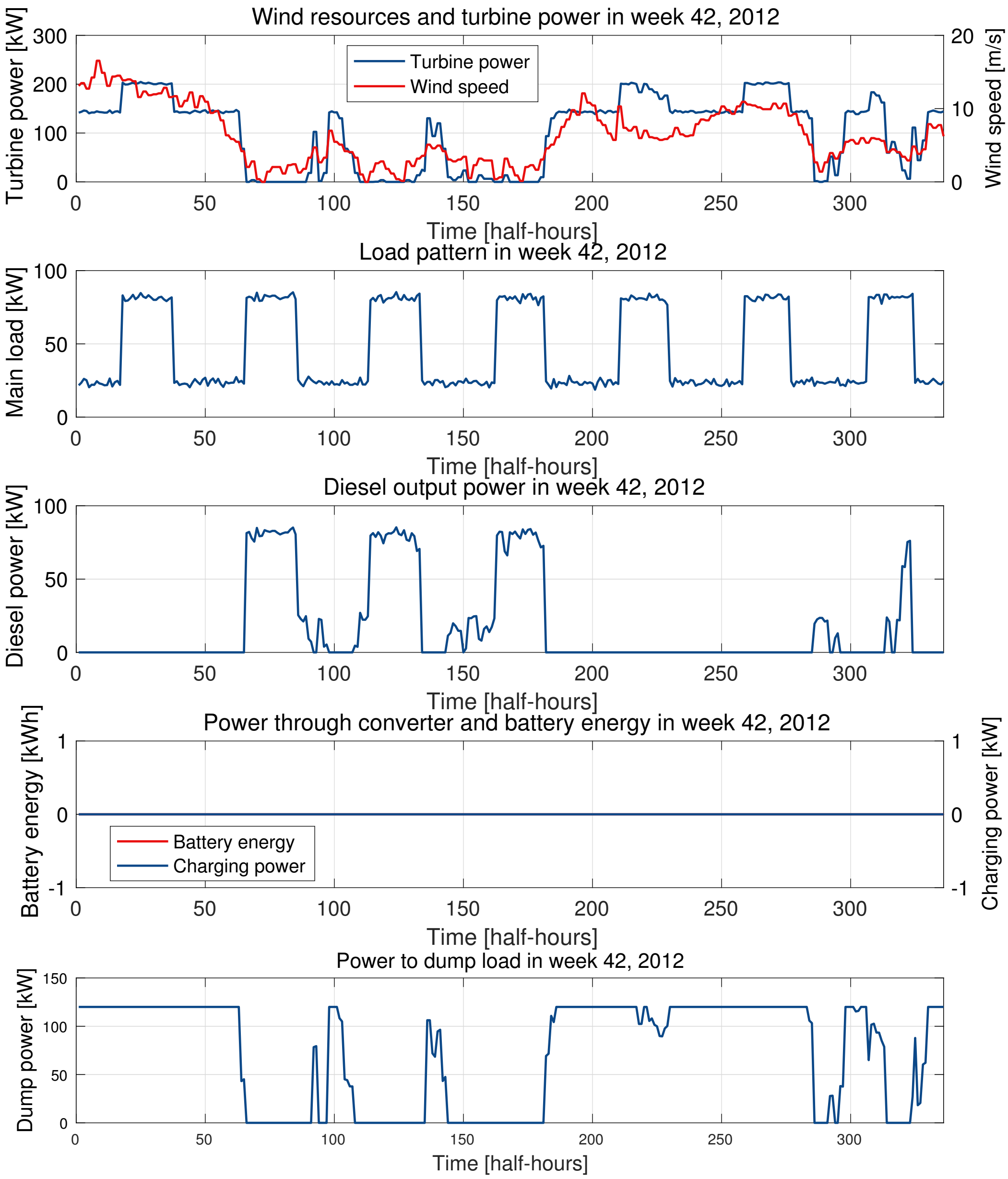


Figure 5.27: Wind-diesel, arbitrary week output

Table 5.8: Wind-diesel summary

Measure	Value	Unit
Diesel fuel	24 630	litres
Diesel energy delivered	58 011	kWh
Dump load energy consumed	817 738	kWh
Main load energy consumed	470 270	kWh
Wind turbine energy delivered	1 230 001	kWh
Lost energy due to derating	404 628	kWh
Hours with diesel in operation	1234	hours
Number of diesel starts	398	times
Number of dump load starts	412	times
DE average power	47	kW

This table shows very similar results to the results from BC1 with a battery current capacity of 1 Ah (Table 5.3, which is expected. *One important result that should be noted is that diesel fuel reduces from about 170 000 litres/year originally, to about 25 000 litres/year solely by including the EWT turbine.* This is quite radical, as it implies that the wind sources at the location are so good that a large battery may not be needed (or economically feasible).

6 | Conclusions

This project comprises an introduction to a hybrid wind-diesel solution for fish farming applications. First, chapter 2 and 3 gives a sound theoretical basis to the Norwegian fish farming industry and the different components constituting a hybrid wind-diesel system. These are important aspects as understanding the system and the industry are crucial concepts for further work on the topic.

An energy storing element is included in the hybrid system to increase flexibility and renewable penetration. The energy storing element is chosen to be a battery system, due to its cost, physical size and ability of long-term and short-term storage. In this project battery transients below 30 minutes are not looked into, hence the battery can be interpreted as a long-term storage. Multiple battery types are available on the market today, which all have their strengths and weaknesses. Key factors for choosing the appropriate technology for this purpose are connected to:

1. Safety, low possibility of leakage
2. No toxic components are desirable
3. Low need for maintenance and a relatively long cycle life
4. Able to endure frequent and partial charging/discharging at both high and low powers
5. As low cost as possible

Flow, lithium-ion and advanced lead-acid fulfils most of the aforementioned criteria, but have the drawback of higher price than traditional lead-acid and nickel batteries. Thus, a future decision connected to battery chemistry has to include both investment and maintenance costs.

In chapter 4, the modelling of each input variable was explained. The wind profile is time series based, measured at the proposed location and transformed to hub height. Average wind speed in the period 1994-2014 is 8.7 m/s, which can be considered very good. Further, the main load is constructed by means of a deterministic and a stochastic part, in order to reflect the fleets consumption profile as accurate as possible. Yearly main load energy consumption is expected to be around 470 000 kWh. The dump load is intended to consist of electrically driven equipment for production of O_2, freshwater and high pressure washer for sea lice removal. Detailed physics and realistic energy consumption of these components have not been acquired yet, but a special focus will be aimed towards this in the consecutive master thesis. An EWT DW52250, 250 kW wind turbine has been chosen for running the simulations. This shows promising characteristics and will be looked further into. Each of the components were modelled in MATLAB. Ultimately a control strategy based on logical system decisions, were implemented in order to assess system behaviour during one year.

In chapter 5, several simulations were carried out. The base case was formed by chosen, but realistic input values, just to provide a stating point for the sensitivity analyses. These showed that increased battery capacity, DoD and battery power capability results in reduced diesel fuel and operation. Increase in battery size seemed to have the largest impact, but this might be due to the larger variable interval of battery capacity than for DoD and battery power capability. Changing the lower dump load margin between 1 and 40 kW did not affect the system performance significantly. Changing the upper dump load margin on the other hand, had a radical impact on energy lost, turbine energy produced and dump load energy consumed. Increasing the maximum dump load power can reduce the power lost to almost zero around values of the turbine rating (250 kW).

Common for all the sensitivity analyses was that average DG power per hour in operation was fairly constant around 50-55 kW. In the base case, rated DG power was set to 100 kW. Hence, a solution of two smaller or one large and one smaller diesel aggregate might be desirable to avoid low loading of the DA.

The three last special cases inspected performance regarding operation with wind only, diesel only and wind-diesel together without battery storage. The most notable result here was that diesel fuel can be reduced from around 170 000 litres/year to about 25 000 litres/year, solely by including a wind turbine. Thus the impact of the battery is actually small in comparison, and a very large battery may not be needed. This enhances the assertion of excellent wind resources. Such a reduction involves a reduction of more than 1 million NOK/year, only in diesel purchase cost.

6.1 Shortcomings and further work

To round up this project, some of its shortcomings and possibilities for further work in the consecutive master thesis are listed here:

- Due to the lack of time, detailed size and configuration of the components have not been decided. Instead, a more general approach to the system components was chosen to form robust a decision basis for further work.

- Costs of components and maintenance are not surveyed. This is also a reason for why specific components have not yet been decided, since cost ultimately plays the major of the system's feasibility. After all, the cost connected to the hybrid system (most likely) cannot exceed the present costs in today's solution with diesel aggregates, if the prevalent actors in the industry should find the solution interesting. Therefore, costs could and should be included later on.

- The analyses are steady-state, hence voltage fluctuations, power quality and other transients are not taken into consideration. Reactive power is also neglected.

- Some aspects such as component efficiencies are not included in the simulations. Neither is the possibility to charge the battery in cases where the diesel otherwise would deliver only a small amount of power, thus avoiding low-power operation.

- Other simulation improvements should make a restriction on how how long the diesel and dump load has to run when started. This is due to increased wear and tear with too frequent starts. However, the results shows that neither diesel starts or dump load starts are extremely high (even though with a small battery).

Further work may comprise cost calculations, dynamic simulations and specific component choices, amongst other things. The specific plan will be worked out in the beginning of 2017, in collaboration with supervisor Kjetil Uhlen and co-supervisor Pål Preede Revheim..

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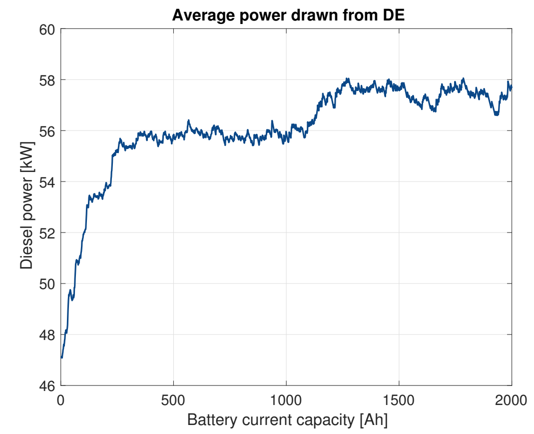
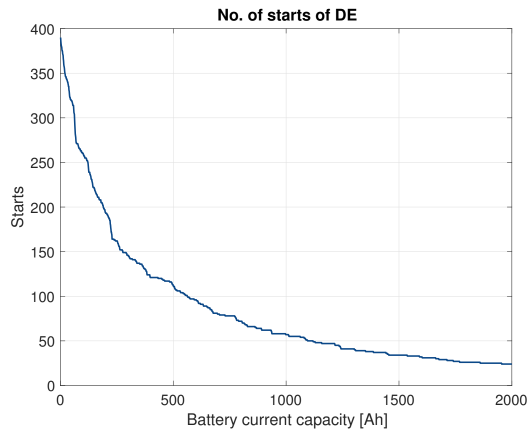
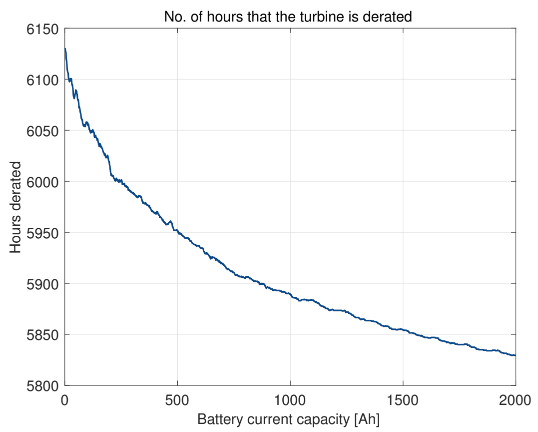
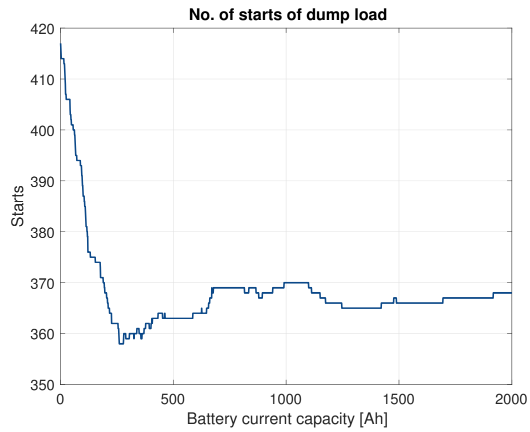
7 | Appendix - Additional sensitivity plots

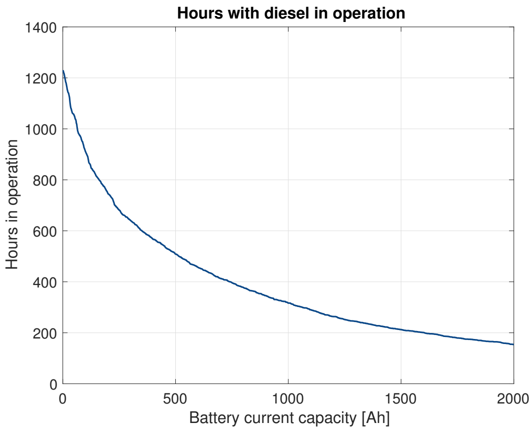
Additional figures for BC1:

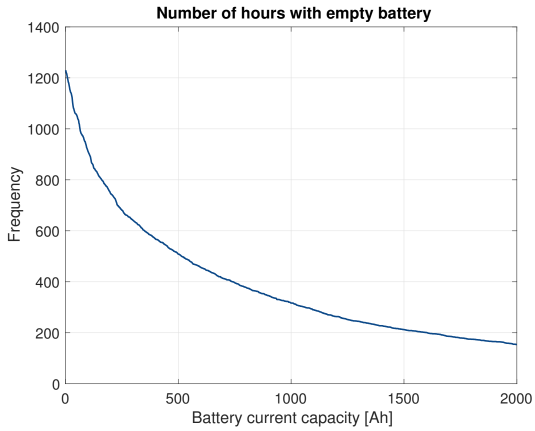


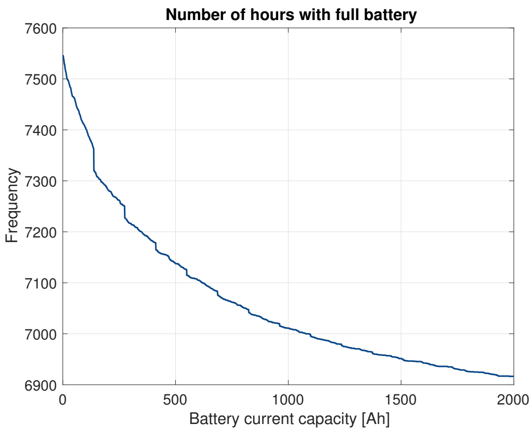


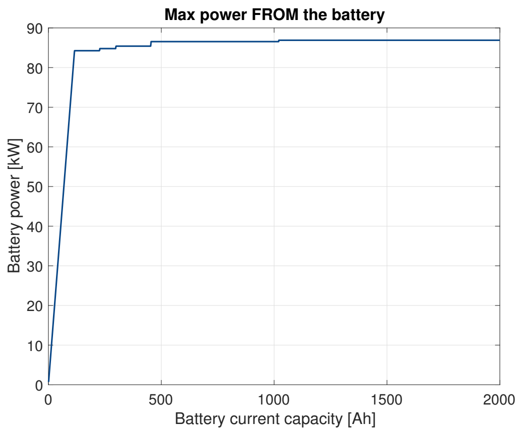


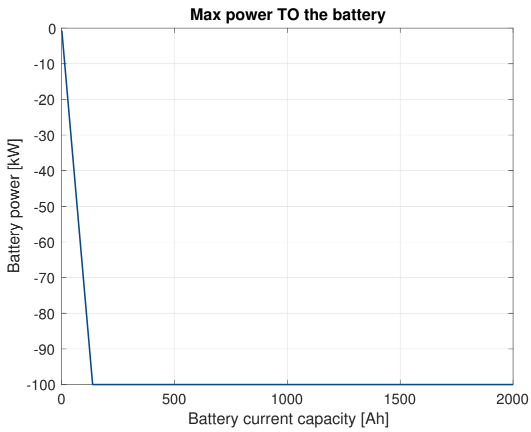



Hours with diesel in operation
Hours in operation
Battery current capacity [Ah]
0
200
400
600
800
1000
1200
1400
0
500
1000
1500
2000

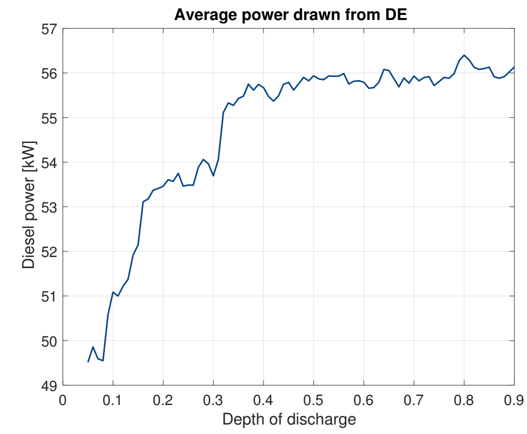

Number of hours with empty battery
Frequency
Battery current capacity [Ah]
0
200
400
600
800
1000
1200
1400
0
500
1000
1500
2000

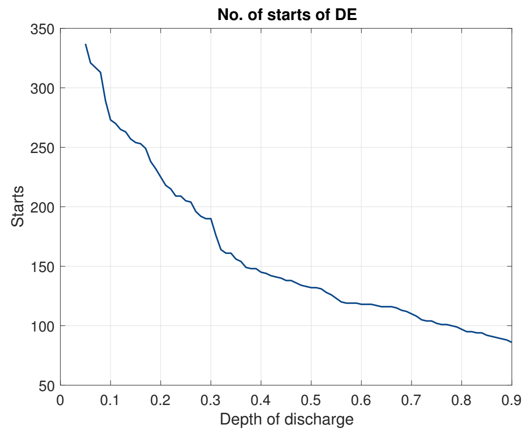

Number of hours with full battery
Frequency
Battery current capacity [Ah]
6900
7000
7100
7200
7300
7400
7500
7600
0
500
1000
1500
2000

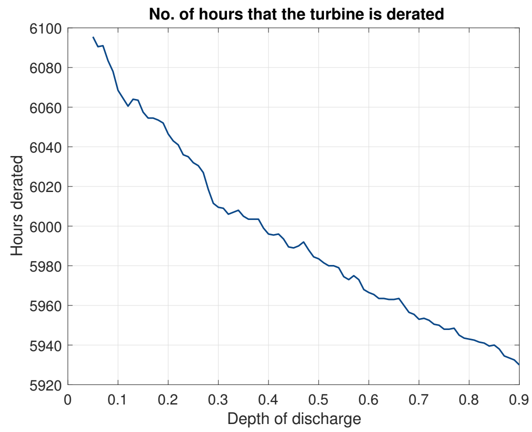

Max power FROM the battery
Battery power [kW]
Battery current capacity [Ah]
0
10
20
30
40
50
60
70
80
90
0
500
1000
1500
2000

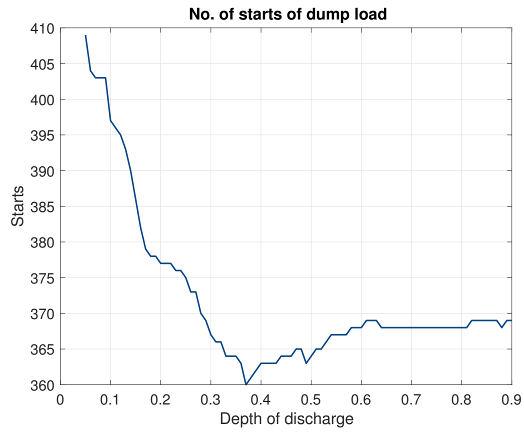

Max power TO the battery
Battery power [kW]
Battery current capacity [Ah]
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
0
500
1000
1500
2000

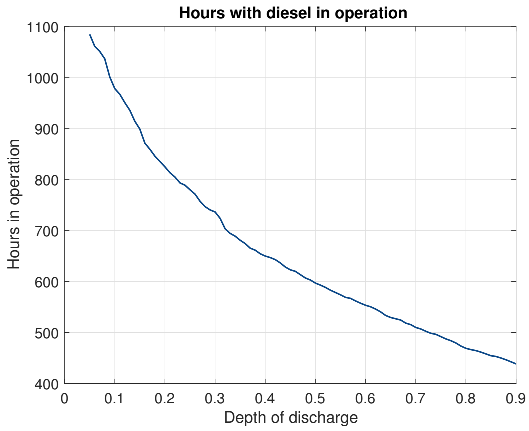
Additional figures for BC2:

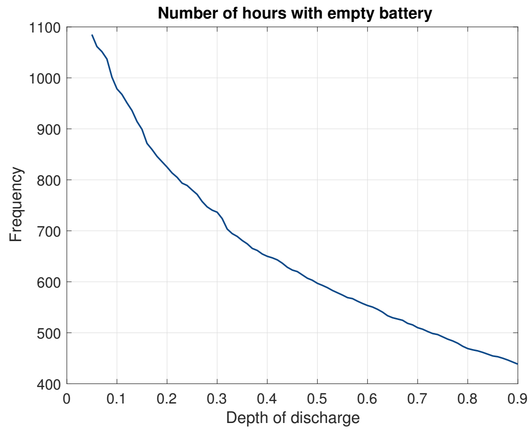


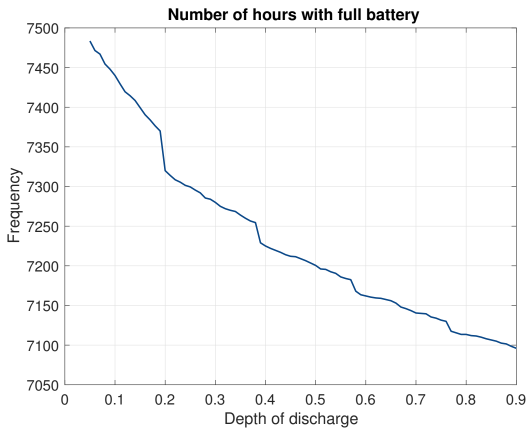


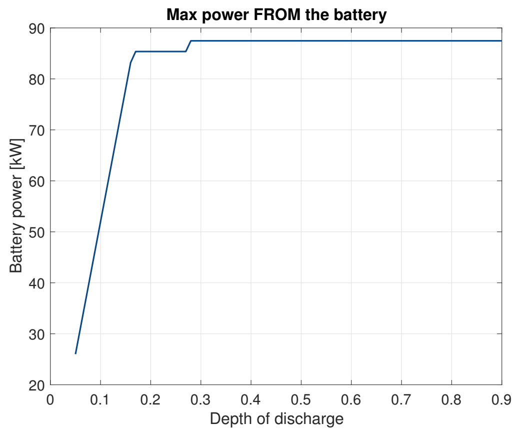


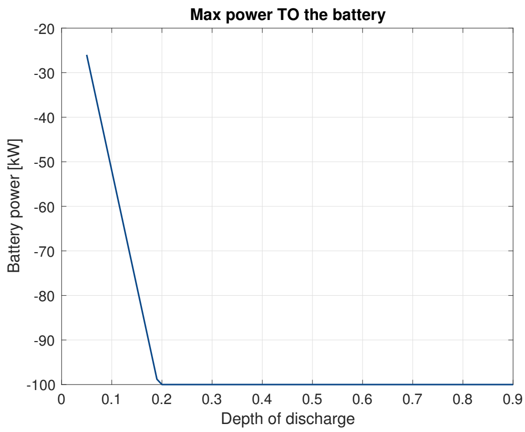



Hours with diesel in operation
Hours in operation
Depth of discharge

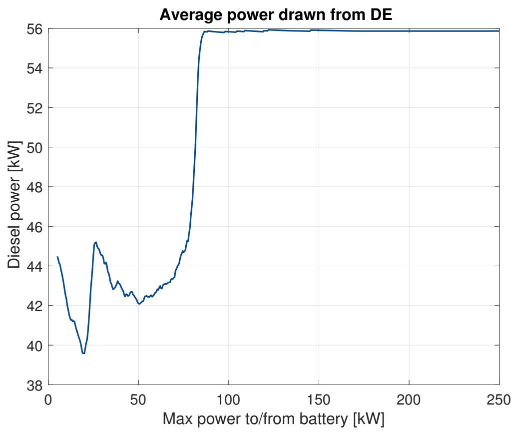

Number of hours with empty battery
Frequency
Depth of discharge

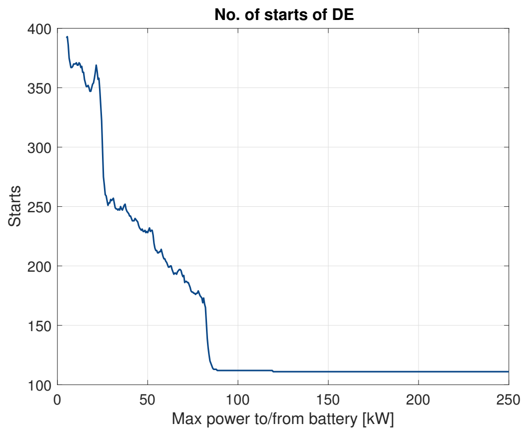

Number of hours with full battery
Frequency
Depth of discharge

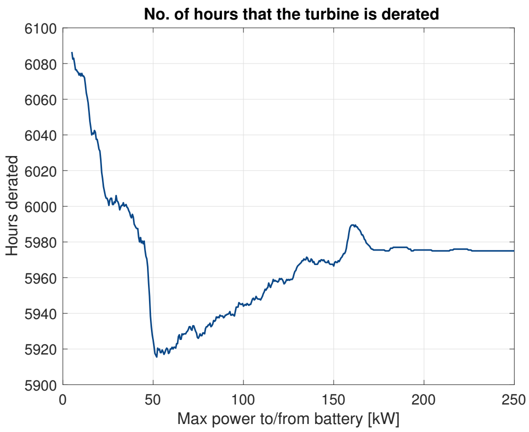

Max power FROM the battery
Battery power [kW]
Depth of discharge

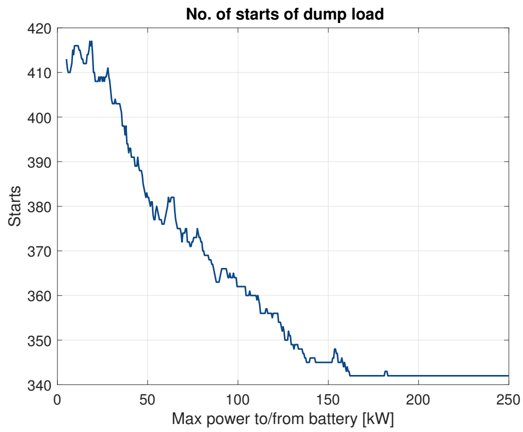

Max power TO the battery
Battery power [kW]
Depth of discharge

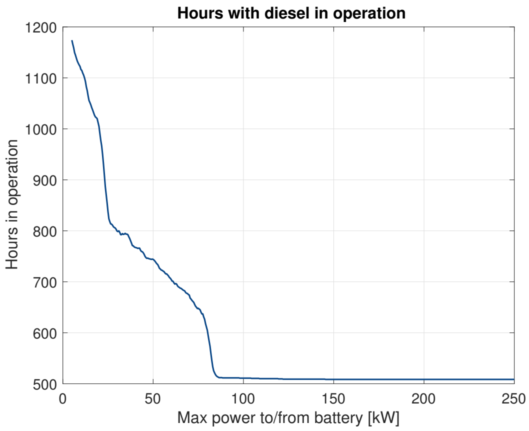
Additional figures for BC3:

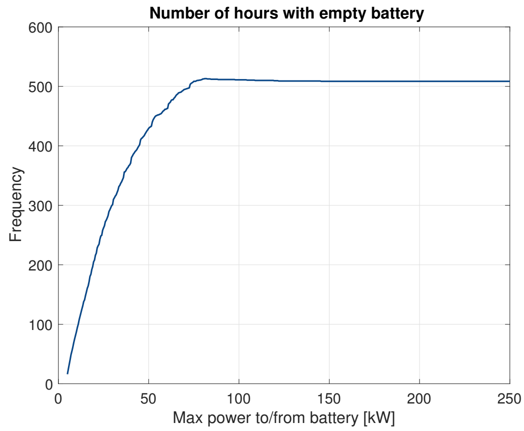


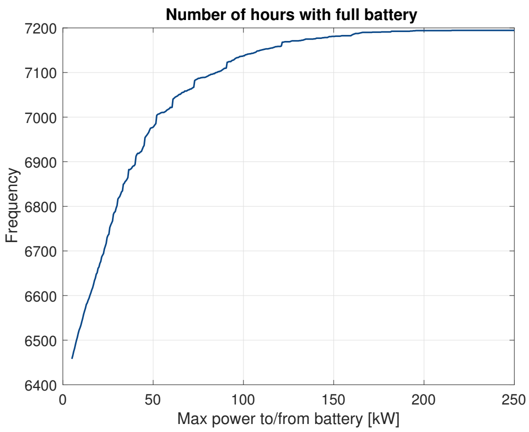


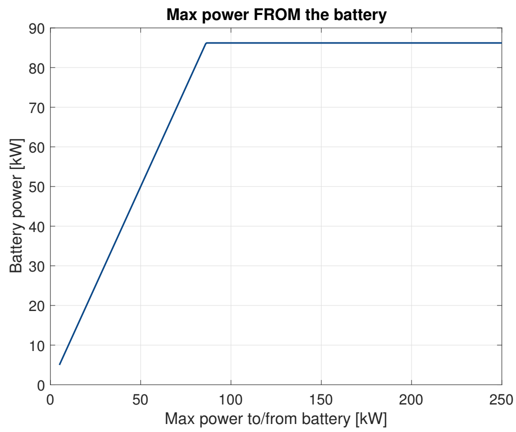


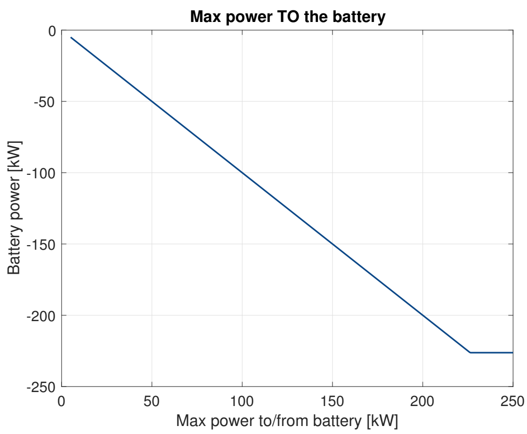



Hours with diesel in operation
Hours in operation
Max power to/from battery [kW]

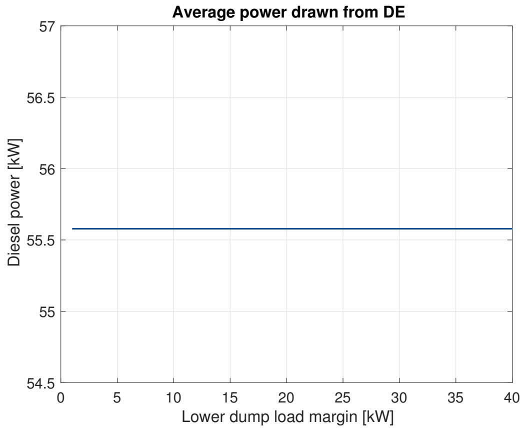

Number of hours with empty battery
Frequency
Max power to/from battery [kW]

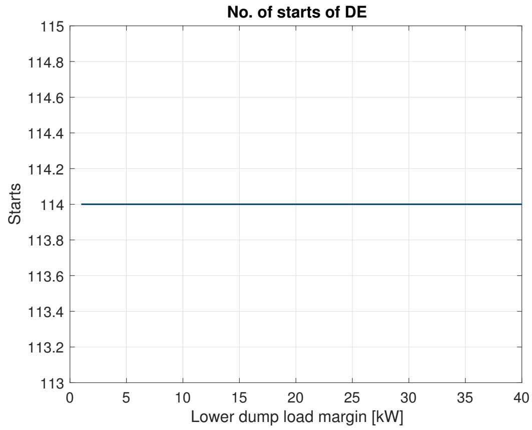

Number of hours with full battery
Frequency
Max power to/from battery [kW]

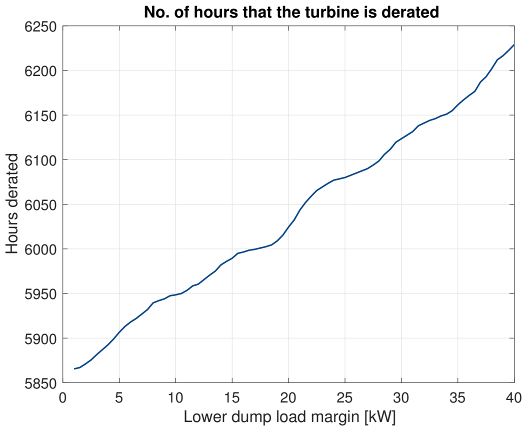

Max power FROM the battery
Battery power [kW]
Max power to/from battery [kW]

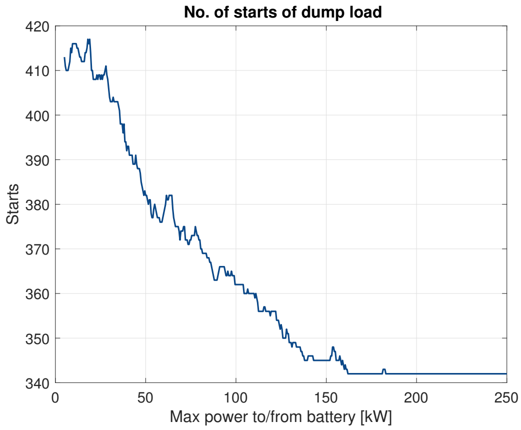

Max power TO the battery
Battery power [kW]
Max power to/from battery [kW]

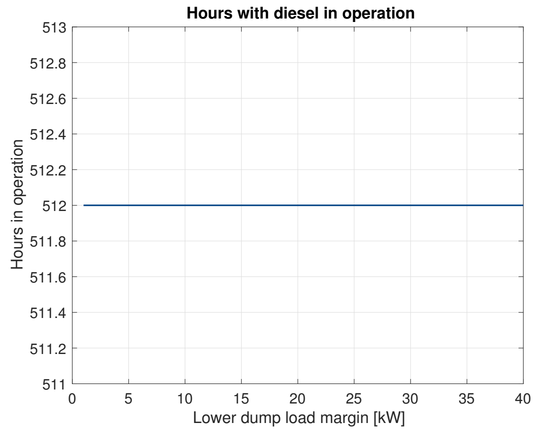
Additional figures for BC4:

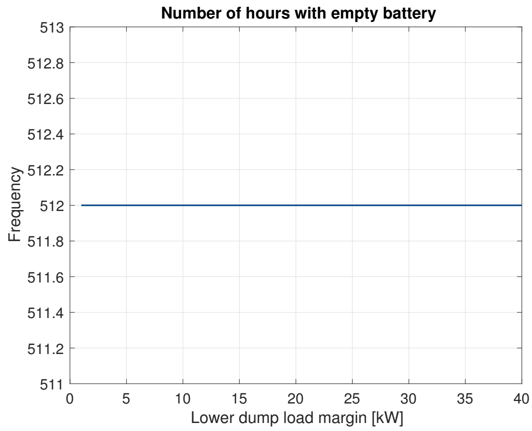


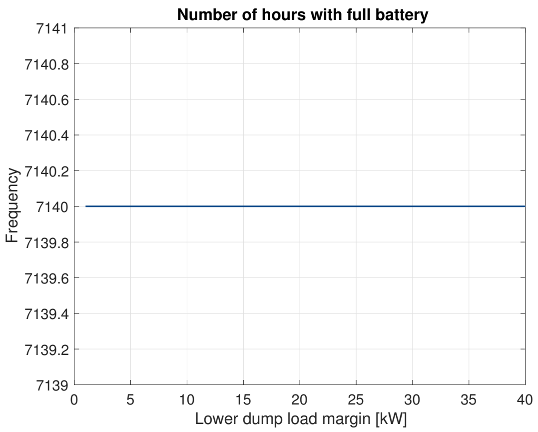


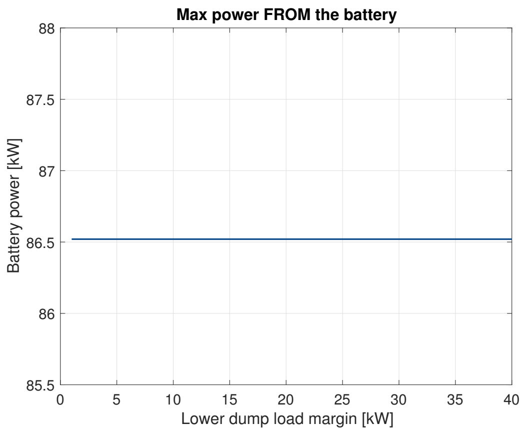


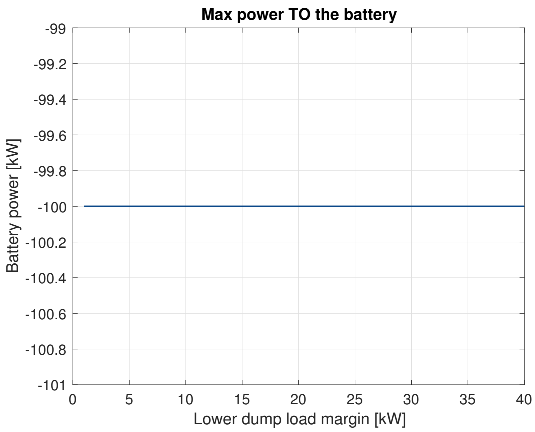



Hours with diesel in operation
Hours in operation
513
512.8
512.6
512.4
512.2
512
511.8
511.6
511.4
511.2
511
0
5
10
15
20
25
30
35
40
Lower dump load margin [kW]

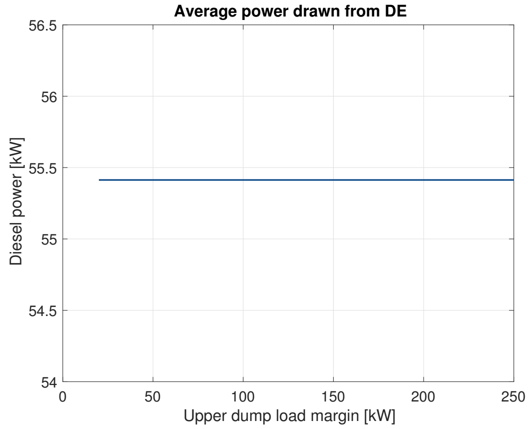

Number of hours with empty battery
Frequency
513
512.8
512.6
512.4
512.2
512
511.8
511.6
511.4
511.2
511
0
5
10
15
20
25
30
35
40
Lower dump load margin [kW]

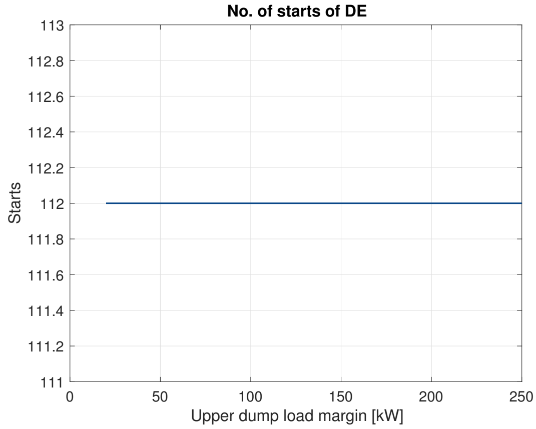

Number of hours with full battery
Frequency
7141
7140.8
7140.6
7140.4
7140.2
7140
7139.8
7139.6
7139.4
7139.2
7139
0
5
10
15
20
25
30
35
40
Lower dump load margin [kW]

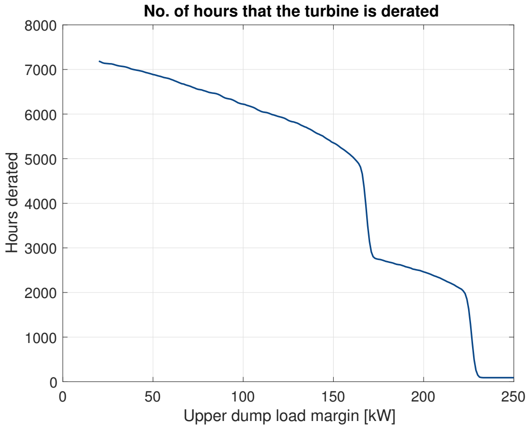

Max power FROM the battery
Battery power [kW]
88
87.5
87
86.5
86
85.5
0
5
10
15
20
25
30
35
40
Lower dump load margin [kW]

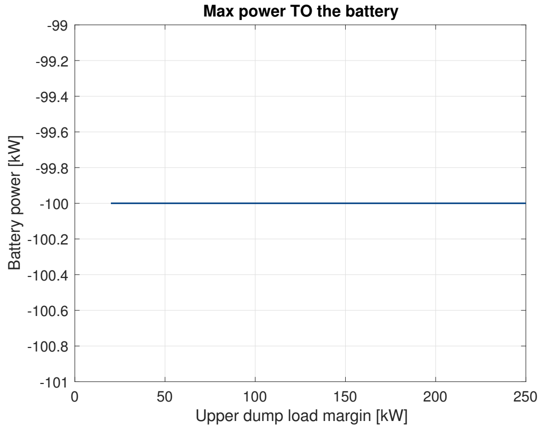

Max power TO the battery
Battery power [kW]
-99
-99.2
-99.4
-99.6
-99.8
-100
-100.2
-100.4
-100.6
-100.8
-101
0
5
10
15
20
25
30
35
40
Lower dump load margin [kW]

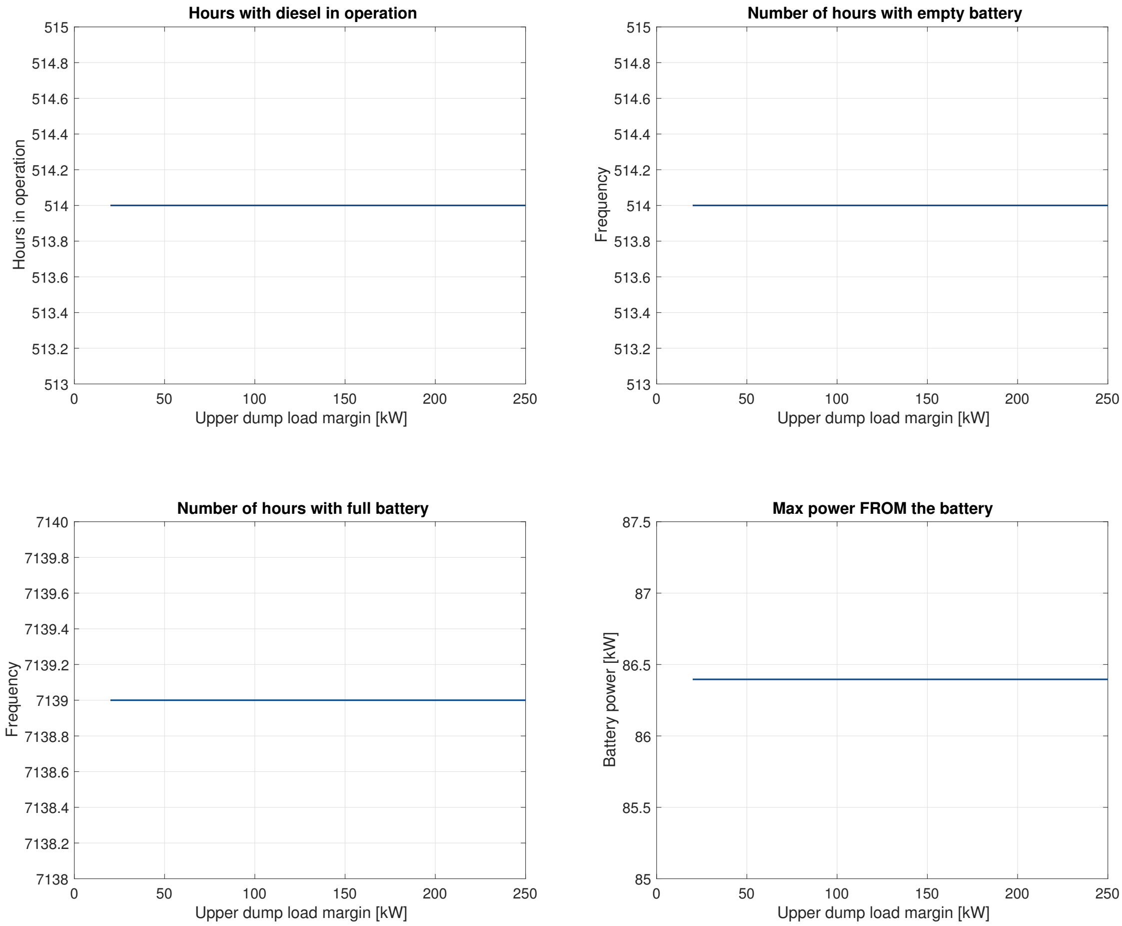
Additional figures for BC5:










Hours with diesel in operation
Hours in operation
Upper dump load margin [kW]
Number of hours with empty battery
Frequency
Upper dump load margin [kW]
Number of hours with full battery
Frequency
Upper dump load margin [kW]
Max power FROM the battery
Battery power [kW]
Upper dump load margin [kW]

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Norwegian University of
Science and Technology