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Kite power in a microgrid

Design and sizing of distributed energy resources for a microgrid solution based on Kite Power

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TU Delft

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by

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TU Delft

Abstract

Airborne Wind Energy is a promising technology that is becoming the point of interest for many applications. One market in which the AWE systems can open a path as a renewable distributed generator is in offgrid communities or camps. Nowadays, this market is dominated by fossil fuel energy like diesel generators. Even though the diesel is cheap, in some cases the complexity to transport the diesel can increase its price considerably. A military camp is an example of this cases. AWE systems designed by the start-up Kitepower can offer a solution to this type of application. Nevertheless, there are some points in the AWE mechanism that should be improved. The most important of these aspects is the cyclic power production that generates a power gap.

This thesis compares solutions as 2 KP systems, other distributed generators (DG) and storage systems (SS) to find the best option to mitigate the power gap. For the integration of the components with the KP system, micrograds designs and layouts were studied. This led to one of the most important things in a microgrid that is the SS sizing. Here, also a method to size the SS to fill the power gap is proposed based on the distribution of power generated by the KP system each cycle. To test the sizing and the operating of the system, a model was built in Simulink. The results show that the method finds a power balance between the power produced and the power generated.

Finally, an efficient integrated system is proposed to mitigate the power gap of the KP system. Additionally, a method is developed to start the design and size additional DERs for future offgrid microgrid projects.

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Nomenclature

A	Area of the kite
C_L	Lift coefficient
E_{DG}	Distributed generator energy
E_{kpc}	Energy from Kitepower system per cycle
E_{kp}	Energy from Kitepower system
F_L	Lift force
P_{kpc}	Power from Kitepower system per cycle
P_{kp}	Power from Kitepower system
P_{SS}	Load Power
P_{SS}	Storage System Power
v_a	Apparent wind velocity
ABB	Asea Brown Boveri
AC	Alternate current
AWE	Airborne Wind Energy
D	Drag
DC	Direct current
DER	Distributed Energy Resources
DG	Distributed Generator
DOD	Depth of discharge
EDLCs	Electrostatic Double Layer Capacitors
IRENA	International Agency of Renewable Energies
KP	Kitepower
KWG	Kite Wind Generator
L	Lift
LCOE	Levelized cost of energy
LCOS	Levelized cost of stored energy
LEI	Leading Edge Inflatable
PV	Photovoltaic

SMES	Superconducting Magnetic Energy Storage
SOC	State of Charge
SS	Storage System

Contents

1 Introduction

Since the discovery of electricity, mankind has been developing a wide dependency on this type of energy. But even though the world's dynamics are highly attached to electric power, 17% of the entire population is still without access to electricity[1]. The remaining 83% is not totally covered by the immense electric net known as "the grid". some rural areas and off-grid communities depend on autonomous local power sources. According to Sierra Club, in 2013 25 million people had access to electricity through off-grid solutions [1]. The need for electricity in remote areas has led to a wide variety of power sources known as micro-grids systems. These microgrids commonly have a Diesel Generator and can be combined with secondary energy sources. With every year that passes, renewable energies are becoming more common as the primary energy source for off-grid systems. The most popular forms of renewable energy are photovoltaics (PV) and wind energy. Due to their performance improvements, prices have become more competitive in the last decades.

In addition, there has been plenty of research into the development of new technologies. One is Airborne Wind Energy (AWE) that generates power through a tethered wing. This technology offers several advantages for off-grid users, making it a potential replacement for current existing systems on the market.

The AWE system has been the focus of interest for many companies, institutions and research groups because it offers several advantages over conventional wind turbines. Firstly, the kite is able to reach higher altitudes where the wind has a higher speed and is more consistent, which leads to a higher available energy per unit area. Secondly, for an AWE system much less material is needed than for a wind turbine of the same capacity, which means less production cost and hence less investment. Third, the AWE system has less visual impact than the conventional wind turbines, making it potentially more accepted by society [2].

The AWE generators are divided into two types, the onboard power generation and the ground-based power generation. The first consists of a kite carrying a turbine on board. The electric power generated by this kind of AWE system is transmitted through the tether. The second is also called pumping generation. Here, the power of the wind is converted through the tether traction force using a generator installed on the ground. The operating flight of these two types is in crosswind direction. By this, the lift force F_L of the kite increases with the square of the apparent wind speed v_a[2], this speed is the sum of the kite's kinematic velocity and the wind velocity. Compared to a kite that is kept at a static position in the sky, the crosswind flight leads to an increase of the tether tension. This is also reflected in the power extracted as it is proportional to the cube of v_a [2]. The American engineer Miles Loyd was the first to investigate the power extraction of a kite. His theoretical computation of power led to high power densities for AWE if it is compared to conventional renewable sources (PV and wind turbines) [3].

Nowadays, some AWE companies are achieving a reasonable performance of their system for market penetration. One of the most prominent niches for an AWE system is off-grid power generation. Some examples are remote communities or rural areas where the grid is not able to supply energy. Through microgrids solutions, some of these communities have access to electricity. These microgrids generate energy through distributed generators (DG's)[17]. Some examples of DG's are diesel generators, PV stacks, small wind turbines and fuel cells.

Hence, the AWE system is suitable for becoming a DG to build microgrids. But there are still some aspects that need to be improved in order to become highly competitive in the energy industry. The start-up Kitepower (KP) has developed a ground-based AWE system based on pumping operation, and the central aspect that needs improvement is the discontinuous production of power.

Discontinuous power production means that the power extraction is cyclic. Power is obtained in the period when the kite flies onwards (reel-out phase), contrary to the reel-in phase where the system consumes power. The conventional DGs on the market are usually able to supply constant power. There are others that have a random production, but they are connected to devices that stabilize the power. Therefore, there is a need to fill the power gap during the reel-in phase. This thesis is mainly focused on improving this issue through integrating another source or a Storage System (SS) to the AWE system developed by Kitepower. Compensating the power gap also leads to the integration of the system with a microgrid.

In this thesis, different technologies of energy storage and DG's are combined to create a microgrid that can solve the reel-in energy gap of the AWE system. Furthermore, this thesis will also explore the most suitable equipment needed as a backup power supply for the case presented. By the end of the project, an efficient, AWE microgrid system will be proposed in order to reach an uninterrupted power supply system.

1.1. Kitepower AWE system

Kitepower (here called KP for easy handling) is a startup that has made a lot of progress in the Airborne Wind Energy (AWE) topic. They have developed an innovative energy generator that uses a flexible inflatable kite. They have achieved high efficiency through complex control systems leading to a competitive performance in the wind energy industry. However, to become an embedded technology in the renewable energy industry, there are challenges that need to be solved. Additionally, its integration with the energy infrastructure needs to be studied to develop a friendly interface with the equipment operating in the potential applications of AWE.

In this section, a summary of the AWE operational mechanism is given to understand this technology, and to have a better view of the challenges that this technology is facing to become a functional system in the energy industry. In addition, the microgrids are introduced bas they represent a way to implement the KP AWE system to the market.

1.1.1. Operating principles

The AWE systems have mainly two types of tethered wings, rigid wings and soft wings, each with its advantages. The rigid wings, for example, keep their shape independently of the wind conditions and have a higher lift to drag ratio than the soft wings[2]. The soft wings have low hazard potential, an essential characteristic considering that safety is a focal point for the AWE systems operation. Also, it is highly manoeuvrable due to the span-wise torsion, which is convenient for operating the kite [2]. They need less mass per square meter making them cheaper. These soft wing characteristics led Kitepower to design a LEI tube kite (a soft Wing/C-shape kite, see Fig.1.1).

Figure 1.1: ***Leading Edge Inflatable kite of KitePower (Source: http://www.kitepower.eu)***

The Kitepower AWE system power generation is based on pumping cycles. The generator is installed on the ground, and its operation is separated into two phases, the reel-out and reel-in phase (see Fig1.2). The kite generates power with the traction force of the kite during the reel-out phase. Here, to maximise the power extracted from the wind, the kite flies as close to crosswind direction as possible. The crosswind motion leads to a considerable increase in the aerodynamic forces over the wing compared to a static kite [2]. In a crosswind motion the lift force F_L is a function of the square of the apparent wind velocity (${v_a}^2$), as follows:

$$F_L = \frac{1}{2}\rho A C_L {v_a}^2 \tag{1.1}$$

Thus, if v_a is ten times higher than the wind speed v_w, F_L will increase by a factor of hundred in comparison with a static flying kite [3], leading to high power densities.

In the reel-out phase, the kite flies in the form of eight manoeuvres until the optimal tether length is reached as indicated on the r.h.s of fig.1.2. In addition, the reel-out velocity is an essential parameter for the system's performance. Studies have been performed to define the optimal reel-out velocity and shown that this is one-third of the wind speed projected onto the tether [7]. Additionally, it also depends on the maximum tether force, so the reel-out velocity is defined by the wind conditions.

After the maximum tether length is reached, the reel-in phase follows. During this phase, the kite is positioned at a low angle of attack leading to a low lift to drag ratio (L/D) compared to the reel-out phase [3]. Additionally, the elevation angle is increased [2]. As the system has to consume energy to retract the kite to the starting point, the above procedure reduces the forces acting on the tether, leading to a considerable reduction of the power needed to reel-in. This power is a small fraction of the power produced during the reel-out phase, fig.1.3 shows that the reel-out phase reaches 20 kW of generated mechanical power, while the reel-in consumes less than 10 kW.

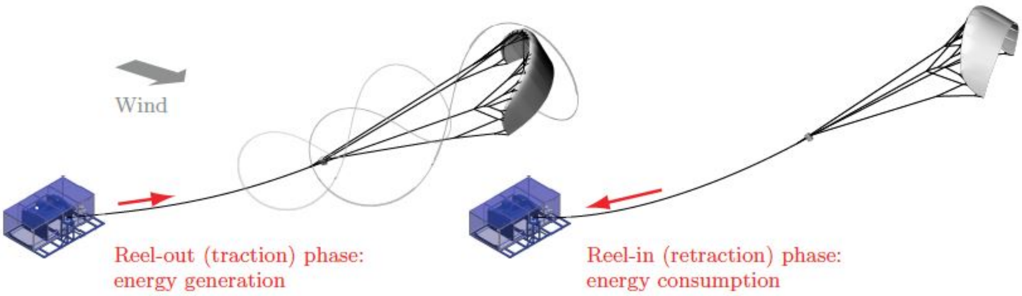


Figure 1.2: ***Pumping Cycle Kite Power operation [7]***

To increase the performance of the system, the reel-in phase time needs to be shorter than the reel-out. Like the reel-out phase, the reel-in time also depends on the wind conditions. However, based on experimental data, the cycle time has an established average period. A typical time range for the pumping cycle of the 20 kW AWE system is from 60 to 180s of reel-out phase. Followed by 60 to 90 s for the reel-in phase [2].

The 100kW system is taken in this thesis as the main equipment for the integration of the micro-grid. Nevertheless, no experimental data is available for a system of this size. However, the 20kW data can be scaled up to provide information for the microgrids simulation. An important thing to remark is that this AWE system size is used because it proposes a competitive size for its commercialization for off-grid applications.

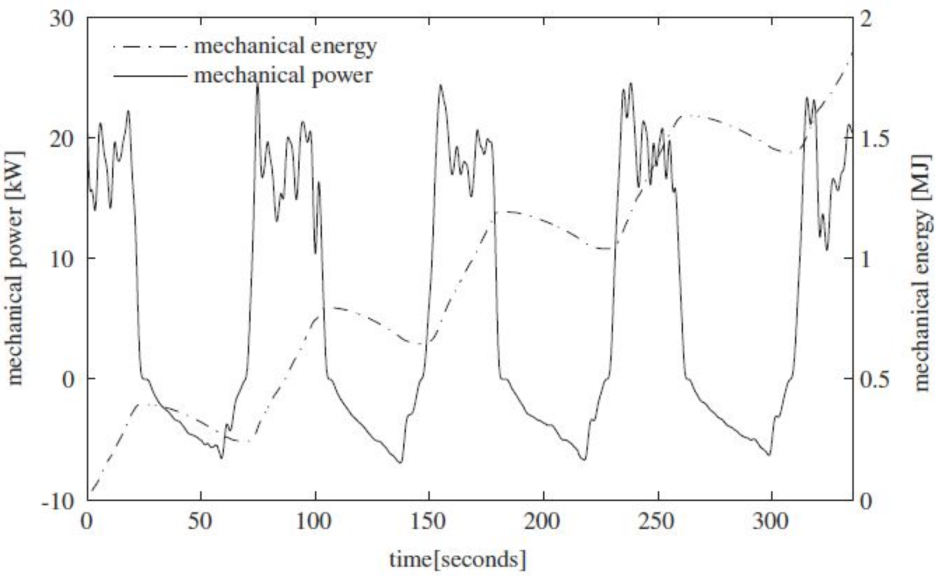


Figure 1.3: ***Traction power and mechanical energy over four pumping cycles [2]***

1.1.2. Kitepower generator ghallenges

The main grid that feeds most of the cities in the world has specific operating conditions. The parameters that play a role in the stability of the main grid are the frequency, voltage, active and reactive power. From these parameters, the power flow of the grid is controlled, as they measure the balance between the load demand and the power produced [21]. When the load demand changes, the parameters change as well, leading to a deviation from the standard operating conditions that should be counterbalanced by the power production. The balance between the supplied and demanded energy is kept by a control system that administrates different power sources and storage systems. The principal function of the main grid is to satisfy the load demand under any conditions.

When a microgrid is operating in islanded mode, it takes the role of the main grid. Its primary purpose is to fulfil the load's needs. Thus, as can be seen in figure 1.3, the output power of the kite power system needs to be regulated and stabilized. This is fundamental for the microgrid market introduction of the AWE system.

To convert the variable power production into a constant power supply, three main aspects need to be taken into consideration:

1. Power gap: The first and most important aspect is related to the cyclic power generation of AWE system. In the reel-in phase when the system is consuming power, fast response equipment is needed that can provide enough power for the load demand. This is required merely because the operation of the users cannot be interrupted, the power supply should be consistent and stable.
2. Power stabilization: Due to the randomness power of the renewable sources, the output voltage and current of most of the renewable DGs is highly variable. The voltage or current needs to be stabilized into fixed levels to provide optimal conditions to the electrical buses for the load connection.
3. Back up power supply: Eventually, the system should be prepared for the worst case scenario, which could be the absence of the wind or even a malfunctioning of the AWE system, so a secondary reliable power source is needed as a back-up. It is well known that most of the renewable energy off-grid systems have a backup power source that ensures the supply of electricity under any circumstance. The AWE will be no exception since it will be offered as a part of an integrated power supply solution.

Based on these aspects an analysis is performed in this thesis between several types of equipment to obtain the most suitable technology. In the next section, the equipment in consideration is presented, and it is described why it is adequate for the AWE characteristics.

1.2. Microgrids

1.2.1. A potential market for AWE system

The term ”microgrid” is used for different interpretations depending on the country or organization. According to the United States Department of Energy, ”micro-grids are a group of interconnected loads and distributed energy sources within clearly defined electrical boundaries that act as a single controllable entity with respect to the grid"[1]. The multinational company Asea Brown Boveri (ABB) that develops technology for electricity generation, defines a micro-grid as "distributed energy resources and loads that can be operated in a controlled, coordinated way; they can be connected to the main power grid, operate in "islanded" mode or be completely off-grid" [4]. From all of the micro-grid definitions, what most of them agree upon is that a microgrid should be able to operate completely disconnected from the grid. In addition, the International Agency of Renewable Energies (IRENA) established that a microgrid operates in a power range from 5 to 100 kW [1].

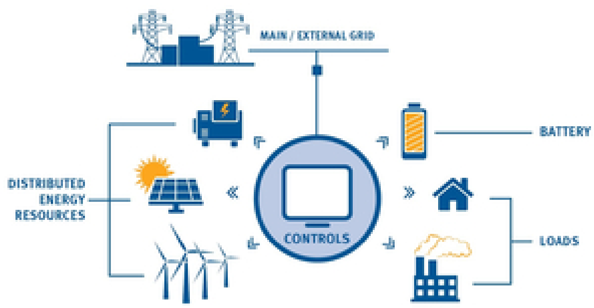


Figure 1.4: ***Microgrid layout representation***

Considering the previous definitions, a KP system of 100 kW suits the microgrid industry. Microgrids are widely used for off-grid applications, and in this sector the most abundant source is the diesel generator. In 2013, five million households obtained energy through off-grid solutions [1]. In other words, there are millions of diesel generators providing power where the grid does not reach; this offers a huge potential market for the AWE system. Additionally, of the diesel generators that can be potentially replaced, an estimated 1.1 billion people are still living without electricity in these days [6]. Kitepower AWE system represents a possible solution for communities without access to electricity. The 100 kW Kitepower system proposes a competitive size for the electrification of these communities. According to a global evaluation of 155 mini-grid systems, the average power for the electrification of villages is 69.9 kW [5].

It is important to mention that KP is not the only one seeking to enter into the offgrid microgrid's industry. Several AWE companies are making research to open a path into this industry. According to [39], AWE systems could be a diesel killer in the future. Some of these companies are Windlift that develops portable AWE technology, eWind, that seeks to serve farmers and Altaeros that also looks to supply energy to villages, mines and military bases. These companies and a lot more are working to remove the fossil fuels from the offgrid applications.

Knowing the promising market for AWE, the improvement of the AWE system functioning is crucial. The off-grid systems supply a constant amount of power for daily activities. As the AWE system has a cyclic power production, the continuous and stable supply of power is the most critical challenge to solve in this thesis. Specialized equipment should be combined with the AWE system to compensate the energy gap and further problems.

1.2.2. Main components

In [17], a microgrid is an integrated system in which distributed energy resources (DERs) create a grid that feeds distributed loads. The DERs and loads constitute the main body of a microgrid. In this section, a quick description of these elements is given.

Distributed Energy Resources

DERs are the components that supply power to the load. They are divided into two principal categories:

1. Distributed Generators(DG). These devices are the energy generators of the microgrid. They can generate power based on renewable or non-renewable sources. The DGs used in each microgrid vary with the location and application. DGs can be diesel generators, photovoltaic cells, small wind turbines, fuel cells, etc. Nowadays the most common DGs used in microgrids are based on non-renewable sources [17].

2. Storage System (SS). These systems store the extra energy generated by the DGs when the load demand is low. The energy stored is released when the DGs are not able to fulfil the load power demand. They also help to stabilise the output of renewable DGs as they compensate the power difference between the production and demand. These elements make a more robust system as they improve the reliability, stability and overall system performance [17]. Some examples of SS are Batteries, Supercapacitors, Flywheels, compressed air, etc.

Loads

Loads are the components that consume the power supplied by the DERs. They are divided into two principal categories, critical and non-critical[18]. They are described as follows:

1. The critical loads need high-quality and reliable power supplied [18]. They should not be disconnected. Some examples are industrial production lines or specialized equipment in hospitals. The control strategies implemented in the microgrids have as a priority to supply these loads.

2. The non-critical loads are more flexible about their energy demand. They require lower service quality than critical loads. They can be disconnected if the power produced by the DGs is not enough to satisfy the critical loads. Some examples of these loads can be a heating or a water purification system.

Besides the elements above, microgrids are constituted of other components. Some contribute to the stability of the operating conditions [18]. And some others protect the microgrid integrity. Some examples of this equipment are power inverters, rectifiers, transformers, breakers, fuses, etc.

1.2.3. Microgrid architectures

Microgrids can be designed to operate with alternate current (AC), direct current (DC) or both of them at the same time [17]. This current is transmitted to the loads through lines called buses. Each one of the power distribution (AC-DC) has its advantages and disadvantages. To design a microgrid, a detailed study of the application should be performed to choose the most suitable operating mode.

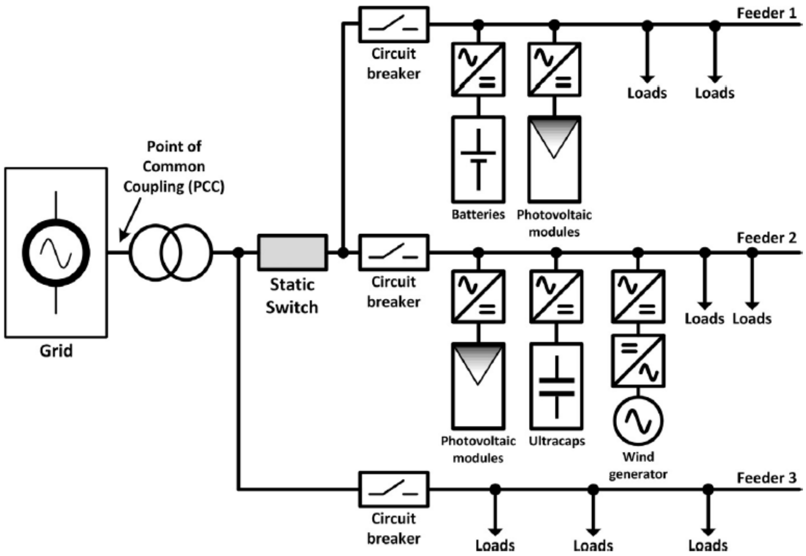


Figure 1.5: ***AC microgrid[18]***

Based on these two types of current distribution, a wide variety of microgrid architectures can be designed. They depend on how the AC and DC buses are connected. The three most basic microgrid architectures are described here.

AC Microgrid

In the electricity industry, AC is preferred over DC for electricity transmission. This is because it is easier to manipulate the voltage levels in AC than in DC. Voltage manipulation is used to decrease power losses[17]. As a consequence, the world's electric infrastructure is build to work in AC. Thus, most of the loads are designed for this type of power distribution.

Because of the aforementioned reasons, AC microgrids offer an advantage over DC microgrids [17]. To understand an AC microgrid architecture, an example is shown in figure 1.5. An AC microgrid consists of one or more AC buses or feeders. All the devices and loads should be connected through an AC interface.

In an AC microgrid, the frequency and voltage need to be regulated. Some DC components connected to the AC buses need to have a power converter to comply specific conditions. For example, if the microgrid has PV stack as a DG, it delivers direct current (DC) instead of AC. Then, an inverter should be placed in the PV output to transform the current from DC to AC. The same happens with a Battery, Ultracapacitors, Fuel cells, etc. For the wind turbines, first a rectifier should be placed and then an inverter. This is to transform the variable frequency delivered by the wind generator into a fixed frequency demanded by the AC bus. For DG's using synchronous machines as diesel generators, it is possible that they can be connected directly to the AC bus depending on the nominal operating conditions.

Most of the loads in the world are already standardized for fixed AC conditions. For AC loads with different nominal operating values than the distribution lines, components (as transformers) are include that convert the AC signal into suitable parameters. The DC loads are equipped with a rectifier to convert the AC signal to DC.

The advantages of this microgrid architecture are: first, the AC microgrid is suitable to implement into already existing buildings. Second, the standards and regulations are well defined for this technology; it is easier to create a useful AC microgrid. Third, It is easier to have an interconnection with the grid. For this reasons it is expected that this type of microgrid dominates the microgrid industry in the near future [18].

The disadvantage of an AC microgrid is the high number of components in the system. Every DC DG and load need a power converter. Each power converter reduces the efficiency of the system. Also with every extra component in the system, the reliability decreases. In other words, the more elements there are in the system, the failure probability is higher. Also, the control algorithm complexity increases comparing it to a DC control algorithm. This is because there are more parameters to take into consideration like the frequency and reactive power.

DC Microgrid

The DC microgrid consists of one or more DC buses. In figure 1.6, an example of a DC microgrid can be seen. If the DC microgrid is connected to the main grid, this connection should be made through a bidirectional AC/DC converter.

In a DC microgrid, the devices should be connected through a DC interface. A benefit is that most of the renewable DGs and SS used in the microgrids have DC output. For the AC loads there needs to be a DC/AC inverter to adapt the power transfer to AC signal. Some DC loads can be connected directly to the DC bus. Some loads need a DC/DC converter to adjust the voltage to the desired level.

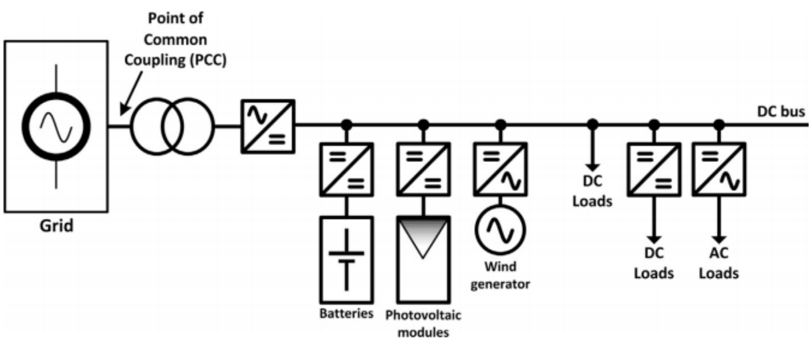


Figure 1.6: ***DC microgrid[18]***

The DC microgrid advantages over the AC microgrid are the flexibility to adjust the DC bus conditions to connect the DC loads directly. This improves the efficiency of the DC bus as there is no need to convert the current from DC to AC. This also means that the number of components decreases in the system, fewer components mean higher reliability. In addition, DC power supply has a high quality because there is no frequency and reactive power in the system. As a consequence, the stability is higher, and control algorithms are simpler than in AC systems.

The main drawbacks of DC microgrids are the lack of research and development of this technology. As a consequence, there are no standards or regulations for DC operating conditions. It is difficult to set a fixed parameters for a DC microgrid, and this complicates the connection and the expandability of the loads. Further, it will lose the advantage of connecting directly the AC loads that are already standardized. Additionally, when the DC microgrid is connected to the main grid, the bidirectional AC/DC converter handles the whole power flow of the microgrid. This reduces the reliability of the system.

Hybrid AC-DC Microgrid

In figure 1.7, an example of a hybrid AC/DC microgrid is shown. This type of architecture consists in an AC microgrid with an additional DC bus. This DC bus is connected through a bidirectional AC/DC converter. With this kind of microgrid, the AC DG's and loads are connected to the AC bus. Additionally, the DC DG's and loads can be connected to the DC bus without the need of a converter.

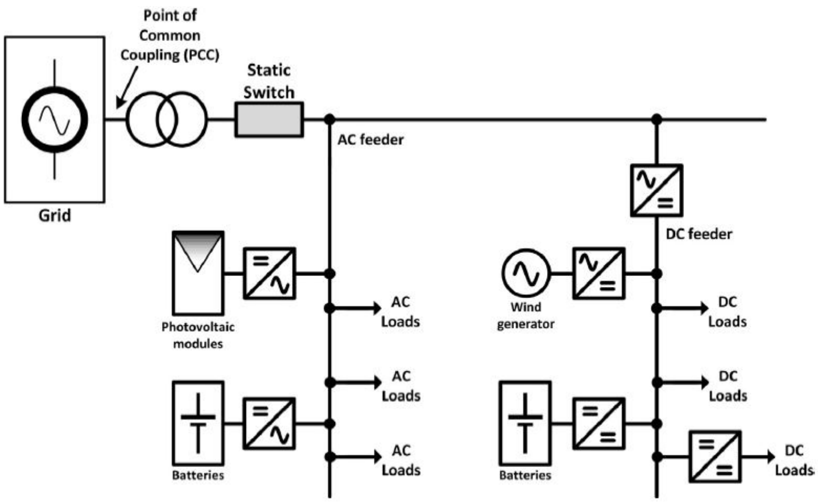


Figure 1.7: ***Hybrid AC/DC microgrid[18]***

The main objective of this architecture is to combine the advantages of both types of microgrid (AC-DC). The AC standardize loads and DGs are connected to the AC bus. The DC bus reduces the number of (DC/AC) interfaces, improving the efficiency and reliability of the Ac microgrid.

1.3. Main objective

The main characteristics of the AWE system that limits it to compete against the actual micro-grids systems were addressed in section 1.1.2. The primary objective of improving these aspects is to create a microgrid that can supply uninterrupted power to the users. It represents a challenge because no technology has worked with a cyclic mechanism of the pumping AWE system. The current technology in the microgrids is going to be combined with the AWE system to seek a reliable and efficient system.

Based on this purpose, the next questions are suggested in order to have a well-defined path. Answering the follow questions will reach a higher understanding of how to design a microgrid and the essential parameters to take into account.

Question 1:

What are the potential advantages of an AWE microgrid over current off-grid solutions?

Sub-questions:

What is the performance of the AWE microgrid compared to the most used off-grid systems? (Energy consumption, power supply, etc.)

What are the parameters to improve for the KP system to integrate it with a microgrid solution?

What are the critical external parameters that should be considered to design an AWE microgrid?

Question 2:

How to design an AWE microgrid that can fulfil the energy needs according to the application?

Sub-questions:

What are possible components comprising a general microgrid?

Which components can stabilize the power output of the AWE system?

What could be a good method to design and size an AWE microgrid?

Question 3:

What is the most efficient and the most cost-attractive AWE microgrid configuration?

Sub-questions:

Which equipment combination constitutes the most efficient microgrid and with the longest lifetime?

Which microgrid configuration is the least costly and most attractive for the user?

What are the economic differences between and the advantages of the different components that can constitute an AWE microgrid?

2

Component analysis

It is known that the AWE system has never worked in an offgrid microgrid before. The SS's and the DG's in the actuality have never worked with a similar mechanism of energy production. There is no data on lifetime, cycle life, efficiency, etc. for this type of operational behaviour. Here, it is intended to create a microgrid that uses the 100 kW KP system as the principal DG. Thus, an overview of the most outstanding technologies used for microgrids is made to find the ones that fit most with the pumping mechanism.

Nonetheless, the functioning process of the AWE microgrid will differ depending on the DERs used to for the microgrid. But is has to be taking into account that the most important issue to solve is the energy gap. Based principally on this and the other challenges mentioned in section 1.1.2 and 6.1 a selection after the evaluation of several DERs is made.

2.1. Distributed generators

Here, four selected DG's that could form part of the microgrid to stabilize the power output are shortly described. The first DG to be analyzed is the KP system itself. As the principal DG in the microgrid is a 100kW KP system, it is considered a second KP system to mitigate the energy gap by a synchronized operation. The advantages and disadvantages of this operating mode are evaluated to have a better view of the most suitable applications.

The next evaluated DG's are diesel generators, PV systems and fuel cells. They were selected because they are the main known technologies in the microgrid industry, some are cheap, and some are environment-friendly. Hence, their performance was analyzed to determine if they are suitable to work with the KP system in the same microgrid.

2.1.1. Kitepower system

For two KP systems it is essential to mention an important concept in solving the power gap, this is ”synchronize the systems”. Operate two synchronized AWE systems is one of the most discussed options to mitigate this gap. During the reel-out phase of one AWE system, the second will be at reel-in phase. The two Kitepower systems will change cycles synchronously to provide uninterrupted power over time.

When a single Kitepower system is operating, the operator seeks to reduce the reel-in time as much as possible. This is done to increase the energy produced by the system in one cycle. However, in this research, it is found that reducing the reel-in time when two KP systems are operating at the same time can have some drawbacks if they are offgrid. To explain this, the energy of two KP systems needs to be calculated to compare their performance with a microgrid with another DERs.

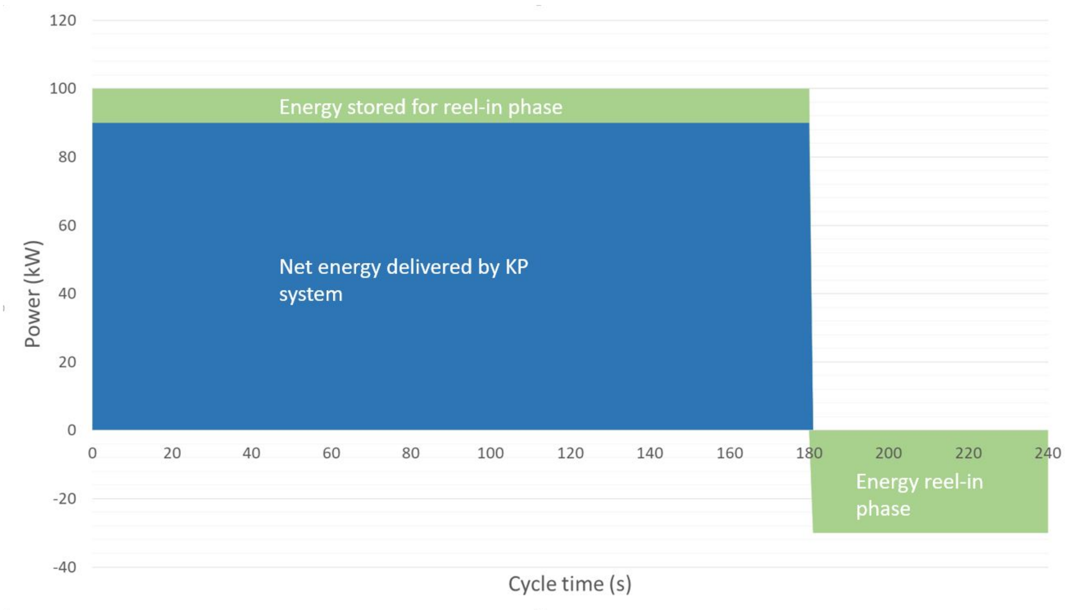


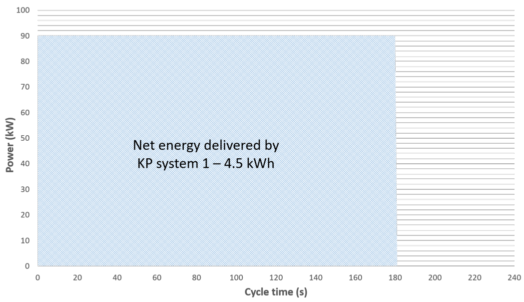
Figure 2.1: ***Hypotethic energy distribution of one cycle of an AWE system***

First of all, it is needed to know that a fraction of the energy generated by the KP system should be stored to have sufficient energy for the reel-in phase. Figure 2.1 is a hypothetical representation of the ideal AWE cycle. Here neither the transition times nor the unpredictability of energy production of the system is considered. Additionally, in a real case, the power does not remain constant over the time that the reel-out/in lasts, due to the unsteadiness of the wind velocity. Nonetheless, the power is considered constant to simplify the calculations.

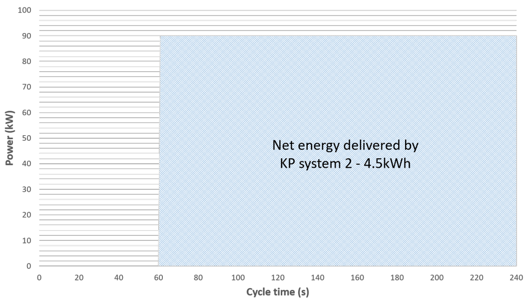
The energy stored for the reel-in depends on the kite performance, it can be reduced or increased depending on the operating conditions. Graph 2.1 shows that part of the energy produced during reel-out phase is reserved for the reel-in phase. Because of this, the power and energy generated by the KP system decrease.

Let’s consider this cycle that lasts 240s to make the energy analysis. The reel-out time is 180s, and reel-in is 60s. This cycle for two synchronized KP systems leads to a 120s of overlapping in the energy produced. From this cycle, a KP system working at maximum capacity approximately produces a net energy of 4.5 kWh during the reel-out or a 1.5 kWh each 60s. Thus, to fill the 60s energy gap, 1.5kWh is needed for each system. The opposite KP system will produce this amount of energy. Now, during the 120s there will be 6kWh produced by the two systems. This means there will be 3kWh extra per cycle, 45kWh per hour or 1080 kWh per day, this can be seen in figure 2.2.

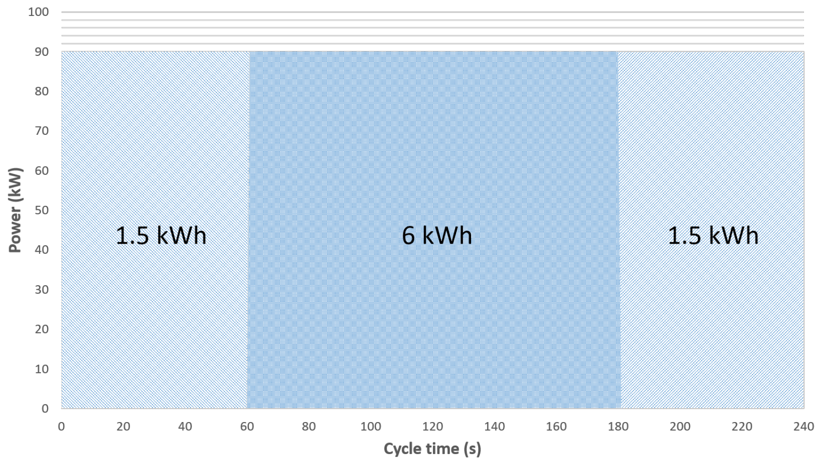
Now, if a microgrid with two KP systems is connected to the main grid, it can absorb the extra energy. However, if the microgrid is operating in islanded mode or it is in an offgrid application, the excess of energy needs to be stored or dumped. To avoid massive losses an SS needs to be considered to save this energy. As it is uncertain when the stored energy is going to be used, the size of the SS should be very large. Thus, to minimize the losses and to avoid the oversizing of the SS the reel-out and reel-in periods should be adjusted. The ideal adjustment is to divide the reel-out and reel-in time equally. Nonetheless, there will always be overlapping of energy generation due to the transition time between phases of the kite. But, the losses and the size of an SS could be minimized if the overlapping is minimized to an optimum value. Additionally, a flexible load can use the extra energy produced reducing the size of the SS.



(a) ***Energy generated by KP system 1 during one cycle***



(b) ***Energy generated by KP system 2 during one cycle***



(c) ***Energy generated by two KP systems over time***

Figure 2.2: ***Energy distribution of 2 synchronized KP system with an optimum reel-out time***

On the other hand, the performance of a Kitepower system will be affected if the reel-out and reel-in time are equal. The produced energy of the system will be less over the lifetime compared with a system with a shorter reel-in time. However, it should be considered that there is a possibility of extending the lifetime of the KP system by cycles adjustments.

To have a better understanding of how the performance is affected, the energy produced between the two cases is compared. It is important to remark that using synchronized KP systems to mitigate the power gap, the initial cost of the microgrid will be higher than just one KP system with SS. But the LCOE of two KP systems will still be lower as the LCOE of an SS is still high nowadays. .

2.1.2. Diesel generator

A diesel generator is a well-known technology embedded in the energy industry. It is not friendly to the environment, and the efficiency is very low. However, it has been dominating the offgrid power supply for a considerable amount of time. Because this equipment is available in most of the potential applications for the KP system, considering it as part of the microgrid could have some advantages.

Some diesel generators have the capacity to respond fast enough to fill the power gap. Their starting time is around 10 seconds from completely off due to inertia and synchronism of the generator [33]. So it is necessary to have precise control to start the engine before the reel-in starts. This represents a disadvantage because the control system should be ready to respond to a rapid change of the wind conditions, something that is not crucial for a component with a response's timescale of milliseconds. In addition, there is no information on the efficiency and lifetime of a diesel generator when used in cycles like AWE. To improve the response time, the diesel generator can be on the whole cycle. But this still represents a considerable amount of fuel consumption. An issue that is not desired by the customer. To fill the power gap, the diesel generator was discarded as an option.

In the other hand, for a backup energy source, a diesel generator is the most suitable technology. This is because in the worst case when the AWE system is not able to supply any power, a reliable and cheap backup system is needed. As the Diesel generator is a mature technology in the market, it can ensure power supply for long periods of low prices depending on the location. In addition, the diesel generator is already being used as a backup system for renewable energy system in off-grid communities [1], so it represents a safe component to be integrated into the AWE system. In addition, as the size range is vast, it can be sized according to the load with more accuracy. This can save some initial costs, and it can avoid power losses.

2.1.3. PV system

Considering a PV system to fill the power gap, means that it should be able to provide the total power consumed by the user. Thus, during the day, it would not make sense to operate the AWE system. However, considering a small PV system for ancillary services could be feasible.

In the case that the AWE microgrid has an SS, it has to be considered that it could discharge faster than it charges with the AWE system. This is because just a fraction of the power generated by the AWE system will be used to recharge the battery. The amount of power directed to the battery will depend on the user consumption. It is possible that the battery can charge completely under periods of small power consumption, but for the case that the power consumption of the users is constant over long periods, a small additional source should be considered to assist the recharge rate. PV system can be a suitable solution here. A cost-benefit study should be done here to get the feasibility of adding PV.

2.1.4. Fuel cell

A fuel cell is a device that generates energy from Hydrogen, and its residue is water. There are many types of fuel cells, and the basic operation is very different. Some operate with high temperatures and some with low. The ones that operate with low temperatures need a very pure Hydrogen fuel. Their efficiency is high compared with other DGs as gas turbine or fossil fuel engines.

A fuel cell was considered in this analysis to support the power gap. Additionally, the fuel cell can use the excess of energy by generating Hydrogen from water by a reverse process. This system is extremely friendly with the environment, and with enough fuel can sustain the microgrid for extended periods. The drawbacks of this device are that the capital cost is high and it needs a Hydrogen storage infrastructure. The Hydrogen storage can be complex and expensive as it requires special conditions. In addition, Hydrogen needs particular safety regulation increasing the maintenance cost. But for further applications, the extra energy generated by the AWE system can be used to produce hydrogen.

2.2. Storage systems

For selecting the SS of a microgrid, it is essential to consider the operational mechanism of the KP system. Based on this, an analysis of SS's can be done to select the most suitable according to the microgrid necessities.

The SS's considered in this first analysis are Li-ion battery, flow battery, supercapacitors, superconducting magnetic energy storage (SMES) and flywheels. The principal characteristic taken into account to select these devices are the efficiency, cycle life and the time response. As there is an immense amount of cycles, the SS should have a significant cycle life. Additionally, as its purpose is to spread the energy, a minimum amount of losses when the energy passes through the SS is needed. Thus, a high-efficiency SS is necessary to fill the power gap. Now, a short description of the SS being considered for the AWE microgrid will be given starting with the Li-ion battery.

2.2.1. Lithium-ion battery

The lithium-ion battery is the first SS considered to fill the power gap of the Kitepower System. This battery can offer several advantages for the AWE microgrid. Fig.2.3 shows that the Li-ion can store more energy per unit of mass and volume than other conventional batteries in the market (Nickel-metal Hydride or Lead Acid). Another significant advantage of this battery is that it can offer high cycle life. But for this, special attention should be paid to the battery depth of discharge (DOD)[8].

The DOD is the percentage of battery capacity that has been discharged expressed as a percentage of maximum capacity [9]. In other words, the DOD indicates how much energy has been consumed from the battery related to its nominal full capacity. When the DOD is at 100%, the rated energy capacity of the battery has been entirely depleted.

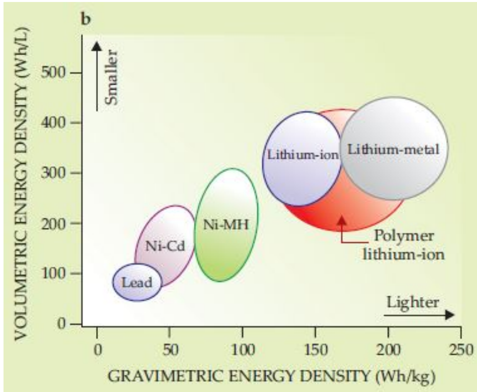


Figure 2.3: ***Comparison of the energy store capacity between rechargeable batteries [12]***

In [23], the cycle life for three types of Li-ion batteries is calculated. Fig.2.4 shows the number of cycles against the DOD of each battery. Here can be observed that with a DOD higher than 80%, the number of cycles is limited to less than ten thousand. But as the DOD decreases the cycle life improves significantly. According to the model made in [23] and the battery datasheet of [14], if the DOD is less than 5% the number of cycles is approximately one million (this is just estimation as no battery has worked for such a small DOD and cycle time). However, the cycle life is also dependent on other variables like the operating temperature of the battery[12]. Particular attention to this condition should be paid to reach high cycles life.

To size a Li-ion battery to fill the energy gap, the DOD should be a driving parameter for it. To have at least 10^6 cycles, the DOD should be limited to less than 5%. It can be considered the 4% for the safety factor.

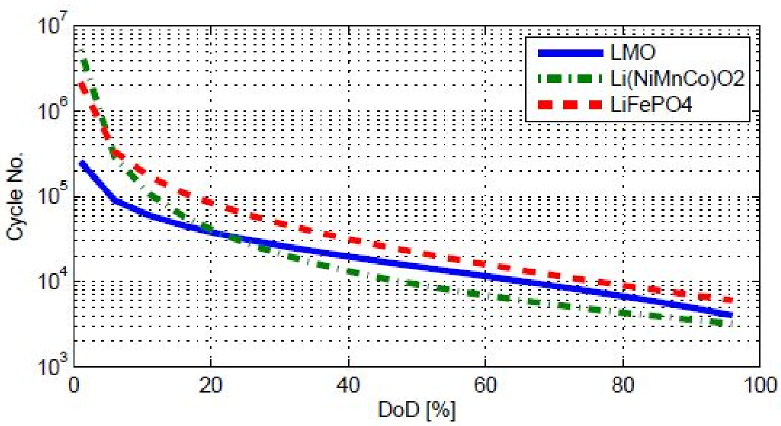


Figure 2.4: ***Number of Cycles according to the DOD of a Lithium-ion battery [14]***

An advantage of the oversizing is that the battery would be able to sustain the load consumption for more time than the other SS devices considered in this thesis. In addition, one of the advantages of this battery compared with other batteries is that it has an energy efficiency range from 85% to 95%[28][26]. Offering better operational parameters than other commercial batteries as NiMH (66% of energy efficiency) and lead acid (50% to 90% of energy efficiency)[10].

2.2.2. Redox flow batteries

This battery has some advantages that can be used for the AWE microgrid. RFB batteries are electromechanical cells where the chemical is provided by two chemical components dissolved in liquids contained within the system and separated by a membrane[29]. These batteries store the electrolytes in divided tanks. This means that the storage capacity depends on the size of the tanks[29]. The advantage of this battery is its long cycle life. Theoretically, it has infinite cycle life. But the specific power is very low compared with the other components taken into account in this analysis[25][27], Table 2.7 shows that its power density is 166 W/kg. As the power and energy calculations shown, it is needed a small amount of energy and a high amount of power per each cycle. Hence, the size of the battery flow would be much higher than any other SS, leading to extra infrastructure cost.

In addition, the efficiency is very low compared to the other SS treated in this thesis. It is between 75% and 85%; this is a low value for what this research is looking. The losses could be very high considering that it will have a high number of cycles in its lifetime. This device is not recommended to be considered for further applications.

2.2.3. Superconducting Magnetic Energy Storage (SMES)

The SMES is a component used to store energy through a magnetic field. This device stores DC electricity using cryogenics and superconductivity technology. SMES offers a lot of advantages compared with the other SS.It has an extremely high power density, high efficiency and high cycle life. AS this SS is based on superconductor technology, the efficiency can be higher than 95% [25][27]. This is because there are no resistive losses, leading to fast response as well [30]. The magnetic field is produced through the superconductor, then, it releases a high amount of energy in a short period. This sudden release of energy leads to very high power densities for this device.

It is certain that this component can give more than 10^6 cycles. The number of cycles is mainly constrained by the fatigue of the support structure. According to [31], the number of cycles can be considered infinite; this is a favourable advantage to work together with the AWE microgrid. The main drawbacks are that the capital cost per kWh is very high compared with the other SS technologies and the LCOS is also high due to the maintenance of the cryogenic system. However, the principal characteristic to fill the energy gap is that a high power device is needed, not a high energy one. Hence, this application can offer an advantageous combination of lifetime and efficiency to fill the power gap. Additionally, the significant initial costs can be compensated with fewer replacements compared with the other SS.

2.2.4. Supercapacitors

Supercapacitors, also known as electrochemical capacitors (ECs) or ultracapacitors, are components with higher capacitance values than conventional capacitors (electrolytic capacitor). As can be observed in fig. 2.5 and 2.6, their power range is between the electrolytic capacitors and rechargeable batteries.

The supercapacitors are divided into two types depending on the storing method. The Electrostatic Double Layer Capacitors (EDLCs) and the pseudocapacitors [12]. Both components have

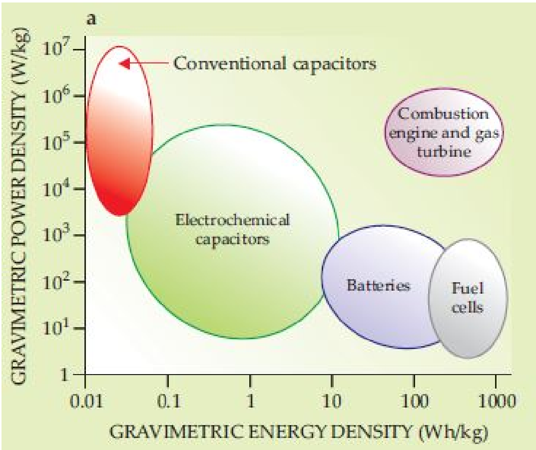


Figure 2.5: ***Number of cycles vs the Depth of Discharge of a SAFT Lithium-ion battery [12]***

a higher power density than any battery. In other words, supercapacitors can receive and transfer charge much faster than any battery.

Additionally to the high power density, the supercapacitors have a long cycle life. These components can reach up to one million cycles at 25°C [11]. An important advantage over a Lithium-ion battery is that their cycle life does not depend on how much energy is discharged from the supercapacitor. In a Lithium-ion battery, the variation of power demand over a day will cause a fluctuation on the DOD; this could lead to an unreliable cycle life estimation. In addition, the efficiency is very high, it can reach efficiencies of 95% [25][27][28].

The supercapacitors are typically used for applications that need fast charge and discharge cycles such as electric cars. At first instance, the supercapacitor properties are suitable for filling up the energy gap of the AWE system, but an economic analysis needs to be done to see the financial advantages.

2.2.5. Flywheel

A flywheel is a mechanical energy storage device. They resist changes in rotational speed by their moment of inertia. These devices have high specific power and low specific energy. Their response is very fast, and the cycle life and efficiency are very high. These devices are good competitors against Supercapacitors and SMES. According to [32], the flywheels cycles can exceed 10^6 because of the excellent material properties they are made of. They have high power density and low energy density.

They are also very efficient components, 93% to 95% according to [25], 80% to 99% according to [26] and 70% to 95% according to [27]. They still have a quite higher cost than supercapacitors and SMES. But for some applications, they can represent a very suitable SS for an AWE microgrid.

2.3. Non-critical load - heater and MD water power unit

This is not a DERs, but it should be considered a controllable load for the excess of power that the DGs could generate. When the user consumes only a small fraction of the energy produced by the AWE system, the SS could reach its full charge and then there will be extra energy that needs to be used or dumped. There are many options for this application. One could be the distillation of water. Clean water can be produced with the wastewater by membrane distillation. This application can be very useful for remote communities. Another option is a simple heating system. These components should be versatile to be installed depending on the customer's needs. But it is essential to make a forecast of the load to get an idea of how much excess of power could be generated, and from it, the component that best matches the needs can be proposed.

The important aspect of a controllable load is that it can improve the performance of a microgrid considerably. It can reduce the losses and help to mitigate the randomness of the KP system power production.

2.4. DERs discussion

The principal purpose to select a DG or an SS is to solve the power gap of the AWE system. It is known that there is no other application in the market with such a gap as in this system. None of those SSs and DGs have ever worked with this kind of cyclic energy production. Thus, for their comparison and their selection, the data is quiet limited. Therefore, it should be understood that there is no just one solution, there are several methods and several types of equipment that can solve the energy gap. To decide which to use is not an easy task. There is a need to establish specific parameters based on the load profile, users needs and wind profile. But this information is scarce for the application that is studied here. Hence, here is some recommendation for selection of the components for further applications.

Due to the cyclic operation of the AWE system, another DG that is not an AWE system is not recommended. They are not designed for this type of activity. Their lifetime or efficiency could be profoundly affected when operating in a cyclic generation. Thus, the best recommendation for another DG to work together with an AWE system is another AWE system. They should work synchronously and the reel-out/in time should be adjusted depending on the microgrid application.

Because of the performance in an offgrid application could be affected if two KP synchronized systems are installed, an SS to solve the energy gap is recommended in this thesis. However, to select one that best fit the consumer's needs, they should be compared every time a KP microgrid is designed.

Fig. 2.6 shows the specific power against the specific energy of all the SS systems considered in this analysis. Based on the study done, to fill the energy gap of the KP system, it is preferred an SS with a high specific power than with high specific energy. However, as the number of cycles in the AWE system is exceptionally high (eq. 6.5 and 6.6), it, together with the efficiency are the most critical parameters taking into account. Thus, it is needed a component that can

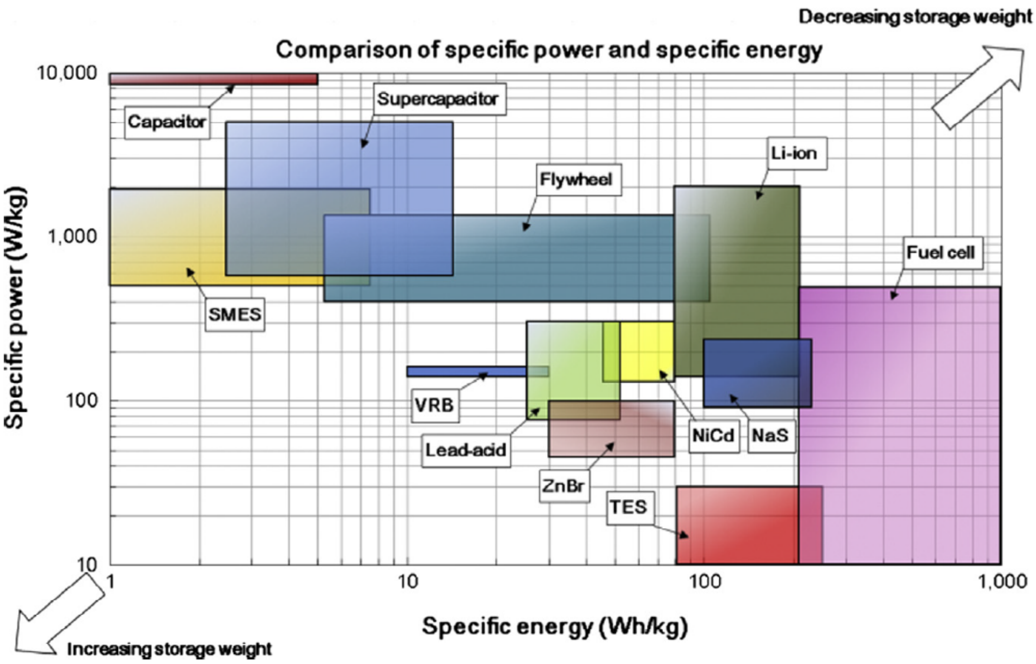


Figure 2.6: ***Specific power and specific energy of the most common SS[24]***

Storage System	Cycle Life	Specific E (Wh/kg)	Specific P (W/kg)	E Density (Wh/l)	P Density (W/l)	Capital Cost (€/KW)	Cost (€/KWh)	LCOS (€/KWh)	Efficiency	Life (years)	Respons e Time
Li-ion Battery	1000 - 1000000	100 - 300	100 - 4000	200 - 400	1300 - 10000	2100 - 2750	200 - 560	0,25-0,45	0.9	5 -15	ms
Superconducting magnetic energy Storage (SMES)	10^6 - infinite	1 - 10	10 - 10^8	0.2 - 10	1000 - 4000	200 - 300	840 - 8400	0.4 - 0.9	0,95 - 0,99	20	ms
Flow Battery	1500 - 15000 (theoretically infinite)	10 - 50	166	20 - 70	0.5 - 2	1270 - 1650	400 - 1100	0.15 - 1.3	0.75 - 0.85	5 -15	ms
Supercapacitors	~ 1000000	2.5 - 5	1000 - 10^5	10 - 20	40000 - 120000	200 - 300	300 - 5000	0.15 - 0.35	0.95	20	ms
Flywheel	<10^6	10 - 30	1000 - 10000	20 - 80	5000	590 - 1450	1000 - 25000	0,15 - 0,25	0.95	15	ms-min

Figure 2.7: ***Data of the different SS analyzed.[24][25][26][27][28]***

operate with high numbers of cycles and high efficiency. Therefore; SMES, Supercapacitor and Flywheel are recommended for this application. Table 2.7 show that they have high power density, high cycle life and high efficiency compared to the batteries.

For higher cycle than 10^6, it is recommended SMES or Flywheels. The SMES could be used for the cold places while Flywheels can be used in warm areas. Most of the supercapacitors do not ensure higher cycles than 10^6, but its price is lower than the other devices. It can be suitable for some application.

Nonetheless, the Lithium-ion battery can be used to fill the energy gap as it operates with a theoretically high number of cycles if the DOD is short. But this means that the sizing of the component should be large to maintain the DOD small and the number of cycles high. Even the prices of the Li-ion batteries are going down; the power capital cost could be very high due to the oversizing of the battery. However, it can be very useful for an offgrid application that has a highly variable load or in microgrids that are connected to the grid but have high probabilities to work in islanded mode. The performance of the microgrid can also be improved significantly by using a hybrid SS. Using a SMES to mitigate the power gap and Li-ion for long periods it could be one example.

In the other hand, is usual that a microgrid always has a SS for any complications and stabilization issues. Thus, an AWE microgrid should consider a battery according to the user needs. But it is more recommended to mitigate the power gap with a high power density SS than with a battery. In the next section, the selection parameters will be specified, and an AWE microgrid is proposed.

3

Sizing formulation

The sizing should be adequate for any application of the KP system. A precise sizing for a real use cannot be made due to the lacking of real data. Therefore, a sizing method for the KP system in a microgrid is proposed, and then some specific cases are simulated.

In a microgrid, there should be a balance between the power produced and the power consumed. Based on the power balance, the optimum size of the DERs to fulfil the customer's needs should be obtained. An algorithm is proposed to find the best size for the microgrid arrangement proposed here.

3.1. Microgrid sizing

In a microgrid, fulfil the load needs is the main objective. The load or energy consumption can vary depending on the location, type of loads, amount of users etc. In most microgrids, the SS is used to balance the power between the load and the DG's due to their variation over a day or longer periods. However, for microgrid with just one KP system, one of the main SS's purposes is to stabilize the cyclic output power of the pumping KP system mechanism. One of the problems is that the size of an SS will be very different if it is just used to mitigate the power gap than to balance the power difference over a long term. To have an accurate differentiation between the power and energy needed for the two cases, two different SS will be considered; one to fill the power gap, and another to balance the power between the load and DG's. It is important to mention that to size the latter SS, a stable power output of the KP system is considered as one DG output.

First, it is needed to define the main objective of the entire system. In this thesis to balance the power flow between the power produced and consumed is the principal objective. The difference between the power supplied and the power consumed should be the minimum possible. The power difference will be called ΔP. Hence, the following equation is established:

$$\Delta P(t) \leq \epsilon \tag{3.1}$$

Where ϵ is the threshold defined by the application, the ideal value for most of the cases is 0. This equation is the objective, from it, the main parameters and variables to reach the power balance are presented. Now, ΔP can be written as follow:

$$\Delta P(t) = P_s(t) - P_c(t) \tag{3.2}$$

Where P_s is the power supplied, P_c is the power consumed and. P_s refers to the power generated and it also considers the power stored. Thus, this parameter can be show as follow:

$$P_s(t) = \sum P_{DER}(t) = \sum P_{DG}(t) + \sum P_{SS}(t) \tag{3.3}$$

Where P_{DG} is the power of the distributed generators and P_{SS} is the power of the Storage system. The power consumed P_c of the equation 3.2 can be decomposed as follow:

$$P_c(t) = \sum P_L(t) + P_G(t) \tag{3.4}$$

Where P_L is the load power and P_G is the power of the grid. It is important to remark that P_{SS} in equation 3.3 and P_G in equation 3.4 can be negative to indicate the flow direction as the SS sometimes absorbs energy and the grid sometimes provides. Now, equations 3.1 and 3.2 can be written as follow:

$$0 = \sum P_{DG}(t) + \sum P_{SS}(t) - \sum P_L(t) - P_G(t) \tag{3.5}$$

Usually, data for the power generation and the load can be estimated. Thus, $P_{SS}(t)$ of equation 3.3 is the only unknown variable; this is because the SS is used to compensate the difference between the DG's and the load. Equation 3.5 is used to obtain the optimum size of the SS.

Now, it should be specific constraints that should be fixed for the system; this put operational thresholds that ensure an optimum operation in the microgrid. To establish a safe operating range through fixing a maximum and a minimum SOC is the most important constraint for an SS. The range is mainly defined by the equipment operating specifications. The constraint is represented as follow:

$$SOC_{SSg}^{min} < SOC(t) < SOC_{SSg}^{max} \tag{3.6}$$

These constraints help to define the total size of the SS, but this size is mainly to balance the power over long periods. To size the SS that mitigates the power gap, another method is proposed.

3.2. KP system sizing - compensating the power gap

In the microgrid of this thesis, the KP system is the main DG. Thus, the term P_{DG} in the equation 3.5 is referred principally to this system. For the equations mentioned above, the KP system should be able to provide uninterrupted power. The DER's that will mitigate the power gap should be sized first. In this section a method to size the DERs to mitigate the power gap is proposed.

To size of the DERs used to fill the power gap; it is needed the energy generation capacity of the KP system. For the calculation of this energy capacity, a forecasting or experimental data from a specific period is required. As the power generation is highly variable due to the wind, an average of this power should be calculated from a particular time lapse.

To calculate the net energy and power supplied by the KP system, the follow equation is used:

$$E_{kp} = \int_0^T P_{kp}(t)dt \tag{3.7}$$

Where E_{kp} is the net energy supplied by the KP system, and the right term of the equation represents the integration of the power over time. T is the total period of the data introduced. To know the energy generated per cycle and per hour, then the total number of cycles in T.With this information, the average energy per cycle can be calculated by:

$$E_{kpc} = \frac{E_{kp}}{n_{cycles}} \tag{3.8}$$

For calculating the energy and power generated per day, the reel-in and reel-out time should be known. These two terms are highly variable through the day, but an average can be estimated from field data. After, with E_{kpc} and the reel-in and reel-out time, an estimated size of the KP capacity per day can be calculated.

To calculate the average net power, The reel-out time should be known, as the power is generated in this period. Then, the net power per cycle can be calculated with:

$$P_{kpc} = \frac{E_{kpc}}{t_{ro}} \tag{3.9}$$

3.2.1. Distributed generator sizing

A DERs comparison is made to know which respond faster and which elements have the best performance to ensure a stable energy output.

The power gap is one of the most important concerns of the KP system. Thus, the DERs should be sized according to this issue. However, DG's and SS's have different characteristics that lead to different sizing methods. For example, if a DG is selected to mitigate the energy gap of an AWE system, it will mean that energy will be generated from another source. In other words, the energy supply of the entire microgrid increases as the DG's increases. It is expressed by the following equation:

$$\sum E_{DG} = E_{KP} + E_{DGn} \tag{3.10}$$

If an SS system is chosen to fill the power gap, this will extract the energy from the AWE system to release it during the reel-in. However, if just a DG is considered to fill the power gap, is still needs an SS to have a stable microgrid's power flow. But the size of this SS would be smaller than an SS used to mitigate the energy gap entirely. Nonetheless, using an SS to ease the energy gap have some advantages.

For the amount of DGs and their sizing, it can be stated that it's sizing will depend on the load needs. In this case, the DG should be able to provide the same amount of power as the KP system. Thus, the size can be equivalent to the maximum capacity of the KP system.

3.2.2. Storage system sizing

To size an SS in a microgrid, [35] proposes a method in which the maximum and minimum generated power and power consumed are taking into account. But for this method, a load and a generation profile are needed. Additionally, the sizing is for long periods of time due to the changes in the renewable resources. It is not considered such a short and large cyclic power production as the KP system. Hence, another method to size the SS of KP system is proposed here.

As mentioned, SS's will not generate energy as a DG's. To solve the energy gap of the KP system through SS's, they will store part of the energy produced during the reel-out phase and then release it during the reel-in phase. In other words, instead of filling the power gap with energy from another source, they will spread the energy produced by the KP system.

According to equation 3.5 and 3.9 the power balance for an offgrid KP system with an SS used to fill the power gap is expressed in the next equation:

$$0 = P_{kpc}(t) + P_{SSg}(t) - P_L(t) \tag{3.11}$$

Where P_{SSg} is the power of the SS used to fill the power gap. This equation is used to define the SS size to fill the energy gap. However, to solve the energy gap with an SS, it is known that there should always be a power balance between the power produced by the KP system and the load. That is why an SS is needed to compensate this power balance when the KP system is at reel-in phase. However, by this method, a fraction of the net energy delivered by the KP system should be directed to the SS, when this happens, the net power delivered in the reel-out phase will decrease as well as shown in fig 3.1. To have a smooth output change between the Kitepower and the SS, the SS should be able to provide the load demand or the maximum output power of the KP system.

It is important to remark that P_{SSg} from equation 3.11 will be negative during the reel-out phase, and positive during the reel-in phase. But it is also important to remember, that during the reel-in phase P_{KP} suposed to be negative, but to simplify the problem, P_{KP} is considered to be the net power. Hence, P_{KP} is considered to be equal to 0 during the reel-in phase. The equations for the reel-out is:

$$P_{kpc}(t) = P_{rSSg}(t) + P_L(t) \tag{3.12}$$

Where, P_{rSSg} is the power needed to be used to charge the SS. The equation of the power balance during the reel-in is:

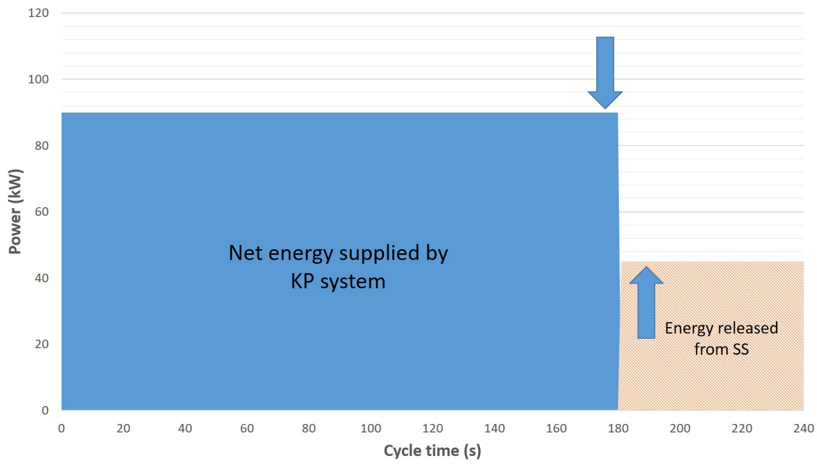


Figure 3.1: ***Example of the energy distribution of an AWE system with SS***

$$P_{SSg}(t) = P_L(t) \tag{3.13}$$

This means that during the reel-out phase the SS should be able to provide the load power demand by itself. Additionally, as the output power from the SS to fill the power gap and the KP will be considered as one output of a DG, the system should be evaluated at full capacity. But this means that during the reel-out, the total power generated by the KP system should be equally distributed between the SS and the load.

Now, the size of the SS to fill the power gap mostly depend on the load power demand. If it is a variable load, the peak power load could be taken and then multiplied by the average or the longest reel-in time that the generation profile has. This will give the maximum energy to fill the power gap. From here the ΔSOC should be calculated to get the SS size. But as the principal DG is the 100kW KP system, there is a maximum power output that this equipment has depending on the reel-in/out time. The SS to fill the power gap will be sized considered full capacity as it is intended to maximize the power output.

To size at full capacity, equations 3.12 and 3.13 are combined and the follow equation is obtained:

$$P_{kpc} - P_{rSSg} = P_{SSg} \tag{3.14}$$

This equation represents exactly what the figure 2.1 shows, but instead saving energy to retract the kite; the energy will be saved to be discharged to the load. For the next equations, it is just considered the net power delivered to the load from the KP system and not the total power generated by it. Now, to get the optimal power output, it is needed to get the net energy delivered from the KP system to the load, for this the following equation is used:

$$E_{kpl} = \int_0^T P_{KP}(t)dt - \int_0^T P_{rSSg}(t)dt \tag{3.15}$$

Where E_{kpl} is the energy provided by the KP system to the load and T is the total time of the power generation sample. Now, the energy used from the SS to supply the load E_{sso} also needs to be calculated, for it, the following equation is used:

$$E_{sso} = \int_0^T P_{sso}(t)dt \tag{3.16}$$

The energy calculated of this equation, is the total energy generated in time T. But, in order to have an easier manipulation of the values, the average energy per cycle is calculated with:

$$E_{kplc} = \frac{E_{kpl}}{n_{cycles}} \tag{3.17}$$

$$E_{ssoc} = \frac{E_{sso}}{n_{cycles}} \tag{3.18}$$

Where E_{kplc} is the energy supplied to the load by the KP system and E_{ssoc} is the energy supplied by the SS per cycle. The equation 3.19 can be decomposed as follow:

$$E_{kplc} = E_{kpc} - E_{rssc} \tag{3.19}$$

Where E_{kpc} is the net energy per cycle supplied by the KP system and E_{rssc} is the energy reserved for the SS per cycle. To calculate E_{rssc}, the efficiency of the SS is needed. This is because the energy needed to charge the SS should be larger of what it is expected to release. Thus, the following equation is used:

$$E_{rssc} = E_{ssoc}\eta_{SS} \tag{3.20}$$

To calculate the power output per cycle of each equipment then the reel-in time and reel-out time should be known. To get this time, an average of each one can be computed from test data got during the interval time T. Then, power from each equipment can be expressed as follow:

$$P_{kplc} = \frac{E_{kplc}}{t_{ro}} = \frac{E_{kpc} - E_{rssc}}{t_{ro}} \tag{3.21}$$

$$P_{ssoc} = \frac{E_{ssoc}}{t_{ri}} \tag{3.22}$$

Where P_{ssoc} is the power output from the SS used to supply the load during the reel-in time, the P_{kplc} is the power output from the KP system used to supply the load during the reel-out time, t_{ro} is the reel-out time and t_{ri} is the reel-in time.

From equations 3.21 and 3.22, it can be stated that:

$$\frac{E_{kpc} - E_{rssc}}{t_{ro}} = \frac{E_{ssoc}}{t_{ri}} \tag{3.23}$$

But from this equation it has also to be considered the energy output efficiency of the KP generator, and combining it with equation 3.20 the follow equation is obtained:

$$\frac{E_{kpc}\eta_{KPgen} - E_{ssoc}\eta_{SS}}{t_{ro}} = \frac{E_{ssoc}}{t_{ri}} \tag{3.24}$$

Now, to reach the optimal power output that satisfies the equation 3.23, an iteration should be made. Through this iteration, the efficiencies are taken into account to calculate the optimum power output accurately. The iteration should be made with the values per cycle.

Figure 3.2 show the flow chart of the iteration done to get the optimum power output. In this method, it is considered from the calculation of the net power of the equations 3.7. This is because the energy needed for the reel-in phase has a direct impact on the energy available for the load, and it is also dependent on the cycle time.

First of all, the KP power generation profile is inserted, this could be a simulation or data from a field experiment. Then, the average cycle time should be obtained. After, the net energy per cycle is computed through the energy integration of the KP system data. This is done through the equations 3.7, 3.8. After, the net power per cycle is calculated by the eq.3.9. This is followed by a guess in the power capacity of the SS to fill the power gap; this is a 0.5 of the net KP system power. Hence, calculating directly the power released by the SS per cycle P_{ssoc}. Then the E_{ssoc} and E_{rssc} are computed. After, E_{kplc} is calculated with the equation 3.19 and then P_{kplc} is calculated with the equation 3.21. This is followed by the calculation of the power difference ΔP. This is to compare the power output based on the equation 3.9. If the difference is less than 0.0001, then the output power from the SS and KP can be considered equal. If it is not, a value of 0.0001 is added to the KP power fraction (i), and the calculation starts again from the calculation of P_{ssoc}. In the appendix, can be seen the python code used for this iteration.

Now, it should be specific constraints that should be fixed for this variable. For the SS needed to fill the power gap. There would be two main constraints; one, the variation of the State of Charge ΔSOC between the charge and discharge of every cycle should have a limit.

$$\Delta SOC < x \tag{3.25}$$

Where x is the maximum variation estated by the operator. The ΔSOC is calculated with the follow equation:

$$\Delta SOC = SOC_{ro} - SOC_{ri} \tag{3.26}$$

Where the SOC_{ro} is the SOC after the reel-out and SOC_{ri} is the state of charge after the reel-in. The second is the threshold for longer periods of time. A minimum and maximum SOC should be established to have a safe operating range. This will define according to the user needs. The constraint is represented as follow:

$$SOC_{SSg}^{min} < SOC(t) < SOC_{SSg}^{max} \tag{3.27}$$

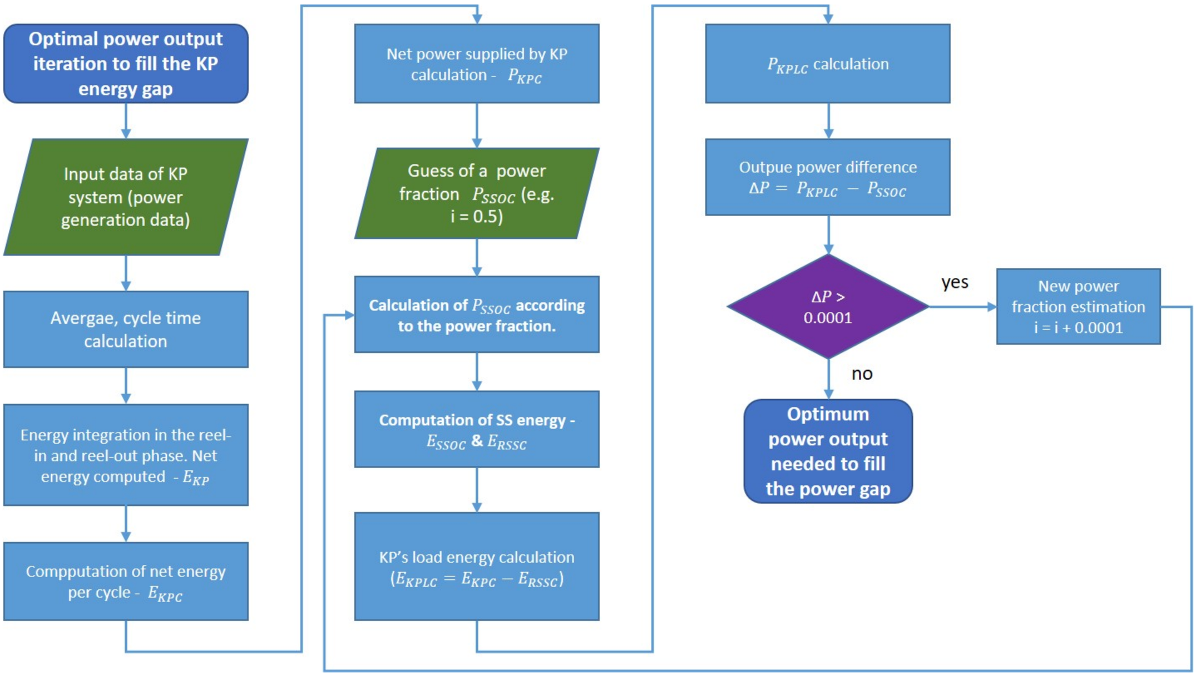


Figure 3.2: ***Iteration flow chart used to find the optimal SS power output to fill the power gap***

However, as this constraint is for longer periods of time, it is just used for the SS dedicated to balancing the power over long periods and not for the one that fills the power gap. These constraints will define the total size of the SS. To size the SS that will balance the power flow for longer periods of time, just the constrain 3.27 should be used.

4

KP microgrid design and layout

To create and simulate some scenarios for the microgrid, it is needed to fix the layout and operating parameters of the KP microgrid. In this chapter, it is explained the factors taken into account to design the microgrid layout. Additionally, the operating conditions are fixed into some standard parameters. Based on the established in previous chapters, the most viable KP microgrid is obtained.

4.0.1. Application - Islanded or grid connected

The first point to take into consideration is the application for which the KP microgrid is going to be designed. It is known that microgrids should be able to operate in islanded or grid-connected mode. Thus, this is the first driving parameter that should be taken into account. The operation scheme depends on the fundamental purpose of the microgrid. If the microgrid is intended to supply energy to remote cities, rural areas or military camps where the main grid does not reach, then it should be designed for islanded operation entirely. It should be able to satisfie all users demand by itself. In addition, it should be highly reliable to reduce the probability of failure.

On the other hand, some microgrids are used for local power production in places where the main grid is supplying energy[1]. It is usually to reduce the energy bills of big companies or some residential communities. These microgrids can be found in urban areas with common DGs as PV or small wind turbines. In addition, these microgrids should be able to work in islanded mode and offers ancillary services to the main grid [22]. For this application, the KP microgrid should be designed to operate grid connected. But, be prepared to work in islanded mode.

This thesis is mainly focused on creating microgrid for a military camp. These camps are known to be in remote areas where there is no grid. They don't have another possible energy source that is not the local DG's that they carry. According to the Dutch Ministry of Defense, their camps are mainly energized by diesel generators. And the cost of the diesel transportation increases the fuel price, being this the reason to look for a more feasible energy source. Thus, an offgrid solution is considered, a KP microgrid for a total islanded operation.

4.0.2. Wind profile - power generation forecast

It is essential to know the operating conditions where the microgrid is going to be installed. For KP systems, means to have an accurate wind profile for the place, this is mainly to forecast the generation pattern over long periods of time. With this information, the further DERs selection can be made with better criteria as the other DERs help to ensure the power supply. For instance, if the wind profile is weak in some seasons, then it will make sense to put a large SS or to install another DG to support the power production.

It is essential the forecasting of power production as the KP microgrid layout varies with this factor. Thus it is recommended to gather as much data as possible to simulate these profiles and get the best DERs selection and size.

It is difficult to know where an army camp is located. Thus, there is no precise data on the operational conditions for the Kitepower System. However, the most important objective is to identify the best solution to eliminate the power gap. Thus, for the first design, a constant power generation is estimated to prove the functionality of the sizing.

It is not considered the power changes generations due to the seasons. This research is principally done for a short time sizing and solution to estimate the best way to mitigate the energy gap and to create a most efficient KP microgrid layout.

4.0.3. Operating settings - AC/DC & Voltage/Current levels

The next aspect to consider is the current type of electric distribution. It can be AC, DC or a mix of the two. It is known that the DC distribution is not widespread these days. But there is some application in which this type of current is needed. As remote data centres and telecommunication buildings[17]. In the case that a microgrid is implemented for existing residential or industrial areas. The best option is to create a microgrid with AC buses. Now, if the microgrid consists of mostly DC DERs and most of the loads are AC. Then the hybrid system is the best option. Once it is defined the current distribution, the bus operational parameters should be fixed to proceed to DERs and loads interaction.

In this part, there should be attention to the interaction between the DERs. It is possible that a DC SS was selected before, but due to the electric user configuration, it is better to change to an AC SS. The DERs selection should also consider the if it is needed AC or DC.

Additionally, the desired conditions by the user need to be known. If the load requires constant voltage or constant current, then the SS should be sized for that purpose. Also, it is necessary to know the range in which these values can operate; it will lead to a more accurate SS sizing.

For this microgrid, it is logical to consider an AC output as most loads are standardized for this type of electricity supply. Besides, the diesel generator supplies voltage and current by AC; it can be advantageously connected directly to the AC bus.

In the other hand, all SS's in this analysis except for the flywheel, operate in DC mode. Additionally, the KP system has already a DC bus that connects a small battery to the motor/generator to start the operations. Here, this DC bus can be used to connect the SS that will fill the energy gap. The advantage is that it has a higher power quality and the control is much simpler for a DC bus than for an AC bus.

For the previous reasons and after being evaluated the different microgrids architectures in [18] and [20]. A hybrid DC-AC microgrid should be considered.

4.0.4. Microgrid sizing

For the AWE microgrid design and the solving of the challenges mentioned in section 1.1.2, it is needed to size the system according to the load and characteristics of the KP system. For accurate sizing, it is required a precise forecast of the power consumption. Thus, a load profile is needed to build a scenario for the AWE microgrid.

This aspect is significant for a microgrid's performance. All the components in the microgrid need to be sized to optimize the overall efficiency. In section 6.1, a path to size a KP microgrid is proposed. The values of the sizing will be different for several cases tested and simulated further in this thesis.

4.0.5. KP microgrid DERs

The DERs have an essential impact on the design of the microgrid. Their combined and coordinated operation should provide a stable amount of power to the load. Depending on the DERs, the control strategy selected will adopt different approaches to manage the power production and storage[17]. A proper administration of the energy is crucial for a profitable performance of a microgrid. Additionally, this part is highly influential for the efficiency and reliability of the microgrid as the number of components affects these two concepts.

One of the primary objectives of this thesis is to propose a functional microgrid for KP. Thus, the central DER is the 100kW KP system. However, it has to be combined with other types of DERs to improve its output power. The analysis of the DERs was made in section 2 and a short description is followed given.

As the microgrid is going to operate just in islanded mode, a second KP system will not be considered. This is to avoid massive losses and to avoid the oversizing of a battery or to implement a dump energy system.

Due to the reason explained in section 2.4, another DG is not a viable option to fill the energy gap. However, for backup equipment, it is considered a diesel generator. The military camps are already supplied by diesel generators these days. Then there will be no investment for a new type of backup system. Additionally, it is easy to store diesel for an emergency than another kind of energy as hydraulic, hydrogen, etc. The maintenance is cheap, and it is reliable equipment.

On the other hand, an SS is going to be considered to fill the energy gap because it will be operating offgrid. The selection of the SS depends mostly on the efficiency, cycle life. Here it is proposed the SMES because is the one that promises more cycle life than any other and has the highest efficiency. Another possible best option will be the Flywheel, as the SMES uses a cryostat for it's functioning, in warm areas maybe its functioning might be affected. Then a Flywheel or a supercapacitor could represent a better option. Additionally, their response time is very fast so that they will adapt quickly to any changes in the KP operation.

4.0.6. KP microgrid layout (architecture)

After selecting the previous parameters, a KP microgrid architecture should be proposed to connect the DERs and the loads. The architecture should be designed to maximize the efficiency of the system. However, there should be considered the financial aspect. To slightly improve the efficiency can represent a high-cost difference due to the components. In this thesis will focus to find the most reliable microgrid for a campsite, and the financial aspect will be in the second term.

In the other hand, to propose an optimal microgrid architecture. The existing settings were the microgrid is going to be installed has to be considered. If the KP microgrid is needed in a place where there is an electrical infrastructure, it is better to adapt the KP system to this infrastructure rather than create a new one. However, this aspect should be carefully worked with the DERs selection, component and control system. The architecture defines the interconnection between them.

Based on the previous statements, the first AWE microgrid architecture is proposed. Its configuration can be seen in figure 4.1. This microgrid doesn't have a connection to the main grid as it is designed for an offgrid application. The two DGs are KP system and diesel generator, and the SS is a SMES.

Figure 4.1 show that the connection recommended for the SMES is through the DC bus. The compensation of the energy gap is done through this bus. The DC bus offers a better power quality because of its simplicity [18]. Thus, for such a big and continuous gap, a DC bus represents better conditions for the stabilization of the output power. Additionally, to compensate the variation in the frequency due to the wind speed randomness, the generator is connected to an AC-DC rectifier. This rectifier fixes the output voltage of the system. Usually, this converter is connected to another converter that transforms back the DC output to AC. But, as the primary purpose is to lose as less energy as possible to fill the energy gap, connecting the SS to compensate the gap through the DC bus will improve the efficiency as the SMES has a DC output that doesn't have to be converted to AC. If the output of the SS is AC, then, it might be a better to fill the energy gap through an AC output. In addition, the control strategy used for DC power management is simpler than in AC. This is because the frequency and reactive power are eliminated when the power is transformed to DC, improving the reliability of the system. It can be observed that the SMES is connected to the DC bus through a DC-DC converter, this is to avoid huge voltage variation due to the change in the state of charge (SOC).

If there are DC loads, they can be connected to the DC bus, but they will need a DC/DC converter to adapt the operating conditions to the load's needs. The non-critical loads should be connected through a breaker so in an emergency they could be disconnected from the microgrid.

To have an AC bus to connect the diesel generator and the AC loads. It is needed to connect a three-phase inverter that can transform the DC voltage to AC. In the case that the SS connected to the DC bus is a battery or another SS with energy for large periods. This inverter should be bidirectional, so the SS could also be charged by the diesel generator. If the nominal output of the diesel generator is the same as the AC operating conditions, the diesel generator can be connected directly to the AC bus, eliminating any converter and improving the efficiency. The AC distribution and loads are standardized, so the loads could be connected to the AC bus without any converter. The AC non-critical loads should be connected to a breaker so they can be disconnected if it is required. Chart 4.2 show the main components of the KP microgrid.

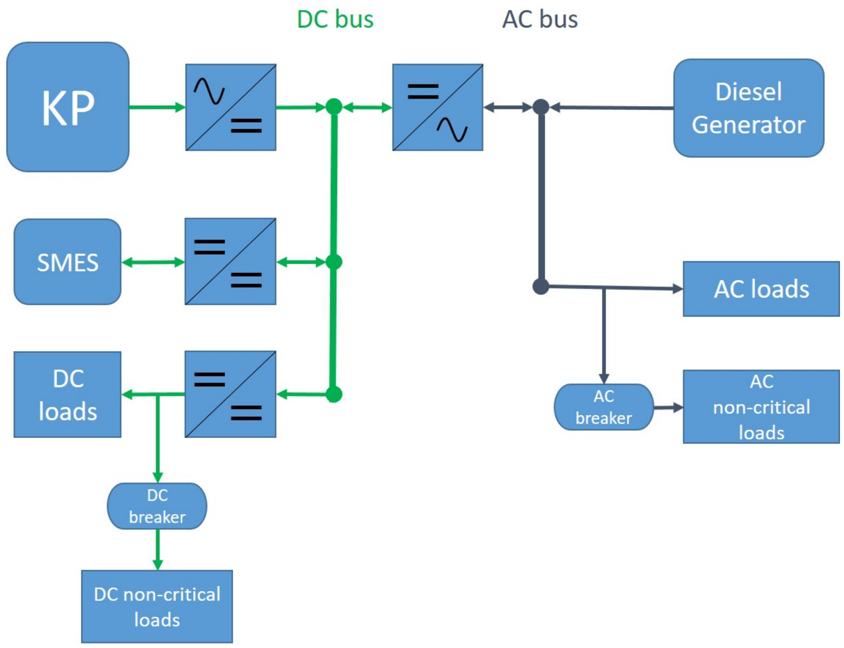


Figure 4.1: ***AWE microgrid configuration with hybrid DC and AC bus***

The buses need to have an established operating conditions. For the AC bus, it is easy as the operating conditions for the AC distribution are standardized in the world. Hence, the AC bus should comply the AC distribution standards. In Europe, the distribution AC voltage is 220V, and the frequency is 50 Hz. Most of the regular appliances are designed for this conditions. It is expected that the AC bus of the AWE microgrid satisfies this setting.

The KP generator has a nominal operating AC voltage is 400V [20]. It is proper to consider this as the voltage value for the connection of the SS and the KP system.

The KP system is a highly variable power source; this leads to the need for an accurate control strategy. The one proposed for the KP microgrid is centralized, this type of control offers a better approach for the coordination of the DERs. The centralized control receives information in real time of the different DERs. Thus, it can manage the power production efficiently and intelligently.

KP microgrid eqipment	
DG	**Qty**
KP system	1
Diesel Generator	1
SS	
SMES	1
Extra components	
DC/DC converter	2
AC/DC converter	1
DC/AC converter	1
DC Breaker	1
AC Breaker	1

Figure 4.2: ***Principal components of the AWE microgrid***

4.0.7. Microgrid components and control strategy

From the previous variables and elements definition. The interface through the buses between the microgrid DERs and load should be designed. The standard components for the interface are power converters, voltage transformers and protection devices. The buses parameters and the load consumption will define the nominal capacities of the microgrid elements.

A control strategy is needed to manage the power flow between the microgrid components. According to [19], there are many types of control strategies for microgrids; centralized, decentralized and distributed are ones of the most used. A detailed study of different control approaches should be done to find the most suitable for the application that the microgrid is going to be used.

The DER's interface has a direct impact on the efficiency, and it is built by physical components (converters, transformers, etc.) and the control scheme. It is essential to make a proper and detailed design to achieve the higher efficiency of the microgrid.

4.1. Efficiency parameters of the system

In this section is presented the main components efficiencies that should be taking into account, and how they play a role in the microgrid power flow.

The efficiency of the power output depends on the efficiency of the DERs and converters. Apart from this, the power flow has an impact on the overall microgrid efficiency. The electrical power output of a Kite Wind Generator (KWG) can be defined as follow:

$$P_E = \eta P_M \tag{4.1}$$

Where P_M is the maximum power extractable from the wind flow, η is the overall efficiency coefficient. This coefficient can be defined as follow:

$$\eta = \eta_{EG}\eta_{GB}\eta_{KWG} \tag{4.2}$$

Where η_{EG} is the efficiency of the electric generator, η_{GB} is the efficiency of the gearbox and η_{KWG} is the performance coefficient of the kite generator. However, η_{KWG} is not going to be considered as the model will just receive the mechanical power input. The mechanical input of the model already considers the efficiency of the KP system. η_{GB} can be approximated to 0.9. η_{EG} of the current AC generator is 0.95. The overall efficiency of the Kitepower system can be estimated to be:

$$\eta_{KP} = 0.9 * 0.95 = 0.86 \tag{4.3}$$

In the table 4.3, the efficiencies of the AWE microgrid elements is shown.

AWE microgrid components	Efficiency %
KP system	~0.86
Diesel Generator	~0.85
SMES	~0.97
Supercapacitor	~0.95
Flywheel	~0.95
Li-ion battery	~85-90
DC/DC converter	~97
AC/DC converter	~93
DC/AC converter	~96

Figure 4.3: ***Approximate component's efficiency of the AWE microgrid***

As aforementioned, the power flow affects the efficiency of the system. For example, if the KP generator supplies the DC load directly. Just the efficiency of the KP and the converters are taking into account, and the efficiency can be defined as follow:

$$\eta_{KP-DCload} = \eta_{KP}\eta_{AC/DC}\eta_{DC/DC} \tag{4.4}$$

$$\eta_{KP-DCload} = 0.86 * 0.93 * 0.97 = 0.78 \tag{4.5}$$

Thus, the estimated efficiency is 69%. But, if the power flows from the KP system to the SS and then to the DC load, the battery efficiency will need to be included in the previous equation. The new equation is:

$$\eta_{KP-DCload} = \eta_{KP}\eta_{AC/DC}\eta_{Batt}\eta_{DC/DC} \tag{4.6}$$

$$\eta_{KP-DCload} = 0.86 * 0.93 * 0.97 * 0.97 = 0.75 \tag{4.7}$$

This is a raw estimation of the efficiency of the energy supplied to the load, but it considers the principal components of the microgrid. It is important to highlight that if an SS with a lower efficiency is installed in the microgrid, the energy provided to the load could decrease considerably per each cycle. That is why it is preferred to use an SS of high efficiency to fill the power gap.

4.2. KP microgrid Simulink model

The KP microgrid was modelled in Simulink. This section shows the model according to the stated in the previous chapters; it can be seen in figure 4.4. Here, It can be noticed the DERs of the microgrid; one KP system, a diesel generator and an SS. It has three power converters, one three-phase AC to DC, that is connected from the KP system to the DC bus, it can be seen in figure D.1 in appendix D, where the internal model of KP system is appreciated. The second is a DC-AC converter that leads to the AC bus where the Diesel generator and the AC loads are connected. And the third that is a DC-DC converter that connects the SS to the DC bus. This one is to stabilize the voltage output of the SS.

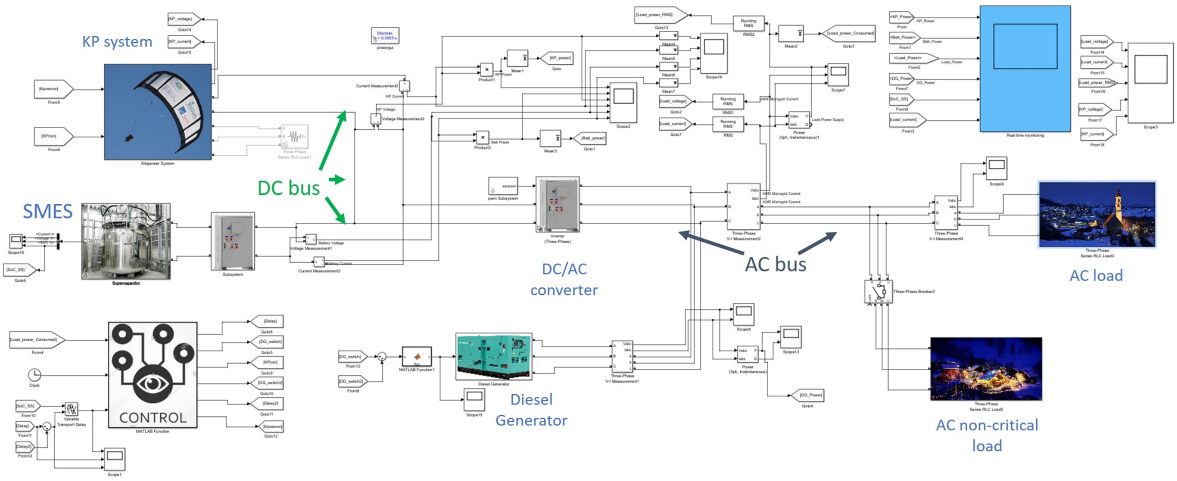


Figure 4.4: ***KP microgrid Simulink model***

The model uses a Supercapacitor for the simplicity to use it in Simulink. But this not represents any inconvenient because the SS is sized the same for the SMES, supercapacitor and Flywheel. The rated capacitance for the first case was gotten based on in the nominal values before presented and the energy calculated for the SS.

The DC bus can be seen on the right side of the figure 4.4. The AC bus can be observed in the middle left. All the way left, the critical load and non-critical load can be seen, they are connected to the AC bus. The diesel generator can be seen at the bottom of the figure; it is also connected to the AC bus.

Initially, the KP system provides power to the microgrid. It is important to mention that the KP generator in this model does not take into account the energy used for the reel-in phase. To simulate the reel-in, a resistance that is activated during the reel-in period is used. During the reel-out of the simulation, the supercapacitor retains part of this energy, while the other fraction is given to the load. After the reel-out period is finished the power provided by the KP system drops and the supercapacitor starts supplying power to the load. This is simulating the reel-in phase in which the time has to be also specified in the model.

The power demand and supplied are set according to the calculations made in the previous chapters. Then, cycles are simulated in order to see how the SS respond to the pumping mechanism. In the next section the parameters used and the cases of the simulation are described. Then the results are discussed. In the appendix, C.4 can be seen the code used to simulate the Model.

5

Studied cases

In this chapter, some study cases are tested to observe if the developed method is giving accurate results. First, it is presented an scenario with constant load to size the SS that compensate the power gap. After, an scenario of variable load to size a SS for a long period is performed.

5.1. KP system for military camp

It would be ideal to have wind data from the place where a camp is installed, but there is no information. Thus, through the equation proposed in the previous chapter, a size based on the maximum capacity of the KP system is going to be recommended.

Additionally, to get the best size for the DERs and further components, it is needed to size the microgrid according to a load profile. The main potential application of KP system is in Dutch military camps, and for this use, there is no accurate load profile available. Nonetheless, according to information given by the Dutch Ministry of Defense and Standards Agreement of the North Atlantic Alliance, a 3 kWh/day per person should be considered for military camps. But in recent missions, they have registered a consumption of 6 to 9 kWh/day per person. Besides, the number of persons in a military camp is highly variable. Hence, it is necessary to design the KP microgrid based on the maximum capacity of a 100kW KP system.

Following the cycle time mentioned in the section 1.1.1, two cases are shown in this section for the energy calculations. These two cases are calculated here cause they represent the extreme operational cases, this is to show the potential size of one KP system. The first case taken is when the reel-out phase lasts the same time as the reel-in phase, this is 60 seconds, and the best case is when the reel-out last 180s and reel-in 60 seconds. Considering an ideal energy production of the 100kW system, the energy production in the reel-out is:

$$E_{p1} = (100kW)(60s) = 6000kJ = 1.66kWh \tag{5.1}$$

$$E_{p2} = (100kW)(180s) = 18000kJ = 5kWh \tag{5.2}$$

According to the fig. 1.3, the power used for the reel-in phase is approximately 30%. Thus, for a 100kW system, this would be approximately 30kW. This quantity is taken for the first case, but it is important to mention that for the new systems this could be less. With this power the energy needed for the reel-in is:

$$E_{c1} = (30kW)(60s) = 3800kJ = 0.5kWh \tag{5.3}$$

To calculate the total energy produced in each cycle the follow equation is used:

$$E_{cyc} = Energy_{ro} - Energy_{ri} \tag{5.4}$$

where E_{cyc} is the total energy produced per each cycle.

The total energy generated per each cycle is:

$$E_{t1} = 1.66kWh - 0.5kWh = 1.166kWh/cyc \tag{5.5}$$

$$E_{t2} = 5kWh - 0.5kWh = 4.5kWh/cyc \tag{5.6}$$

The total cycles of the kitepwoer system in an hour is:

$$cyc1_{day} = (\frac{3600s}{120s/cyc}) = 30cyc/hr \tag{5.7}$$

$$cyc2_{day} = (\frac{3600s}{240s/cyc}) = 15cyc/hr \tag{5.8}$$

The energy produce in an hour and in a day is:

$$E_{p1} = (30cyc/day)(1.166kWh/cyc) = 35kWh/hr = 840kWh/day \tag{5.9}$$

$$E_{p2} = (15cyc/day)(4.5kWh/cyc) = 67.5kWh/day = 1620kwh/day \tag{5.10}$$

If we consider the standard of 3kWh/day per person, then the KP system can energise a camp from 278 to 540 people. If consumption of 9 kWh/day per person is taken into account, the system could energize a camp from 92.8 to 180 people respectively. Figure 5.1 shows the energy produced and the potential camp size vs the ratio of the reel-in time to reel-out time. As the ratio gets close to one (when the reel-out and reel-in phase has the same duration time) the number of people that the Kitepower system can supply with energy decreases. In this example, it is considered that 30% of the power produced (100kW) is needed for the reel-in of the kite. Also, the plots are considering an energy consumption of 3kWh/day per person. In appendix-A, the graphs for 20% 10% power consumed by reel-in are shown. Also in this appendix, it is plotted the potential camp size when the energy consumption is 9kWh/day per person.

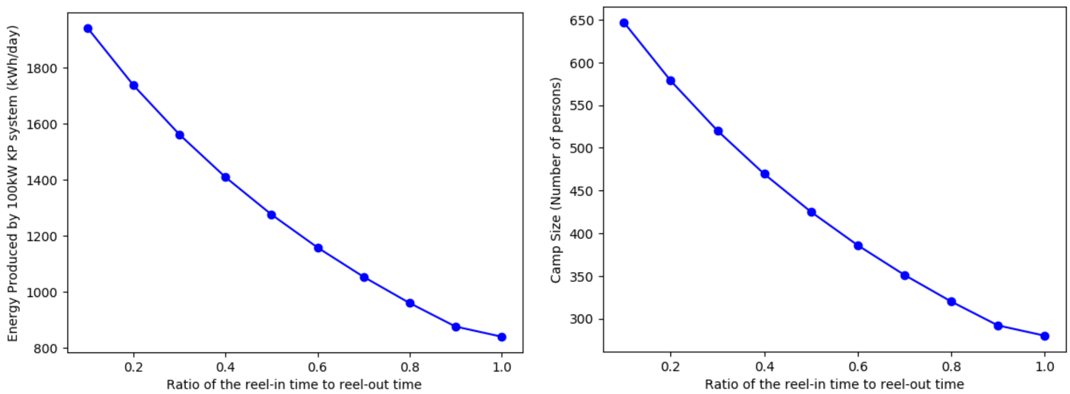


Figure 5.1: ***Energy produced and camp size depending on the reel-in to reel-out time ratio. With 30% of the power produced needed for the reel-in phase and a consumption of 3kWh per person***

According to with the computation, if the KP system output is the ideally 100kW and with a reel-in time being 1/3 of the reel-out time. A 100kW system can supply a camp of between 490 and 540 people, considering consumption of 3kWh/day per person. If a power consumption of 9kWh/day per person is used for the calculation, the camp size will be between 160 and 175 users. This also depends on the efficiency of the entire system; it should be included to have a better estimation of the size.

As the Dutch Ministry of Defense is the closest potential customer for Kitepower, the AWE microgrid will be designed under this parameters. In addition, as the potential market is still unknown, it is better to size the AWE microgrid from the unit size (100kW) and not from the final application. These will give an estimate of how many people or households can an AWE microgrid of 100kW can energize.

This method is first used with constant values to calculate the optimum power for a case of 180s reel-out and 60s reel-in phase and 30kW used for reel-in the kite and an SS efficiency of 95%. If an iteration with a 100kW KP system at constant maximum capacity is run, the optimum energy distribution will be store 1.12kWh to the SS to fill the power gap while the KP system provides 3.38kWh. This values will distribute the energy in a way that the energy released during the reel-in will have the same output power, fig. 5.2 shows this distribution graphically. The output power thus is 67.4 kW for a maximum operating capacity.

Through this method, several power outputs were calculated according to the reel-in/out ratio. Figure 5.3a shows the optimal energy to be stored and release at the reel-in phase and fig. 5.3b shows the output power from the KP system and SS during the power gap. Here can be observed that if the reel-in time increases, the amount of energy needed to fill the power gap increases as well. Hence, the optimum power output decreases. This graph was also calculated when the reel-in power is 20% and 10% of the KP system power; they can be seen in appendix B.

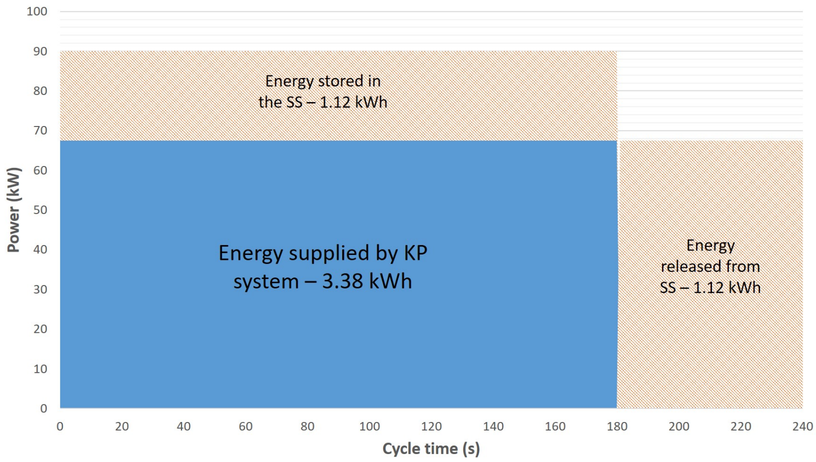
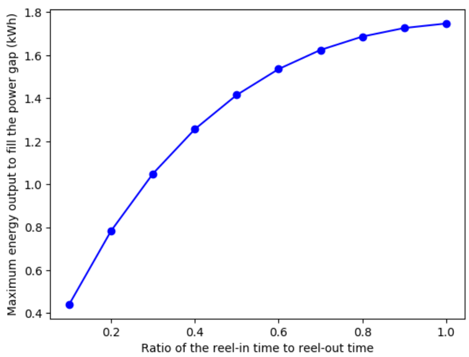
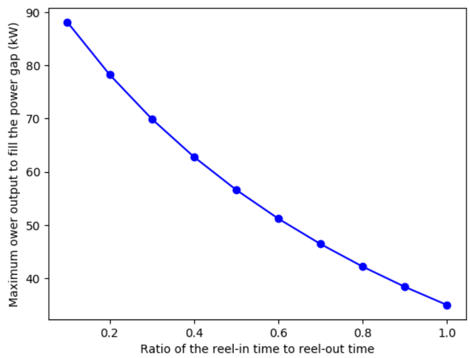


Figure 5.2: ***Energy supplied profile for the microgrid***



(a) ***Example of the energy distribution of an AWE system with SS***



(b) ***Optimal power needed to fill the power gap***

Figure 5.3

The power considered for the design of the microgrid is 70 kW. This was the average optimum output power when the reel-in used power is 30%, 20% and 10% and also for the reel-out/in cycle ratio being considered in this thesis.

For the SS size, it should be able to provide energy for the worst case. According to the graphs of appendix B the most demanding case will be when the energy gap is 2.2 kWh. However, this is just to fill the energy gap, but the SS should be bigger because it should be able to supply power for more minutes to suppress any delay or slight malfunction of the AWE system. Also the ΔSOC should satisfy the constrain 3.26, the ΔSOC is limited to 15%. Thus, the energy size of the SS should be 14.6 kWh.

This SS size is specifically to ensure a constant supply of power during the pumping cycles. An extra capacity can be considered to supply energy for more time as hours. But this should be sized according to the specific load's needs, and it is considered in the equations as a different SS. A DG as a backup power station for this thesis, and it is used to balance the power during extensive periods. The SS will be just dedicated to filling the energy gap.

It is important to remark that this analysis is made in power units (kW). However, the electrical power depends on other variables. These are voltage and current for DC, for AC, the "power factor (pf)" is added to the previous variables. To size the SS accurately, it is needed to know what does the load or user requires regarding these values to establish optimal conditions. It is possible that the output power of the KP system could be the same of the SS, but they can have a different voltage or nominal current outputs. Additionally, there are SS that behave as a voltage source and others that act as a current source. It is essential to know the ranges in which the voltage or current can deviate or if they should be strictly constant. But this should be analyzed for the specific application.

5.1.1. Scenario 1

The model was simulated to observe if the AWE microgrid reaches a balance through the power calculated from the iteration. For this simulation, the size of the supercapacitor is 14.6 kWh, and the size of the battery is 55 kWh. For this first simulation, a constant power production of 100kW is used, the cycle is 180s of reel-out and 60s of reel-in as observed in fig. 5.4.

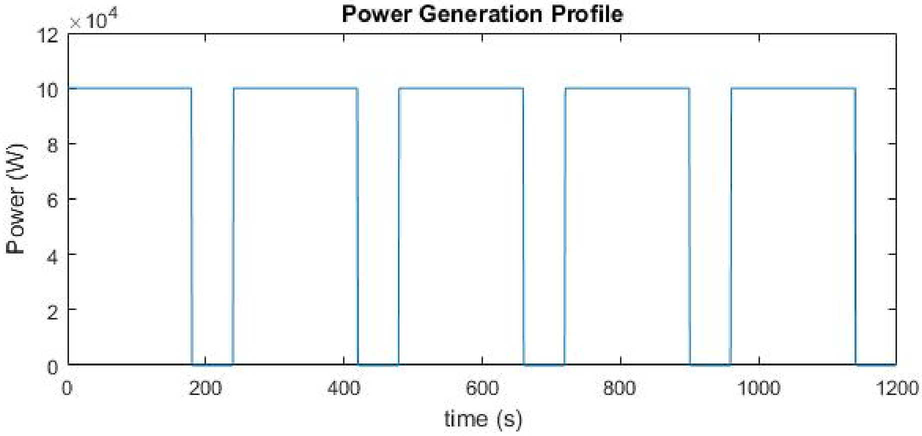


Figure 5.4: ***KP system power generation profile***

According to the iteration, the power output for this power production is 72 kW. To have an ideal smooth power output at maximum capacity, 28kW should be directed to the SS to store energy and then released during the reel-in. Figure 5.5 shows the power consumed by the load in the KP microgrid simulated with a supercapacitor and battery, the load consumption was fixed approximately at 72kW. Figure 5.6 shows the state of charge (SOC) of the supercapacitor and battery for this first simulation. It can be seen that according to the calculated, there is a power balance between the power generated and the load. The SOC variation in the supercapacitor is not higher than 10%, and in the Battery is not higher than 4%. This is convenient for the cycle time of the SS.

Additionally, the size of the SS can be seen in figure 5.6 due to the SOC variations. These sizes are close to the calculated ones.

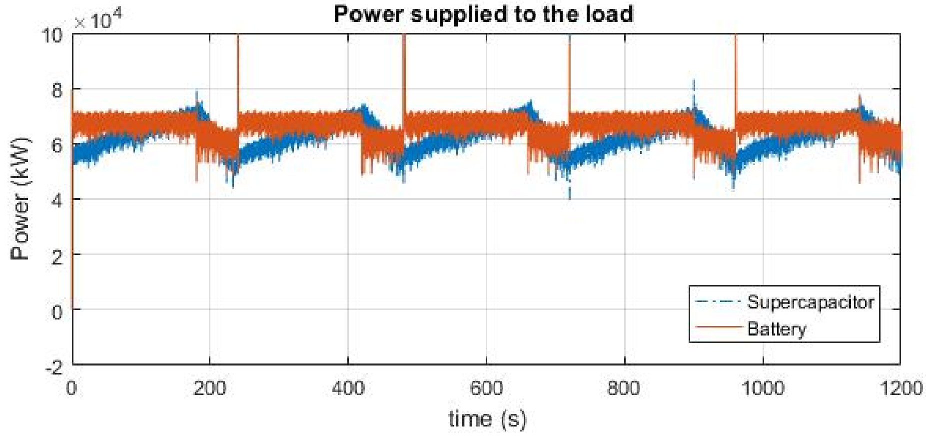


Figure 5.5: ***Power consumed by the load***

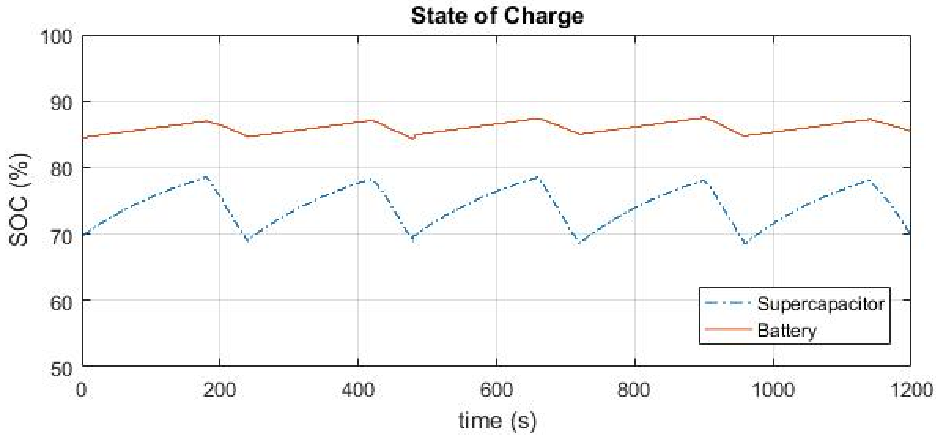


Figure 5.6: ***State of charge of the supercapacitor and Battery***

5.1.2. scenario 2

To prove the method and result, a second simulation result is presented. Here, the power generation profile is variable to simulate the randomness of wind power. Figure 5.7 show the power used to simulate the generation of the KP system.

To simulate the reel-in power a resistance was installed in the model, and it activates every time the power from the KP system drop to 0. Figure 5.8 shows the power consumed by the resistance simulating the reel-in. The power of the reel-in for this scenario is 10 kW.

According to the iteration, the optimum output power for this KP system is 59 kW. Figure 5.9 shows the power consumed by the load, it was fixed close to the 59kW to reach a balance between generated and produced. Figure 5.10 show the SOC of the SS, here can be seen the power balance. The SOC change is less than 10%, and less than the previous scenario as the power generation is less.

By this simulations, it can be seen that in the case of a constant load consumption, the SS can be fixed to create a balance. This is convenient to a military camp as it is expected that the power consumption is close to a constant value. For most of the application, it is

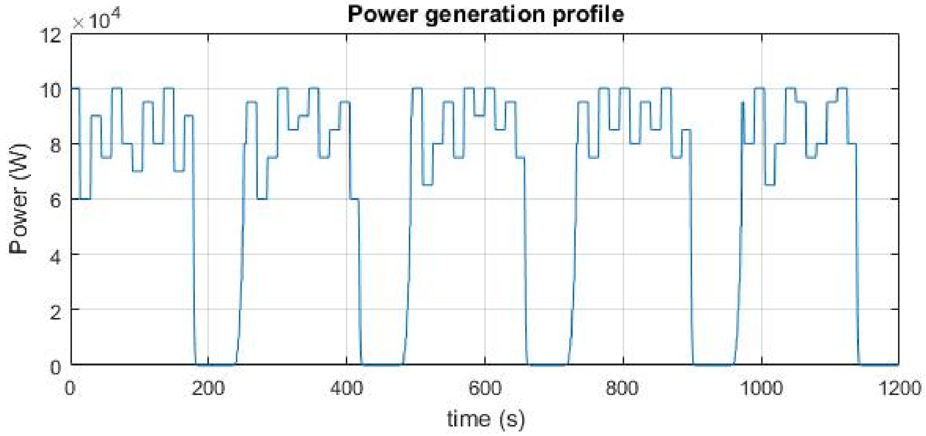


Figure 5.7: ***KP system power generation profile***

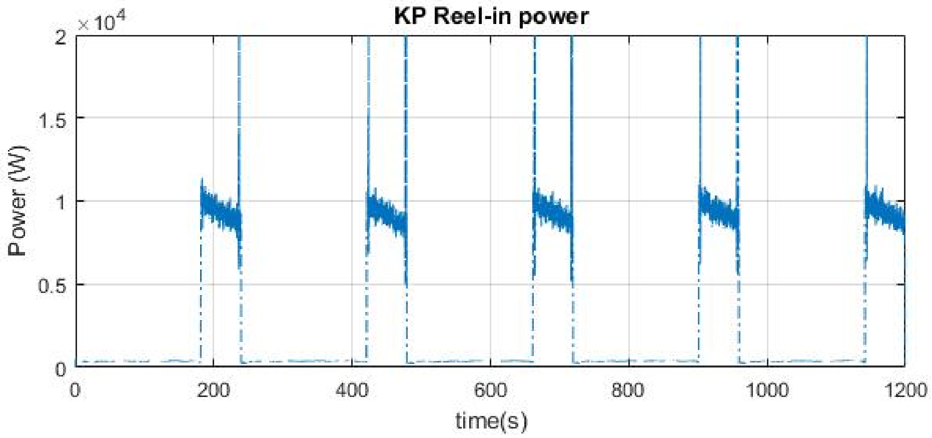


Figure 5.8: ***Reel-in power***

expected to be high variation in power produced and consumed over long periods of time. For this, a larger battery can be included. But for military camps, the unbalanced power can be mitigated with the Diesel Generator.

5.2. Variable load - Long term SS

There are other offgrid applications for an AWE microgrid. Villages and rural communities are some examples. The load for this applications is rarely constant. Thus, an SS should be used to mitigate long variation. This thesis is centred in the application for the military camps, but it is possible that some camps also present a high change in the load consumption. Hence, it is proposed a fast method to size this SS in case it is necessary.

For remote communities, the concept of a household should be used. One household consist of all the people that occupy one dwelling, the occupants could be one family or just one person. In the Netherlands, the average amount of people per household is 2.3[15]. The electricity consumed per household depends on the number of occupants and the appliances that the dwelling has. Due to the large types of appliances characteristics of each household. It is difficult to compile data on precise household electricity consumption according to its devices. However, research made in 2014 by the University of Utrecht for the residential

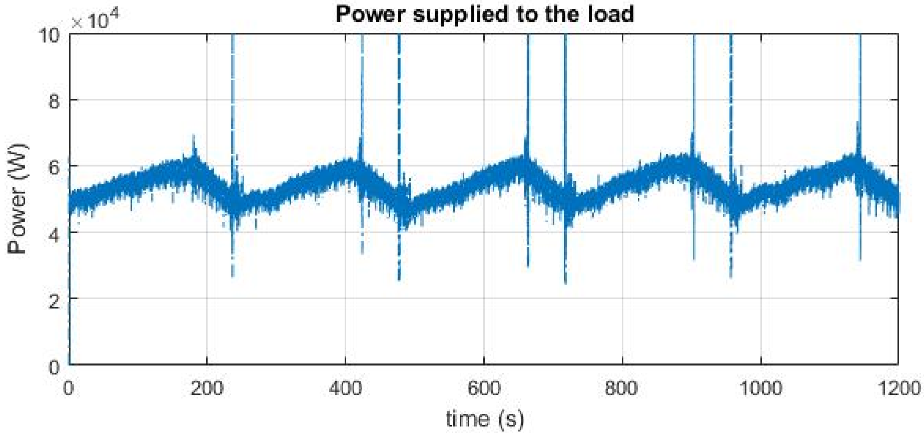


Figure 5.9: ***Power consumed by the load***

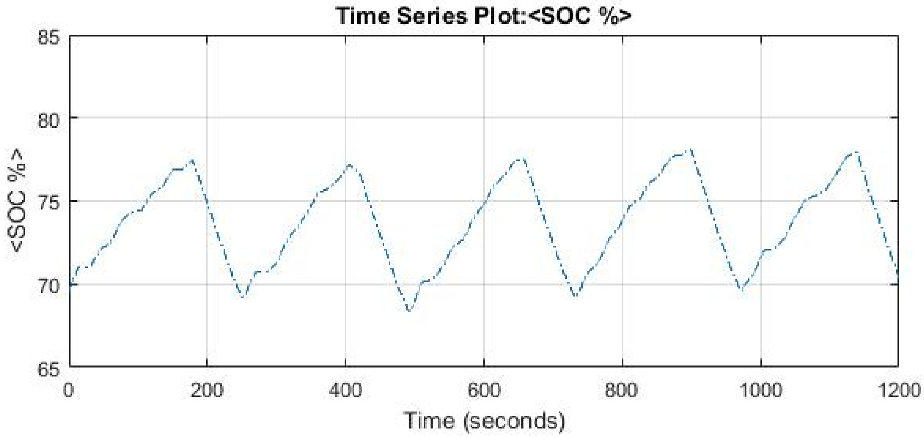


Figure 5.10: ***State of charge of the KP system supercapacitor***

electricity consumption in the Netherlands. Considers appliances shown in fig.5.11, these are the most commonly used in the Netherlands. This gives us a broad picture of the amount of energy that a household could need for daily life activities.

Fig.5.12 shows power consumed by 100 households in Winter in the Netherlands. Data provided by the faculty of "Electrical Engineering, Mathematics and Computer Science" of TU Delft. In this graph, the average power consumption per household is 11.25 kWh/day. According to the World Energy Council, the average electricity consumed by a household in 2014 was 9.02 kWh/day[16]. It is understandable as in the winter the energy consumption is higher than in summer.

To design a microgrid that fits this purpose, a method based on the equations discussed in chapter 3 is performed. This method will work for any further KP microgrid sizing as long as the data of the load and the power generation is possessed. To simplify the problem, the output power of the KP system and the SS used to fill the power gap, is going to be considered as one DG output.

Now, having the power generation profile and the load profile a balance of the power is needed. According to equation 3.5, to find the size of the storage for a long term. The equation is:

Appliance	2000 Adoption (%)	2050 Adoption %
Computer	60	100
Printer	60	100
TV	99	99
TV receiver box	15	93.4
DVD Player	13	90
Electric oven	61.6	80
Microwave oven	74	90
Kettle	97.5	97.5
Washing machine	95	96
Dryer	53	60
Dish washer	38	60
Refrigerator	97	97
Freezer	71	90

Figure 5.11: ***List of appliances considered for the calculation of household electricity consumption [15]***

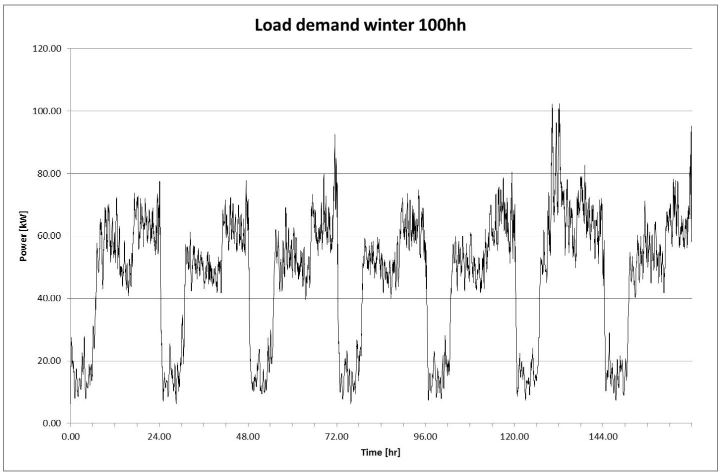


Figure 5.12: ***One hundred households consumption during a week (Source: Faculty of Electrical Engineering, Mathematics and Computer Science, TU Delft)***

$$P_{SSl}(t) = P_{KPs}(t) - P_L(t) \tag{5.11}$$

As explained, the purpose of the power flow is to have a perfect balance between the energy generated and the energy consumed. If the power generated is the same as the average power consumed, the size of the SS will just be to balance the power difference between night and day. Thus, the optimal would be to generate the same amount of power as the average of consumption.

The average of the power consumption in fig. 5.12 is 46.9 KW. If the power generated is the same as the average power consumed, then the SS will just save the excess of power generated during the night and then used during the day. The energy flow will look like the plotted in figure 5.13 if the power generated is 46.9kW, the same as the average power consumed.

The SS size to balance is taken from the maximum energy requirement, so the size is sufficient

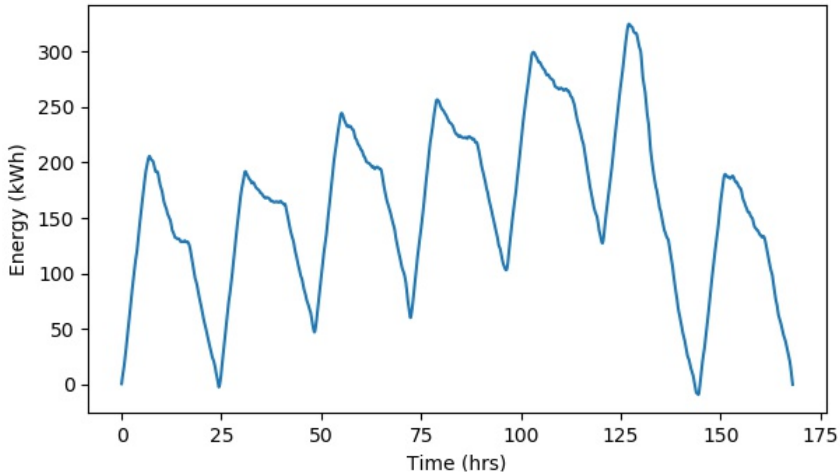


Figure 5.13: ***Energy flow of 100 households in summer with a constant production power of 46.9kW***

to provide energy in the worst predicted case. T between the hour 130 and 140 approximately. For this profile, the energy size calculated for the SS is 345kWh, its SOC during the week will look like figure 5.14. A limit of 95% was fixed for the size. In this figure, it can be seen how the most extended SOC decay matches perfectly with the largest power difference.

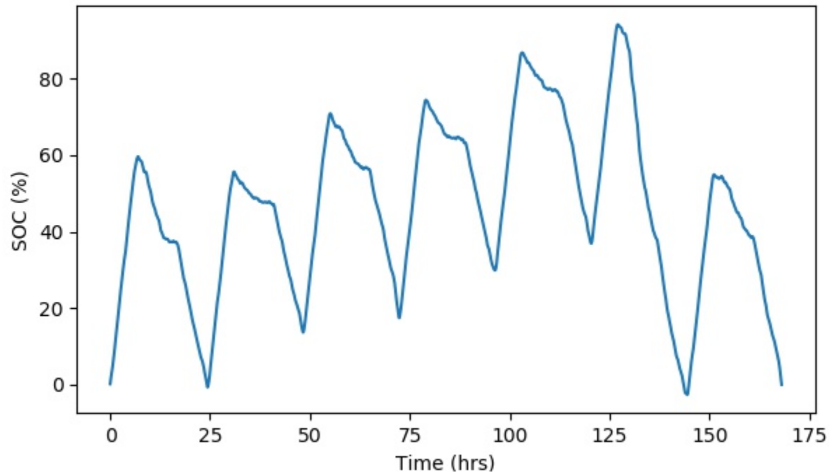


Figure 5.14: ***State of Charge of the 345kWh battery***

In a real case, the generation profile is not the same as the average of the consumed power. So, for the second example, the KP system capacity is taken from the generation profile of the scenario 5.1.2. This generation profile gives a power supply of 59 kW.

The code to size the long-term SS evaluates every time-step the difference between the power generated and the power consumed. The total energy difference over time between the power generated and consumed is obtained. Then, the code evaluates if the energy generated is more or less than the energy consumed.

If the energy generated is more, the size of the battery is based on the consumption; this is because having a size higher than the load power consumption is not viable for this scenario. If the consumption is more than the power generated, the battery size is based on the maximum excess of energy produced. In this situation, when more energy is needed, another source as Diesel Generator can supply it.

In the second example, the energy generated is more than the energy consumed. Thus, the size of the battery is based on the highest drop of the energy consumed. Hence, the excess of power is calculated, and the usage of this power will be dependent on the manufacturer. According to the power balance, the size of the SS is 329 kWh.

From the power balance and the code in the appendix C.3, the excess of power generated is shown in figure 5.15.

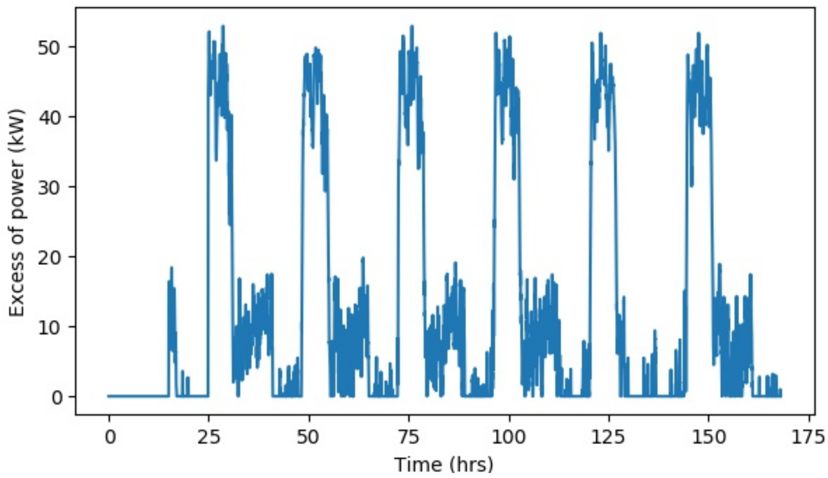


Figure 5.15: ***Excess of energy produce by a KP system giving 59 kW***

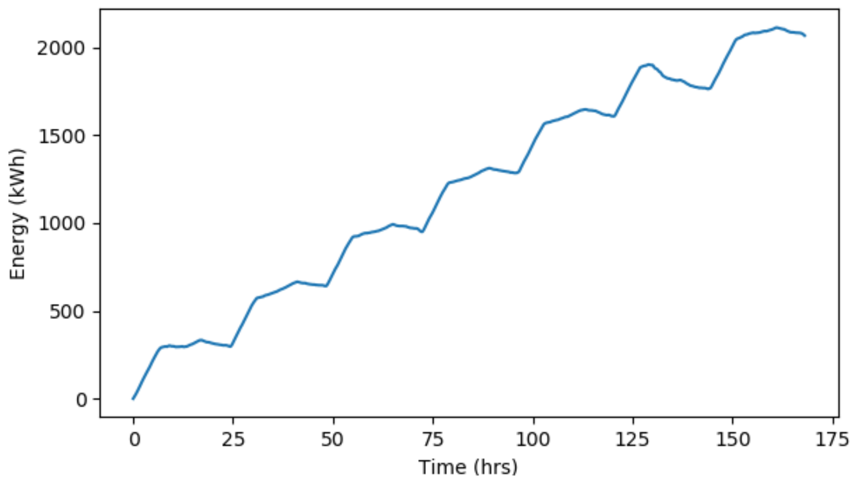


Figure 5.16: ***Energy flow***

Figure 5.16 shows how the energy flow through the week. Here can be seen how the production energy is increasing over time, an expected result because the power generated is higher than the average power consumed. This excess of power can be mitigated by adjusting the power production of the KP system.

Figure 5.17 show the data of a power consumed by 250 households during summer. This was evaluated with the power generated by the KP system. The average power consumed during the week is 87.7 kW. As it is higher than the power produced by the reference KP system, there will be an energy lack that should be provided by another DG.

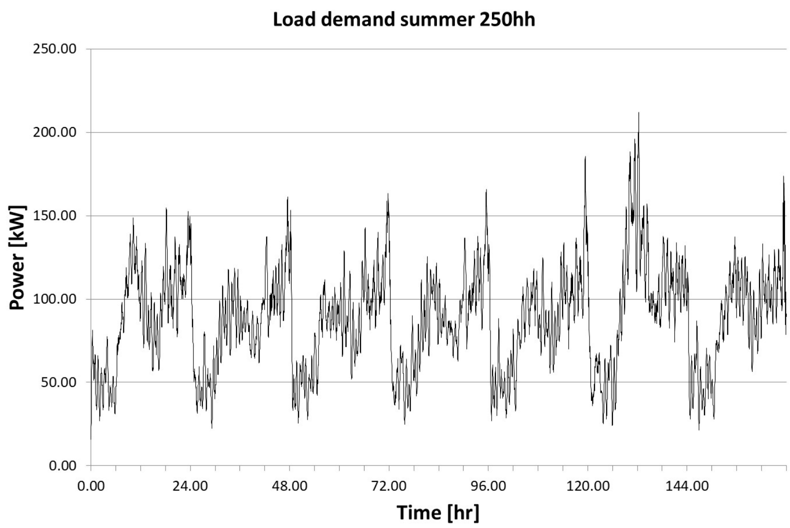


Figure 5.17: ***Load power consumption of 250 households in summer***

Figure 5.18 shows the power difference between the energy supplied by the KP system. It can be seen that it is negative, meaning that there is a lack of energy and it should be mitigated by more KP system or another DG.

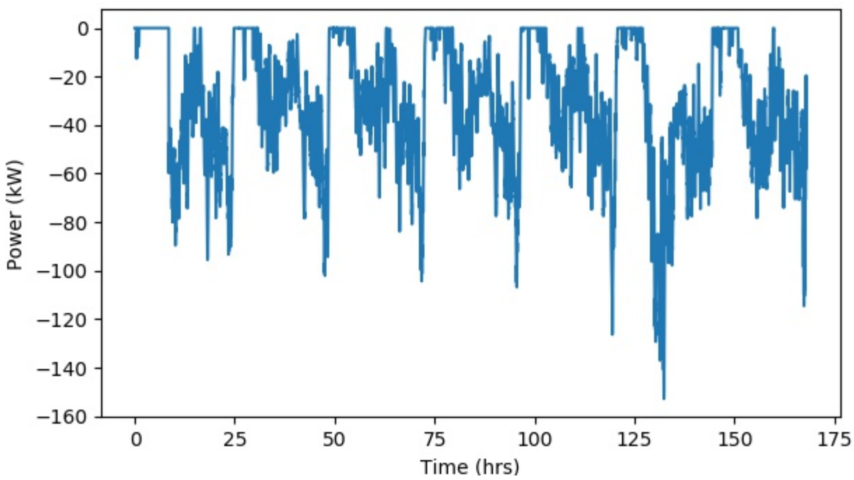


Figure 5.18: ***Power needed of the load***

Because the energy consumed is higher than the energy produced, the size of the SS is based on the maximum positive energy production. The calculated size of the SS for this scenario is 1073 kWh.

The next example is 250 households in winter; it can be seen in the figure 5.19. This scenario is the most demanding, for this scenario the optimum size calculated of the SS is 1888 kWh.

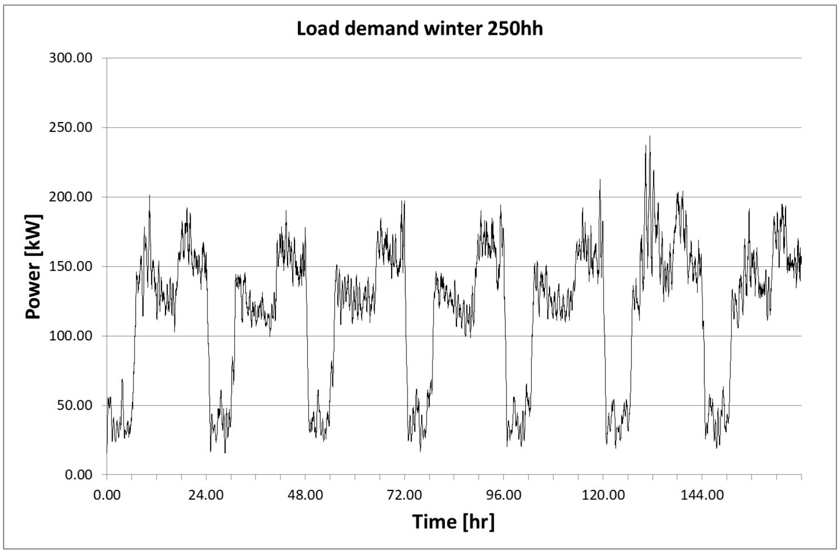


Figure 5.19: ***Load power consumption of 250 households in winter***

5.2.1. Optimize number of KP system or DG's

Now, the purpose is to reduce the usage of the SS and other DG in the KP microgrid system. Thus, once having the power generation profile and the power consumed. A comparison between the number of KP system with the power consumed is done to observe how many systems are needed to reduce the excess of power and the needed energy from another DG.

Looking at the scenario of 250 households in summer 5.17. This comparison is performed and then observe how many systems should be installed.

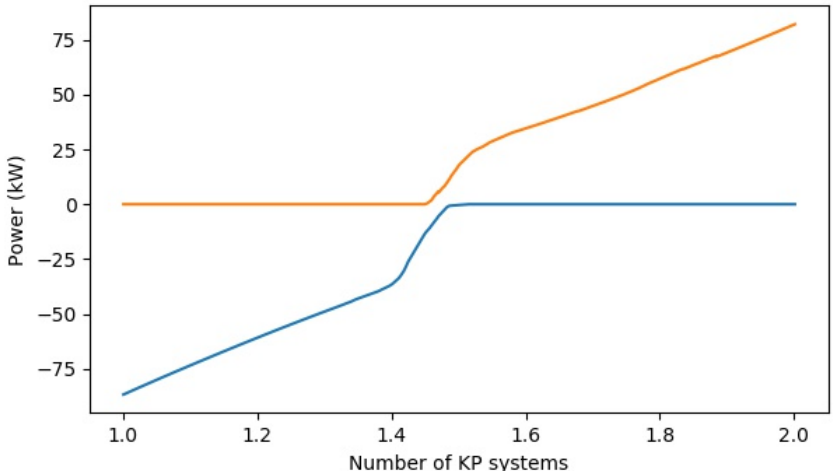


Figure 5.20: ***Power balance according to the number of KP systems***

The KP system power used for this analysis is taken from the section 5.1.2. Figure 5.20 and 5.21 shows the number of KP system vs the power difference. Figure 5.20 shows that the

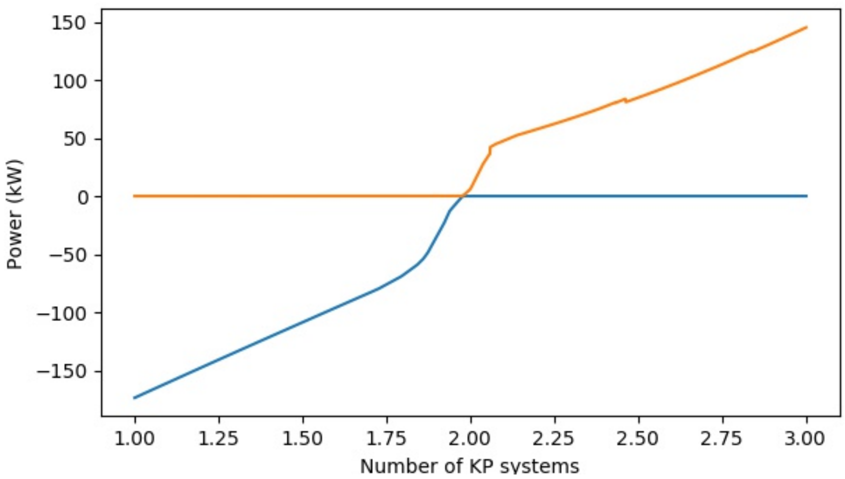


Figure 5.21: ***Power balance according to the number of KP systems***

optimum amount of KP system would be 1.4. This means that with 1.4 systems, the excess and lack of power will be almost 0, and the SS size will be reduced. Figure 5.21 shows that the optimum amount of KP system is approximately 2.

This calculation helps to measure the size of the system. For the scenario of 250 households in summer, it wouldn't make sense to put 1.45 system. Thus, one system can be installed and the other needed power that is shown in figure 5.18 can be supply by a smaller DG like diesel generator or PV. For the scenario of 250 households in winter. It will be better to install two KP systems. With two KP systems, the size of the SS is reduced to 768.17 kWh. Additionally, the excess of power is just the one shown in the figure 5.22. This excess of power can be stabilized easily by the control system of the KP system.

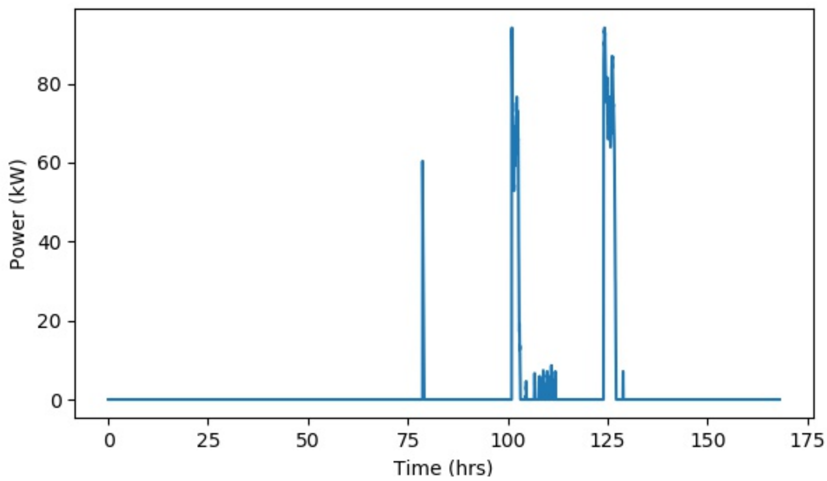


Figure 5.22: ***Excess of power produced by the KP system***

The energy flow for the SS size calculated and two KP system is shown in figure 5.23. It can be observed that the energy flow is better balanced with two KP systems and the sized SS.

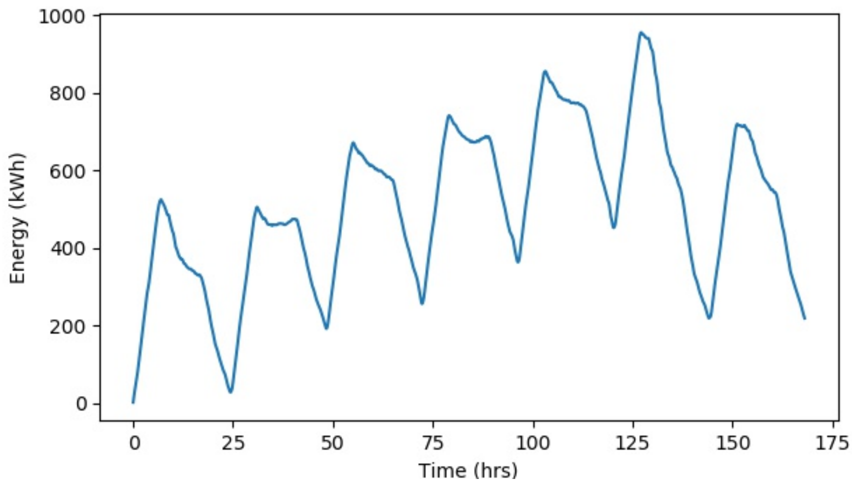


Figure 5.23: ***Energy flow over time***

With this method, real power generating data can be evaluated with the power consumption to reach the optimum number of KP systems and the optimum size of the SS for any application.

6
Design evaluation

It was proven that the method is adequate for sizing and designing a KP microgrid. For a future microgrid designs, it is needed to know more about the KP system wind operational specifications and load profiles. The performance can be improved considerably knowing the exact working conditions of the kite. However, the method can be followed to build a preliminary layout of a KP microgrid for most of the cases.

The Simulink model can be used for further investigations and simulations. Once real field data is obtained, it can be introduced into the model, and then run simulations to know if the SS size is enough for the scenario tested. All the operating conditions and size of the components can be set to any conditions to observe how the system responds.

One of the main objectives of this thesis is to develop a way to design and size a KP system to be integrated with a microgrid. The next section explains the main followed aspects, to create the first layout of the system.

6.1. Design method for AWE microgrid

Figure 6.1 shows the principal seven steps followed to design a KP microgrid layout. The first step is to know the application in which the microgrid is going to be used. After, the operating conditions and sizes should be established. Once having those parameters, the DERs should be analyzed and select the most suitable. Having the DERs, and architecture layout should be designed, followed by the extra component and control selection to built the interface of the microgrid. The two last steps should have feedback to improve the efficiency of the microgrid.

Before going to the design of the KP microgrid, it is needed to understand how to size a KP system and which DERs can couple with the pumping mechanism of the AWE system. The sizing is described in the next section (). Additionally, DERs analysis is done in section 2 to determine which ones are going to be able to couple with the pumping mechanism.

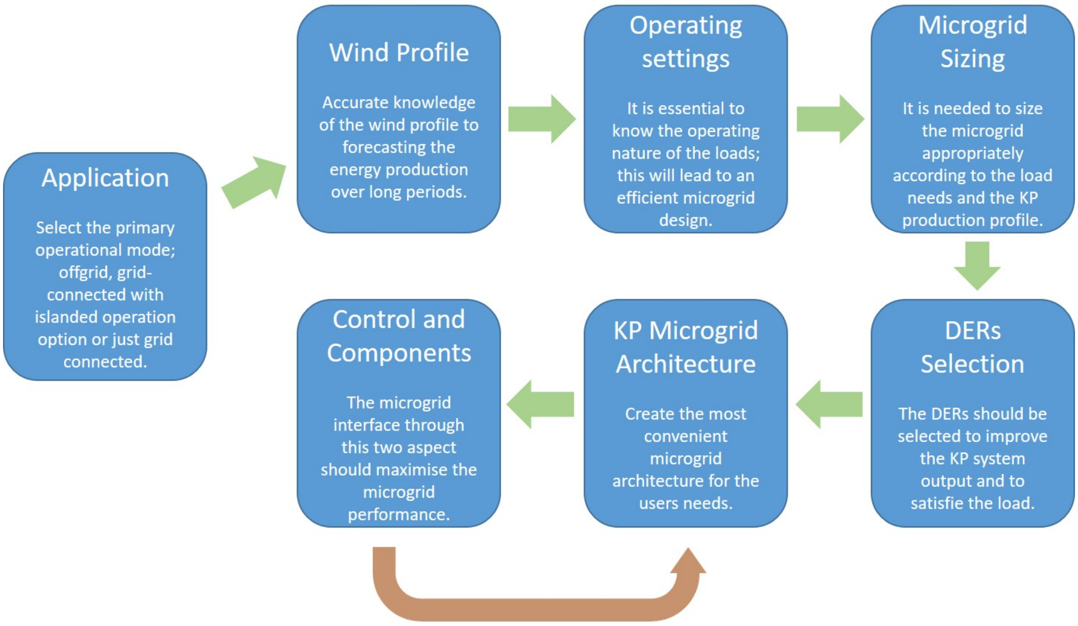


Figure 6.1: ***Energy supplied profile for the microgrid***

6.2. Financial Aspects

6.2.1. Number of cycles of a KP system

A vital aspect to take into account for the financial aspect of the system is the SS cycle life. According to the data-sheet of the KP system, its lifetime is 20 years [34]. It is needed to calculate the number of cycles required for this lifetime. According to section two, one cycle can last from 120 to 270 seconds. The number of cycles needed for the total lifetime is calculated as follow.

$$Cycles_{1hr} = (\frac{1cyc}{120s})(\frac{3600s}{1hr}) = 30cyc/hr \tag{6.1}$$

$$Cycles_{1hr} = (\frac{1cyc}{270s})(\frac{3600s}{1hr}) = 13.3cyc/hr \tag{6.2}$$

The Number of cycles per hour can vary from 14 to 30 cyc/hr, the number of cycles per year will be:

$$Cycles_{yr} = (14\frac{cyc}{hr})(24hrs)(365days) = 122640cyc/yr \tag{6.3}$$

$$Cycles_{yr} = (30\frac{cyc}{hr})(24hrs)(365days) = 262800cyc/hr \tag{6.4}$$

In 20 years

$$Cycles_{yr} = (122640\frac{cyc}{yr})(20yr) = 2452800cyc \tag{6.5}$$

$$Cycles_{yr} = (262800\frac{cyc}{yr})(20yr) = 5256000cyc \tag{6.6}$$

These numbers are significant for the SS system selection. There is no SS that has a cycle life as large as the number of cycles of the KP system over its lifetime. These are driving values to select SS as its replacement times should be as low as possible to avoid high capital costs. However, it is important to highlight that the cycles of the KP system and the cycles of the SS are not the same. The cycle life of the SSs considers 100% of the depth of discharge. The cycle of a KP system will not reach this DOD, so they cannot be compared. Unless a very accurate measurement is done and the power flow is constant. And that is not easy to achieve in a real application. For the further economic analysis, just one SS without replacement is taken into account to have an idea of the potential initial cost to fill the power gap.

6.2.2. Cost SS power gap

After finding a functional size of the SS, it is adequate to know which one could be the most cost attractive. The SMES was proposed for its big cycle life and its high efficiency. Here, its cost is compared with others SS's. For the SMES and the Flywheel and Li-ion battery, there is no data of a precise amount of cycles that they can reach. According to the estimation in most of the papers, none of them will reach the number of cycles that the KP system will have in its entire lifetime. But as they are not the same, if the DOD is low, the SS can reach a lot more cycles than expected. Additionally, [31] states that the SMES has infinite cycle life. But it is still risky in an economic analysis to consider it as an endless cycle system.

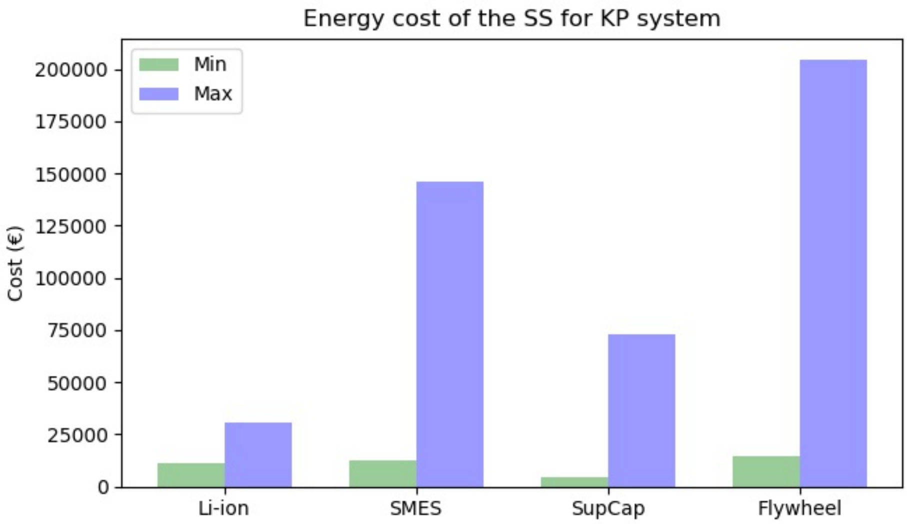
Storage System	Capital Cost (€/KW)	Cost (€/KWh)	LCOS (€/KWh)
Li-ion Battery	2100 - 2750	200 - 560	0,25-0,45
Superconducting magnetic energy Storage (SMES)	200 - 300	840 - 10000	0.4 - 0.9
Flow Battery	1270 - 1650	400 - 1100	0.15 - 1.3
Supercapacitors	200 - 300	300 - 5000	0.15 - 0.35
Flywheel	250 - 350	1000 - 14000	0,15 - 0,25

Figure 6.2: ***AWE microgrid configuration with hybrid DC and AC bus***

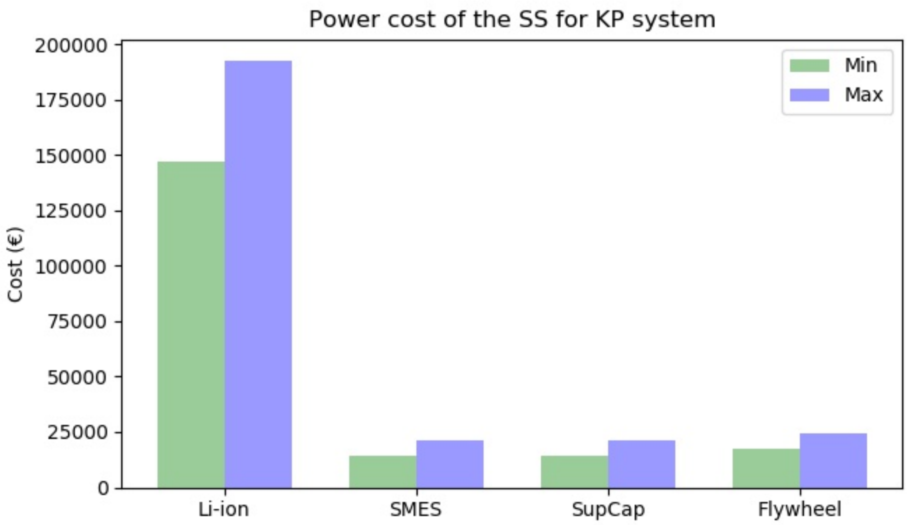
Table 6.2 it is shown the capital cost of the different SS analyzed in this thesis. From it, it is calculated the total cost of each system according to the size of them. The comparison also includes two synchronised KP systems; this is to have a general idea of what would be the difference if the power gap is mitigated with an SS or another KP system.

The size considered for the SS is 70kW of power and with an energy of 17.6 kWh. For the Li-ion Battery is considered 70kW, and 55kWh as the energy cycle should be less than 5% to ensure high cycle life. Additionally, for this analysis, it is just taken into account the cost of the KP system and the first SS. For further designs, it is necessary to contemplate the cost of the DC-DC converter and extra components of the microgrid to have a more accurate result.

First, the total capital cost is calculated based on the size and the values in table 6.2. Some of the values in this table have a wide range. Hence, the minimum and the maximum are shown in order to have a better view of the cost differences. Figure 6.3a shows the total capital cost of the SS according to their respective size. The Li-ion is expected to have the



(a) ***Energy capital cost***



(b)

Figure 6.3: ***Power capital cost***

least cost; this is also because its energy density is superior to any of the other SS here considered. However, figure 6.3b show that the Li-ion has a higher cost due to the power size. For a specific application, this two concepts should be studied in detail.

Figure 6.4 shows the initial capital cost of 5 combinations. It can be seen that the investment for two KP system is more than one KP system with an SS. Nevertheless, it is expected that the SS system will have to be replaced. Thus, this replacement should be taken into account for detailed economic analysis. The cycle life is the primary parameter of the SS, so it is recommended the SS with the highest cycle life.

To fill the power gap for an offgrid application is recommended to do it with SMES or Supercapacitors. Nonetheless, the financial aspect is highly variable. It can depend on the location, size, weather conditions, etc. Thus, the prices can change a lot. It is necessary to evaluate the exact application for any KP microgrid to improve the selection of the equipment.

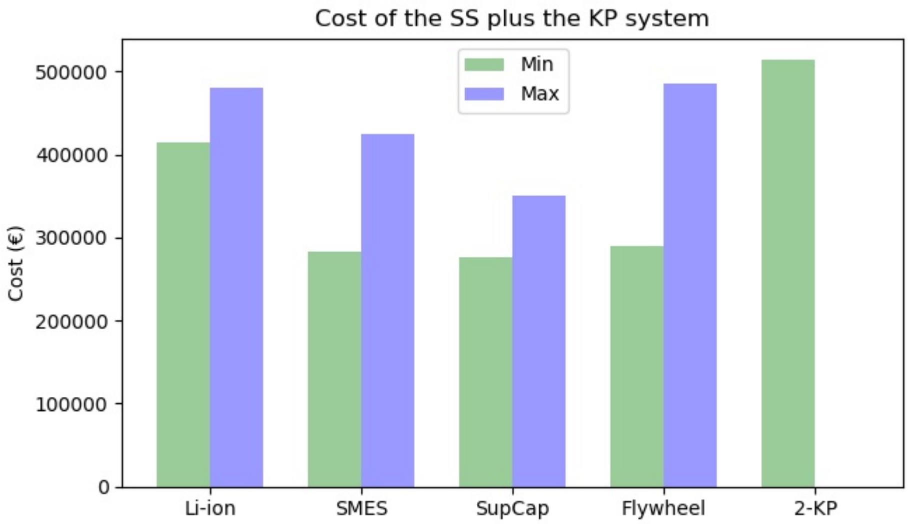


Figure 6.4: ***Capital cost of the SS plus the KP system***

However, considering a load consumption of 59 kW, according to the Dutch Ministry of Defense, the diesel price for the military camps rises up to two Euros per litre. Without taking into account the equipment replacement, the cost per KWh is 0.61. These are higher than the LCOE of the KP system. And similar considering a KP System with an SS to mitigate the energy gap. It is important to mention that for military purpose, the saving of diesel can be translated into saving lives [37]. According to [36], 99% of the fuel is transported by protected trucks, and [38] relates one death in 5 with humvees.

For a complete cost analysis, the long-term battery should be taken into account. As it's size is a lot higher compared to the size of the SS that compensate the power gap, it will impact directly on the initial cost. But to know the accurate size, a detail view for the application should be made.

6.3. recommendations

It is important to make more research about the integration of the KP system with a microgrid as it will eventually enter into the microgrids industry. First, some recommendations are given for further research. And secondly, suggestions to fill the power gap and integrate the KP system with a microgrid are given.

6.3.1. Research recommendations

First, for a precise size of the entire microgrid, it is necessary to have data of the load and wind velocities over long periods. This will make good forecasting of power production, and the SS could be sized with more accuracy.

A load profile should be obtained; this is because having a variable load improves the performance of the microgrid considerably. It is known that for the military camps this is not an option as the power is required at any time. But for further applications, this could be a possibility that can improve the quality of the KP microgrid.

Additionally, more research should start be doing into the full control strategy of an AWE microgrid. This is because the type of operation in this microgrid is new, and there is not similar DGs in the actuality. Thus, a control system for an AWE microgrid should start being a point of concern for this technology.

6.3.2. Design recommendations

Based on the research and results obtained some recommendations are given to take into account for the future KP microgrids designs.

It is very important to select the best SS according to the application of the KP microgrid. In this thesis, it is recommended to use SMES. However, a Li-ion could be used in other applications to solve the energy gap, for microgrids connected to the main grid for example. But this should be avoided for offgrid application due to its low efficiency and its uncertain cycle life. Nevertheless, in most of the offgrid microgrids, a Li-ion battery is considered for emergency energy supply or to mitigate long-term energy variations. Here it is not taken into account as there is a diesel generator for this purpose. But a small battery is recommended in further applications for any ancillary services. Or a hybrid SS could also work: A SMES to fill the power gap and a battery to mitigate long-term energy variations for example. The definition of the size of this battery should be studied according to the user's needs.

For a KP microgrid connected to the main grid, two synchronized KP systems can be considered. The excess power developed in the overlapping can be sold to the main grid. If there is a fault in the grid, then the reel-out/in time can be adjusted to avoid huge losses while supplying energy to the load.

If it is just one KP system, then the main grid can be used to fill the energy gap of the microgrid. It will still represent a reduction of the energy consumed from the grid. An economic analysis should be made to explore the advantages of this situation. However, a large Li-ion battery should be implemented to the microgrid in the case that the main grid fail.

In the case of a KP farm, the energy will go entirely to the main grid. Thus, the energy production should be maximized to the optimum point. The main grid will absorb all the energy, and it doesn't need to be prepared to operate in islanded mode.

6.4. Main objective questions answers

In this section, the questions of the section 1.3 are answered.

Question 1:

What are the potential advantages of an AWE microgrid over current off-grid solutions?

The microgrids that use wind energy as the main DG have small wind turbines. This kind of turbines are short, and they don't reach high altitudes, this represents low wind speed and poor energy extraction. The KP system can reach very high altitudes, and its performance is higher compared with the small wind turbines. The power generation density is higher than PV systems, and it is environment friendly as well. This type of microgrid represents and efficient way to reduce the diesel use for all offgrid applications, and it eliminates the transportation of fuel to remote places that increase the fuel price.

Sub-questions:

What is the performance of the AWE microgrid compared to the most used off-grid systems?

Speaking of the KP system as a DG, its performance is complicated and the challenges are big compared with the conventional Dg's. Additionally, solving the challenges could mean a high cost of the system. But with more research and some improvements of the technology, the AWE system can enter the DG´s market.

What are the important parameters to solve for an AWE microgrid?

The most important challenge to improve in the AWE system is the energy gap. It should be taken a primary consideration when an AWE microgrid is being designed. With this issue solved, the AWE system becomes a serious competitor in the DGs market. The other important parameter is to stabilize the output power as the generation is random. But this challenge is not a severe problem as it has been solved for the wind turbines that are currently on the market.

What are the critical external parameters that should be considered for designing an AWE microgrid?

The forecast of power production should be taken into account. Also the load profile, and it should be stated if the load is flexible or not. With this two parameters, the size of the microgrid components can be optimized, and the performance of the microgrid can be improved

Question 2:

How to design an AWE microgrid that can fulfil the energy needs according to the application? The method to design the AWE microgrid is presented in section 6.1. With this technique, a good approach can be achieved for the preliminary design of the AWE microgrid.

Sub-questions:

What are possible components comprising a general microgrid? The most important is the DERs and converters, they help to stabilize the power output of the microgrid. The main DG is a KP system, from this, the other components should be selected to integrate and optimize the KP microgrid.

Which components match better to stabilize the power output of the AWE system? For an offgrid application, the component that fit best with the KP system is an SS to fill the power gap. In this thesis the SMES is recommended. For any emergency, a diesel generator is recommended as a back-up power supply.

What could be a good method to design and size an AWE microgrid? The method to size an AWE microgrid is presented in chapter 3. Through this proposed method the components of the KP microgrid can be sized.

Question 3:

What is the most efficient and the most cost-attractive AWE microgrid configuration?

According to the financial analysis. The KP system with a SMES and Supercapacitors appear to be the most cost-attractive KP microgrids for the beginning. But if two KP systems is used, then the LCOE will be smaller. But this should be analyzed for each different microgrid design.

Sub-questions:

Which equipment combination constitutes the most efficient microgrid and with the longest lifetime?

The KP system with the SMES represents the most efficient, as the efficiency of the SMES is the highest among the SS here analyzed. Also, it has the longest cycle life, and it leads to a small number of replacements.

Which microgrid configuration is the least costly and most attractive for the user?

For the user, this will depend on the location. If the microgrid is connected to the grid, then the most costly attractive is to have two KP working synchronized or to have one KP system with a large SS as Li-ion battery.

What are the economic differences between and the advantages of the different components that can constitute an AWE microgrid?

The economic advantages depend mostly on the microgrid application, location and operating settings. For instance, if the location is an urban area where the infrastructure is mainly done, then it might be more attractive to built an AWE with an SS that can deliver AC output avoiding converters. If it is a new location or it is an application like communication structures, then a DC system will represent the most cost-attractive option.

7 Conclusions

Creating a AWE microgrid is a challenging task. This technology is new in the field, and its power generation mechanism has never been seen before in any DG. The components in the present are not designed for this type of operation, and they will have to deal with an entire new energy generation procedure.

In this research, the main parameters for creating an harmonic integration between the KP system and the current components in the microgrids are obtained. The first and most important issue is to fill the power gap that the AWE system has due to its fundamental operating method. This energy gap can be solved in many ways. But they depend on the main application of the microgrid. The best way to solve the energy gap is to synchronize two or more KP systems. This is convenient when the KP systems or microgrid have a connection with the main grid so it can damp the excess of energy made through the reel-out overlapping. If the KP microgrid will be used for offgrid applications and for a constant power demand such as a military camp, two synchronized KP systems with a short reel-out/in ratio, will represent big losses or a SS with a huge sizing, leading to an increase in the capital cost. If two synchronized KP systems are used for offgrid applications, it is recommended to adjust the reel-out/in time to be close to one. BHowever, this will represent a decrease in the performance over the whole lifetime of the KP system, and it will increase the LCOE of the system. This is why for offgrid applications it is recommended to use a SS to mitigate the energy gap.

If an SS system is used to fill the energy gap, three important things should be taking into consideration; the cycle life, the efficiency and the capital cost of the SS. The efficiency should be as high as possible to avoid losses in every cycle. A SS with a huge cycle life should be selected to have the least possible replacements. A close look to the cost should be done because depending on the application and location, the prices of the different SS's could vary.

A method for designing a KP microgrid is presented in this thesis, it consist of 7 main concepts; Application, wind profile (accurate power generation profile), Operating settings (power conditions for the AWE microgrid), Microgrid Sizing, DERs selection, KP microgrid architecture and selection of the control and components. They will lead the designer through a simple and fast path to design the first layout of a KP microgrid for any application. Additionally, this method along with the SS sizing method presented, will guide to the SS that fits the most for the KP microgrid depending on the application, the SS selection is one of the most important issues for designing a KP microgrid.

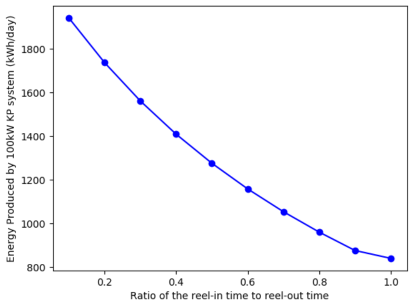
According to the results and the KP system design in this thesis, the SS that fits the most to fill the energy gap of the KP system, is the SMES. This SS has the highest efficiency and the longest theoretical cycle life. It will lead to a short number of replacements. An optimum SS size for a KP system working at maximum capacity is 17.6kWh, the output power should be 70kW, which could increase depending on the power and time needed for the reel-in phase. A bigger size for the SS or another type of SS is not considered as in the microgrid designed here a diesel generator is considered as a backup DG. But for applications where there is no back-up power source or that are not connected to the main grid, a bigger SS or an independent SS, that doesn't play a roll in the energy gap filling, should be considered. Additionally, a large SS system could be used to mitigate power variation over long periods. A method to size this SS for future designs was develop, but real load and production data should be inserted.

The KP system has a lot of potential in the energy industry, it needs to start gaining field through the current DG's in this industry. So its integration with the common components of a microgrid should be researched more thoroughly. The research done in this thesis presents a way to find the main parameters that should be taken into account for further KP system implementations.

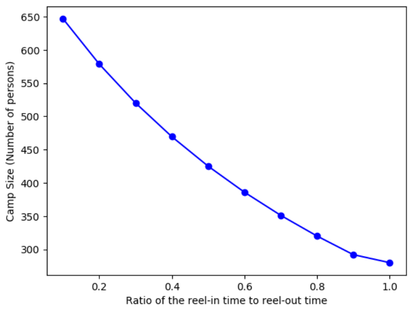
A

Camp size

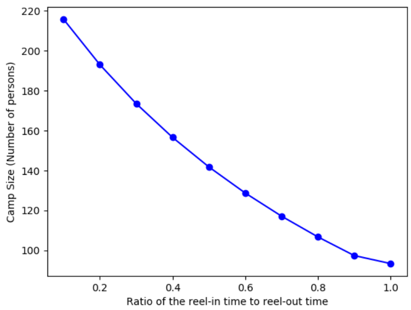
A.1. Camps Size



(a)

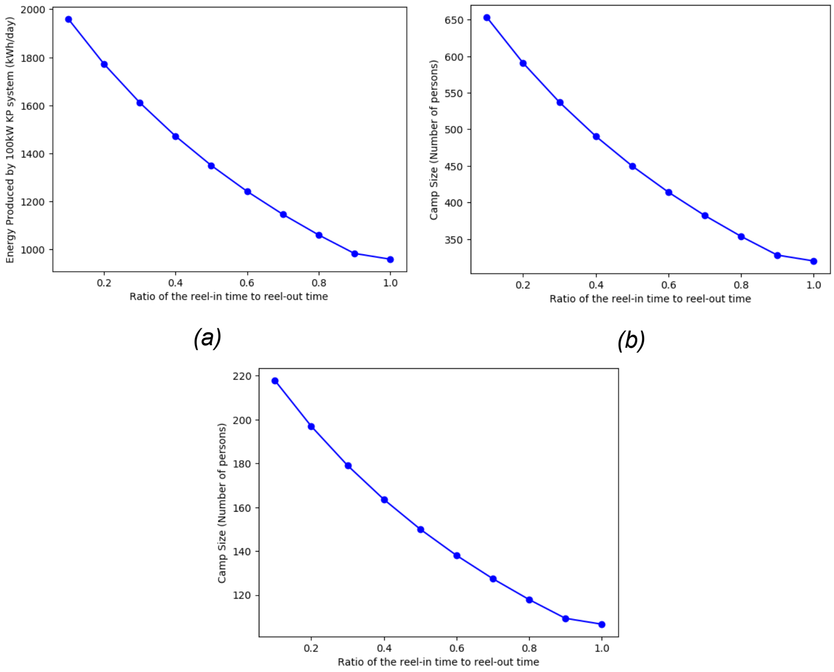


(b)



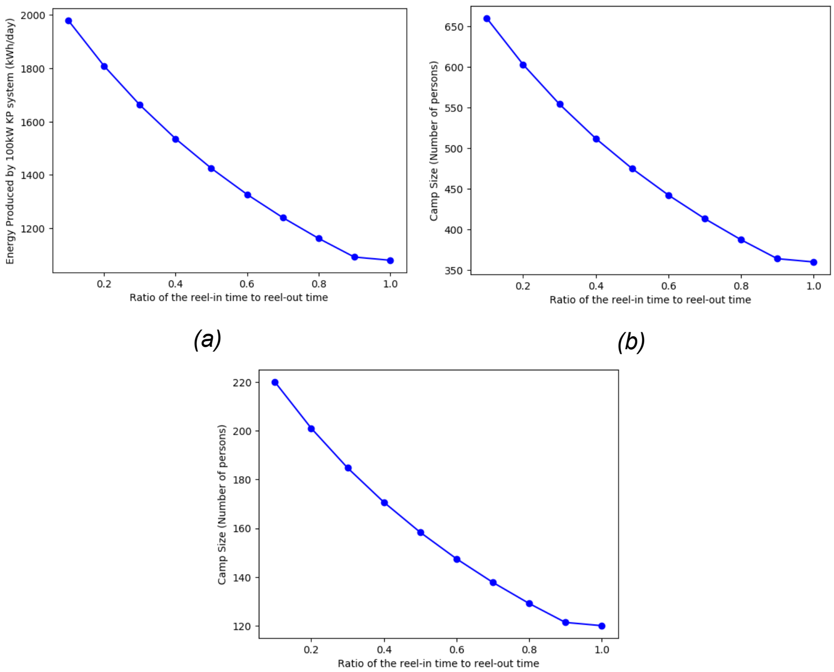
(c)

Figure A.1: ***Energy produced depending on the reel-in to reel-out time ratio, with 30% of the power produced needed for the reel-in phase. b) Camp size with a consumption of 3kWh/day per person. c) Camp size with a consumption of 9kWh/day per person***



(c)

Figure A.2: ***Energy produced depending on the reel-in to reel-out time ratio, with 20% of the power produced needed for the reel-in phase. b) Camp size with a consumption of 3kWh/day per person. c) Camp size with a consumption of 9kWh/day per person***



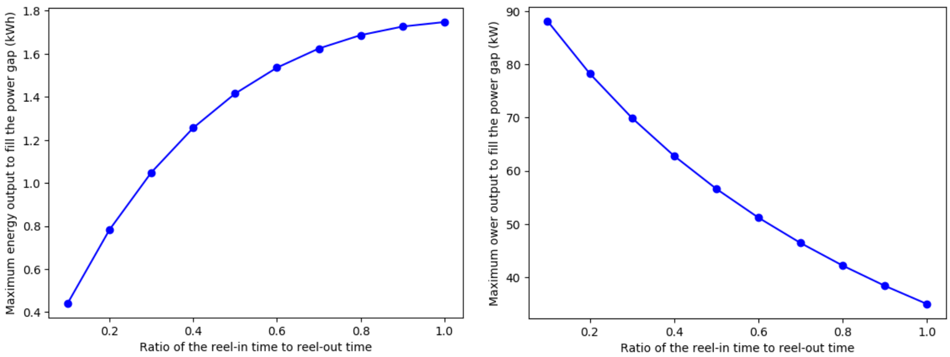
(c)

Figure A.3: ***Energy produced depending on the reel-in to reel-out time ratio, with 10% of the power produced needed for the reel-in phase. b) Camp size with a consumption of 3kWh/day per person. c) Camp size with a consumption of 9kWh/day per person***

B

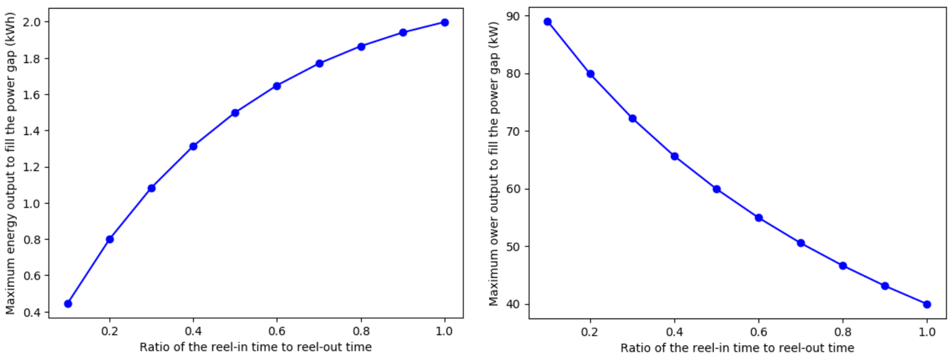
Optimum power output

Here are presented the graphs to know optimal output power and the energy to fill the gap. They show this power for scenarios where the reel-in phase uses 30%, 20% and 10% of the nominal KP system output power.



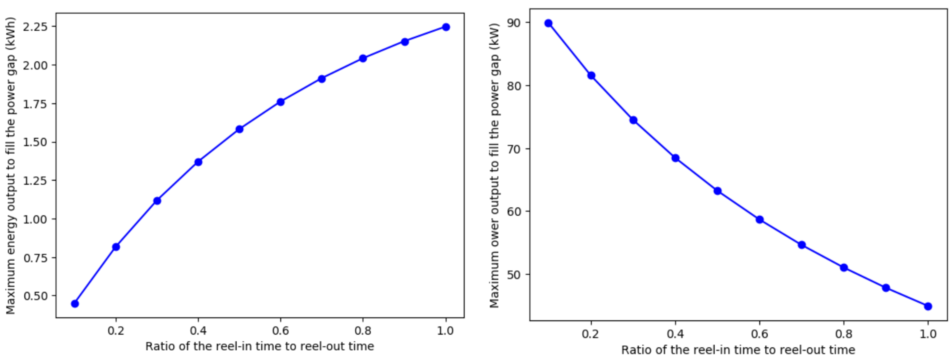
(a) ***Energy Gap*** *(b)* ***Optimal Power Output***

Figure B.1: ***Calculations for 30% of power for the reel-in***



(a) ***Energy Gap*** *(b)* ***Optimal Power Output***

Figure B.2: ***Calculations for 20% of power for the reel-in***



(a) ***Energy Gap***

(b) ***Optimal Power Output***

Figure B.3: ***Calculations for 10% of power for the reel-in***

C

Programming Code

C.1. Iteration code

Here it is shown the python code done to do the iteration to find the optimum output power.

```
import matplotlib.pyplot as plt; plt.rcdefaults()
import numpy as np
import matplotlib.pyplot as plt

#Kiepower data
j=0.1

kp = 100;    #nominal KP system power
pri = 10;     #power used at the reel-in phase
ptri = (0.1); #percentage of the reel-in time respect with the reel-out
    time
tro = 180;  #reel-out time


# calculation of energy needed for the power gap kwh


i = 0.5;
r = 50;

tri = (tro*(ptri));
tcy = tri + tro; #total cycle time
ero = (tro*kp)/3600;     #energy produced at the reel-out phase
eri = (tri*pri)/3600;  #energy consumed at the reel-in phase
```

```
tec = (ero − eri);      #total energy delivered by one cycle of the
    kitepower system

while (r >= 0.1):

    npro = (tec*3600/tro);  #net power delivered by the kitepower system
        in reel−out phase
    npg = (npro*i)*0.95;  #Calculation of the power fraction delivered by
        SS
    epg = ((npg*tri)/3600);      #Energy of the SS
    ned = (tec−epg);     #Energy left of the AWE system
    npro = (ned*3600/tro); #Net power supplied by KP system without the
    r = npro−npg; #Power difference
    i = i+0.0001;

print(npro)
print(npg)
print(tec)
print(epg)
print(ned)
print(r)
print(tri)
print(tcy)
print(ptri)

y2 = epg;
y2 = [y2];
x2 = npg;
x2 = [x2];
z2 = ptri;
z2 = [z2];

for x in range(0, 9):

    kp = 100;   #nominal kitepower
    pri = 10;    #power used in the reel−in phase
    ptri = (0.1)+j; #percentage of the reel−in time respect with the reel−
        out time
    tro = 180;  #reel−out time
    tri = (tro*ptri);

# calculation of energy needed for the power gap kwh

    tcy = (tro*ptri) + tro; #total cycle time
```

```
    ero = (tro*kp)/3600;     #energy produced in the reel−out phase
    eri = ((tro*ptri)*pri)/3600;  #energy consumed in the reel−in phase
    tec = (ero − eri);       #total energy delivered by one cycle of the
        kitepower system
    npro = (tec*3600/tro);  #net power delivered by the kitepower system
        in reel−out phase

    i = 0.5;
    r = 50;

    while (r >= 0.1):

        npg = (npro*i)*0.95;     #Calculation of the power fraction
            delivered by SS
        epg = ((npg*tri)/3600);      #Energy of the SS
        ned = (tec−epg);      #Energy left of the AWE system
        npro = (ned*3600/tro);  #Net power supplied by KP system without
            the
        r = npro−npg;    #Power difference
        i = i+0.0001;


    x2.append(npg);
    y2.append(epg);
    z2.append(ptri);
    j = j+(0.1);
    print(npro)
    print(npg)

plt.plot(z2,y2, 'b−o')
plt.ylabel('Maximum energy output to fill the power gap (kWh)')
plt.xlabel('Ratio of the reel−in time to reel−out time')
plt.show()

plt.plot(z2,x2, 'b−o')
plt.ylabel('Maximum ower output to fill the power gap (kW)')
plt.xlabel('Ratio of the reel−in time to reel−out time')
plt.show()
```

C.2. Iteration code 2

Here it can be observed the python code done to get the optimum power output from a power generation profile.

```
import matplotlib.pyplot as plt; plt.rcdefaults()
import numpy as np
import matplotlib.pyplot as plt
from xlrd import open_workbook



book = open_workbook("podat.xlsx")
sheet = book.sheet_by_index(0) #If your data is on sheet 1

#...

t = []
for value in sheet.col_values(0):
    if isinstance(value, float):
        t.append(value)

pkp = []
for value in sheet.col_values(1):
    if isinstance(value, float):
        pkp.append(value)


tekpj = np.trapz(pkp,t)
tekp = tekpj/3600;


print (tekpj)
print(tekp)

ekpc = tekp/5;

print (ekpc)

#Kiepower data
j=0.1


ptri = (1/3); #percentage of the reel-in time respect with the reel-out
    time
tro = 180;  #reel-out time
ng = 1   #efficiency of the electric generator
nss = 0.97 #Efficiency of the storage system
```

```
# calculation of energy needed for the power gap kwh


i = 0.5;
r = 50;

tri = (tro*(ptri));
tcy = tri + tro; #total cycle time
tec = ekpc*ng;      #total energy delivered by one cycle of the kitepower
    system

while (r >= 0.1):

    pkp = (tec*3600/tro);  #net power delivered by the kitepower system in
        reel-out phase
    psso = (pkp*i);  #Calculation of the energy fraction delivered by SS
    esso = ((psso*tri)/3600); #Energy discharcheg in the reel-in phase
    ekpl = (tec)-(esso/nss); #energy from the kp system to the load
    pkp = (ekpl*3600/tro); # power output of KP to the load
    r = pkp-psso;
    i = i+0.0001;


print(psso)
print(esso)
print(r)

y2 = esso;
y2 = [y2];
x2 = psso;
x2 = [x2];
z2 = ptri;
z2 = [z2];
```

C.3. SS size for long term

Here it is shown the python code done to do the iteration to find the optimum output power.

```
#import matplotlib.pyplot as plt; plt.rcdefaults()
import numpy as np
import matplotlib.pyplot as plt
from xlrd import open_workbook
import pandas as pd
```

```
hrs = 168;
s = 168*60*60;

book = open_workbook("Summer_250.xls")
sheet = book.sheet_by_index(0) #If your data is on sheet 1

lp = []
for value in sheet.col_values(1):
    if isinstance(value, float):
        lp.append(value)

#book = open_workbook("power_profile.xlsx")
#sheet = book.sheet_by_index(0) #If your data is on sheet 1
#
#wpo = []
#for value in sheet.col_values(6):
#    if isinstance(value, float):
#        wpo.append(value)

le = pd.Series(lp)
en = (le*60).tolist() #energy generated per minut
toten = sum(en) #total energy generated
kpp = toten/s; #kitepower power

#we = pd.Series(wpo)
#wen = (we*60).tolist() #energy generated per minut
#totwen = sum(wen) #total energy generated

## my_new_list = [i * 5 for i in my_list]
kpen = (59.19*60); #kp energy in joules

digeus = [];
toenwast = [];
numkp=[];
z=1;

while z <= 2:

    tkpen = kpen*z;


    sss = 200;#Storage Systen size in kWh
    enp=0;
    ssen=0;
    diffen=0;
```

```
ppow=0;
npow=0;
enf=0;
pen=0;
nen=0;
npot=0;
ppot=0;
enkw=0;
enfkw=[];
enst=[];
soct=[];
deltaen=[];
expo=[];
lapo=[];
ppowt=[];
npowt=[];
enft=[];
podi=[];
poex=[];


j=0
x=0

minutes=[];

#put wen[X] instead of Kpp to run the optimization with experimental
    data

for i in en:
        den = (tkpen - i)/3600;# Energy difference between the load
            and KP
        deltaen.append(den);
        enf = (enf + den); #energy flow profile in kWh
        enft.append(enf);
        x=x+1;
        if den>0:
            ppow = ppow + den;
            npow = 0;
            ppowt.append(ppow)
            npowt.append(npow)
           #extpo = extpo + den;
        else:
            npow = npow + den;
            ppow = 0;
```

```
            npowt.append(npow)
            ppowt.append(ppow)
            #poco = poco + den;

exen=sum(ppowt);
laen=(sum(npowt))*(-1);

ren=exen/laen;

if ren<1:
    sss=min(npowt)/0.94*(-1);
else:
    sss=(max(ppowt)/0.94);

x=0;

for i in en:
        den = (tkpen - i)/3600;# Energy difference between the load
            and KP in kWh
        #energy in the battery
        ssen = ssen + den; #Energy Stored or used in the SS in Wh
        enst.append(ssen);
        soc = (ssen/sss)*100; #state of charge calculation
        soct.append(soc);
        j=j+1
        minutes.append(j)
        x=x+x;
        if soc>=95:
            if den>0:
                pep = (den*3600)/60;
                nep = 0;
                poex.append(pep)
                podi.append(nep)
            else:
                nep = 0;
                pep = 0;
                podi.append(nep)
                poex.append(pep)
                continue
        elif soc<=0:
            if den<0:
                nep = (den*3600)/60;
                pep = 0;
                podi.append(nep)
                poex.append(pep)
```

```
                else:
                    nep = 0;
                    pep = 0;
                    podi.append(nep)
                    poex.append(pep)
                    continue
            else:
                nep = 0;
                pep = 0;
                podi.append(nep)
                poex.append(pep)
            continue

    endie = (sum(podi))/3600;
    enwast = (sum(poex))/3600;
    z = z+0.001;

    numkp.append(z)
    digeus.append(endie)
    toenwast.append(enwast)

t1 = 0;
tml = []

while t1 <= 168:
    t1 = t1 + (168/10080)
    tml.append(t1)


##Battery

plt.figure()
plt.plot(tml,enst)
plt.ylabel('Energy (kWh)')
plt.xlabel('Time (hrs)')
plt.show()

plt.figure()
plt.plot(tml,podi)
plt.ylabel('Power (kW)')
plt.xlabel('Time (hrs)')
plt.show()

plt.figure()
plt.plot(tml,soct)
```

```
plt.ylabel('SOC (%)')
plt.xlabel('Time (hrs)')
plt.show()

plt.figure()
plt.plot(tml,poex)
plt.ylabel('Power (kW)')
plt.xlabel('Time (hrs)')
plt.show()

plt.figure()
plt.plot(tml,poex,tml,podi)
plt.ylabel('Power (kW)')
plt.xlabel('Time (hrs)')
plt.show()

plt.figure()
plt.plot(numkp,digeus,numkp,toenwast)
plt.ylabel('Power (kW)')
plt.xlabel('Number of KP systems')
plt.show()

#plt.plot(wpo) #Ploting the wind energy profile
#plt.ylabel('Wind Energy')
#plt.show()


print(exen)
print(laen)
print(ren)

print(max(ppowt))
print(min(npowt))
print(sss)

print(endie)
print(enwast)
```

C.4. Code to run the Simulink Model

This code was used for the control model of the Simulink KP microgrid. It runs and control the simulations for the model.

```
function [x,y,z,s,d,v]= fcn(ldc,w,soc)
```

```
 socs = 95;
 soci = 15;
 vlt = 400;
 mcp = 90000;

if (ldc <= 45000)
    s = 0;
else
    s = 1;
end

if (soc >= soci)
    y = 0;
else
    y = 1;
end


if (soc <= socs)
    if (w <= 90)
    z = vlt;
    v = mcp;
    else
        if (w>=90) && (w<=180)
            z = 0;
            v = 0;
        else
            if (w>=180) && (w<=270)
                z = vlt;
                v = mcp;
            else
                if (w>=270) && (w<=360)
                z = 0;
                v = 0;
                else
                    if (w>=360) && (w<=450)
                        z = vlt;
                        v = mcp;
                    else
                        if (w>=450) && (w<=540)
                            z = 0;
                            v = 0;
                        else
                            if (w>=540) && (w<=630)
```

```
                                        z = vlt;
                                        v = mcp;
                                    else
                                        if (w>=630) && (w<=720)
                                            z = 0;
                                            v = 0;
                                        else
                                            z = vlt;
                                                v = mcp;
                                        end
                                    end
                                end
                            end
                        end
                    end
                end
            end
else
    z = 0;
    v = 0;
end


if (soc <= socs)
    x = 0.001;
else
    x = 30;
end

if (w >= 0.1)
    if (soc <= soci)
        d = 30;
    else
        d = 0;
    end
else
    d = 0.001;
end
```

C.5. Economic Analysis Python code

This code was used to obtain the capital costs per kW of the SS with the KP system. It also shows the graphs to compare the different costs.

```
import matplotlib.pyplot as plt; plt.rcdefaults()
import numpy as np
import matplotlib.pyplot as plt

kp = 100;   #nominal kitepower
pri = 20;    #power used in the reel-in phase
ptri = (1/3); #percentage of the reel-in time respect with the reel-out
    time
tro = 180;  #reel-out time
pkp = 257000; #kitepower price in euros
kplcoe = 0.085; #kitepower levelized cost of energy


tri = (tro*(ptri));
tcy = tri + tro; #total cycle time
ero = (tro*kp)/3600;    #energy produced in the reel-out phase
eri = (tri*pri)/3600;  #energy consumed in the reel-in phase
tec = (ero - eri);      #total energy delivered by one cycle of the
    kitepower system

#Kiepower data

lpc = 67.5;   # load power consumed
lt = 20; #Kitepower lifetime

#size of the Microgrid

awem = lpc*2;
awep = kp-pri;


# calculation of energy needed for the power gap kwh

npkp = (tec*3600/tcy)  #net power delivered by the kitepower system in one
     cycle

#Economical analysis;

kppcc = pkp/npkp; # Capital cost per kW of one kite power system

print ('energy␣produced␣in␣reel-out,␣reel-in,␣total,␣average␣power')
print (ero,eri,tec,npkp)
print ('Capital␣cost␣of␣one␣kitepower␣system␣€/kW')
print (kppcc)
```

```
#Number of cycles in the life of a kitepower system

#kpcy = (3600/tcy)*24*365*lt;
kpcy = 3855000;

print ('Total cycles in a KP lifetime depending on the reel-in and reel-
    out phase')
print (kpcy)

#TWO KITEPOWER System working synchronously

nkps = 2; #total number of kytepower systems
ttri = 90;   #reel-in time
ttro = 90;  #reel-out time
ttcy = ttri + ttro; #total two kp cycle time

tpkp = pkp*nkps; # total price according to the numbers of kytepower
    systems
tero = 2*(ttro*kp)/3600;     #energy produced in the reel-out phase by two
    sinchronized KP systems
teri = 2*(ttri*pri)/3600;  #energy consumed in the reel-in phase by two
    sinchronized KP systems
ttec = (tero - teri);       #total energy delivered by two synchronized
    kitepower systems
tnpkp = (ttec*3600/ttcy)  #net power delivered by two kitepower system in
    one cycle

tkppcc = tpkp/tnpkp; # Capital cost per kW of two synchronized kitepower

#DATA OF STORAGE SYSTEM

#Size of the Storage System
epg = (lpc*tri)/3600; #Enery needed to fill the power gap


#Energy size for the SS that is not Li-ion Battery
tss = 10; #time of duration of the storage system  in minutes
soss= lpc*(tss*60)/3600; #Storage System Size


#Li-ion battery
licy = 900000;     #number of cycles
dod = 0.04;      #Depth of Discharge
lcce = 300;      #Li-ion energy capital cost
lccp = 2425;     #Li-ion power capital cost
```

```
lilcos = 0.35;      #li-ion levelized cost of energy storgae
lef = 1;     #li-ion battery efficiency
lied = 300;       # Li-ion batt energy density Wh/l
lipd = 6000;    # Li-ion batt power density W/l

bs = epg/dod;   #Size pf the battery in kWh
lipc = ((1-lef)+1)*lpc; #Power needed to charnge the Li-ion battery.
liec = ((1-lef)+1)*epg; #Energy needed to charnge the Li-ion battery.
tlcce = lcce*liec;    # Microgrid Li-ion energy  total capital cost
tlccp = lccp*lipc;   # Microgrid Li-ion power total capital cost
totl = (tlcce+tlccp); # total capital cost, power and energy
lkincc = (totl+pkp);    #total capital cost including the kp system
kplicc = lkincc/lpc;     #AWE plus Li-ion total capital cost per KW
lir = (kpcy/licy); #li-ion replacements
lirc = lir*(totl);#Total cost of Flow batt imcluding replacements
totli = lirc + pkp;
likpkw = totli/lpc;     #AWE plus Li-ion total capital cost per KW

veli = (bs*1000/lied); #Li-ion volume according to energy
vpli = (lipc*1000/lipd); #Flow batt volume according to power



#SMES
smcy = 2000000; # SMES cycle's number
scce = 5420;    # SMES energy capital cost
sccp = 250;     # SMES power capital cost
slcos = 0.65;   # SMES levelized cost of energy storgae
sef = 1;     # SMES battery efficiency
smed = 6;       # SMES energy density Wh/l
smpd = 3000;    # SMES power density W/l

spc = ((1-sef)+1)*lpc; #Power needed to charge the SMES.
sec = ((1-sef)+1)*epg; #Energy needed to charge the SMES.
tscce = scce*soss;    # Microgrid SMES energy total capital cost
tsccp = sccp*spc;   # Microgrid SMES power total capital cost
totsm = tscce+tsccp;
skincc = (totsm+pkp);   #total capital cost including the kp system
kpscc = skincc/lpc; #AWE plus SMES total capital cost per kW
smr = (kpcy/smcy); #SMES replacements
src = smr*(totsm);#Total cost of SMES including replacements
totsme = src + pkp;
smkpkw = totsme/lpc;     #AWE plus SMES total capital cost per KW

vesm = (sec*1000/smed); #SMES volume according to energy
```

```
vpsm = (spc*1000/smpd); #SMES volume according to power


#Supercapacitor
sccy = 1000000; # Supercap cycle's number
sccce = 2650;    # Supercap energy capital cost
scccp = 250;     # Supercap power capital cost
sclcos = 0.25;   # Supercap levelized cost of energy storgae
scef = 1;    # Supercap battery efficiency
sced = 15;       # Supercap energy density Wh/l
scpd = 100000;    # Supercap power density W/l


scpc = ((1-scef)+1)*lpc; #Power needed to charnge the Supercap.
scec = ((1-scef)+1)*epg; #Energy needed to charnge the Supercap.
tsccce = sccce*soss;    # Microgrid Supercap energy total capital cost
tscccp = scccp*scpc;    # Microgrid Supercap power total capital cost
totsc = tsccce+tscccp;
sckincc = (totsc+pkp);  #total capital cost including the kp system
kpsccc = sckincc/lpc;  #AWE plus Supercap total capital cost per kW
scr = (kpcy/sccy); #Supercap replacements
scrc = scr*(totsc);#Total cost of Supercap imcluding replacement
totsup = scrc + pkp;
sukpkw = totsup/lpc;     #AWE plus Supercap total capital cost per KW

vesc = (scec*1000/sced); #Supercap volume according to energy
vpsc = (scpc*1000/scpd); #Supercap volume according to power




#Flywheel
flcy = 1500000; # Flywheel cycle's number
flcce = 7500;    # Flywheel energy capital cost
flccp = 300;     # Flywheel power capital cost
fllcos = 0.2;   # Flywheel levelized cost of energy storgae
flef = 1;    # Flywheel battery efficiency
fled = 60;       # Flywheel energy density Wh/l
flpd = 5000;    # Flywheel power density W/l

flpc = ((1-flef)+1)*lpc; #Power needed to charnge the Flywheel.
flec = ((1-flef)+1)*epg; #Energy needed to charnge the Flywheel.
tflcce = flcce*soss;    # Microgrid Flywheel energy total capital cost
tflccp = flccp*flpc;    # Microgrid Flywheel power total capital cost
```

```
totfl = tflcce+tflccp;
flkincc = (totfl+pkp);  #total initial cost including the kp system
kpflcc = flkincc/lpc;  #AWE plus Flywheel total capital cost per kW
flr = (kpcy/flcy); #Flywheel replacements
flrc = scr*(totfl);#Total cost of Flywheel imcluding replacement
totfly = flrc + pkp;
flykpkw = totfly/lpc;      #AWE plus Flywheel total capital cost per KW

vefl = (flec*1000/fled); #Flywheel volume according to energy
vpfl = (flpc*1000/flpd); #Flywheel volume according to power




# results of the calculations

inco = [tpkp,lkincc,skincc,sckincc,flkincc] #total initial cost including
    the kp system
capco = [tkppcc,kplicc,kpscc,kpsccc,kpflcc] #total capital two kp and kp &
     SS cost per kW
repco = [lirc,src,scrc,flrc]     #Total cost of SS including replacement
totcost = [tpkp,totli,totsme,totsup,totfly] # total inital cost
totcostpkw = [tkppcc,likpkw,smkpkw,sukpkw,flykpkw] # total inital cost


volen = [veli,vesm,vesc,vefl]
volpo = [vpli,vpsm,vpsc,vpfl]



syst2 = ('2 KP', 'KP & Li-ion', 'KP & SMES','KP & SC','KP & FW')
y2 = np.arange(len(syst2))

plt.bar(y2, inco, align='center', alpha=0.5)
plt.xticks(y2, syst2)
plt.ylabel('€')
plt.title('Initial Cost')

plt.show()

print('Cost €/KW')
print(inco)

plt.bar(y2, capco, align='center', alpha=0.5)
```

```
plt.xticks(y2, syst2)
plt.ylabel('€/KW')
plt.title('Cost per kW')

plt.show()

print('Capital cost €/KW')
print(capco)

syst3 = ('KP & Li-ion', 'KP & SMES', 'KP & SC', 'KP & FW')
y3 = np.arange(len(syst3))

plt.bar(y3, repco, align='center', alpha=0.5)
plt.xticks(y3, syst3)
plt.ylabel('€')
plt.title('Cost for the replacements')


print('Capital cost €/KW')
print(repco)

print(lir,smr,scr,flr)

plt.show()

plt.bar(y2, totcost, align='center', alpha=0.5)
plt.xticks(y2, syst2)
plt.ylabel('€')
plt.title('Initial cost with replacements')

plt.show()

print('Capital cost €/KW')
print(totcost)

plt.bar(y2, totcostpkw, align='center', alpha=0.5)
plt.xticks(y2, syst2)
plt.ylabel('€/KW')
plt.title('Cost per kW with the replacements')

plt.show()

print('Capital cost €/KW')
print(totcostpkw)
```

D

Simulink Model

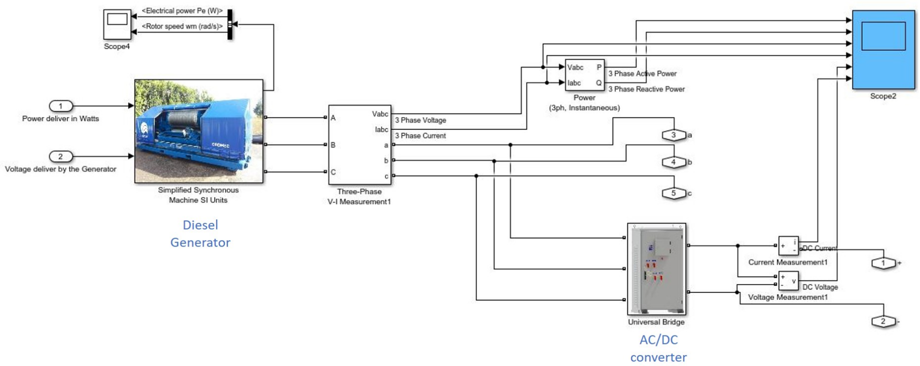


Figure D.1: ***KP generator simulink model***

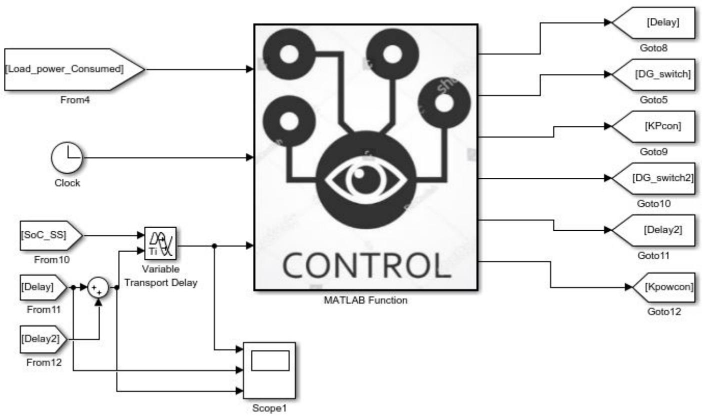


Figure D.2: ***KP generator simulink model***

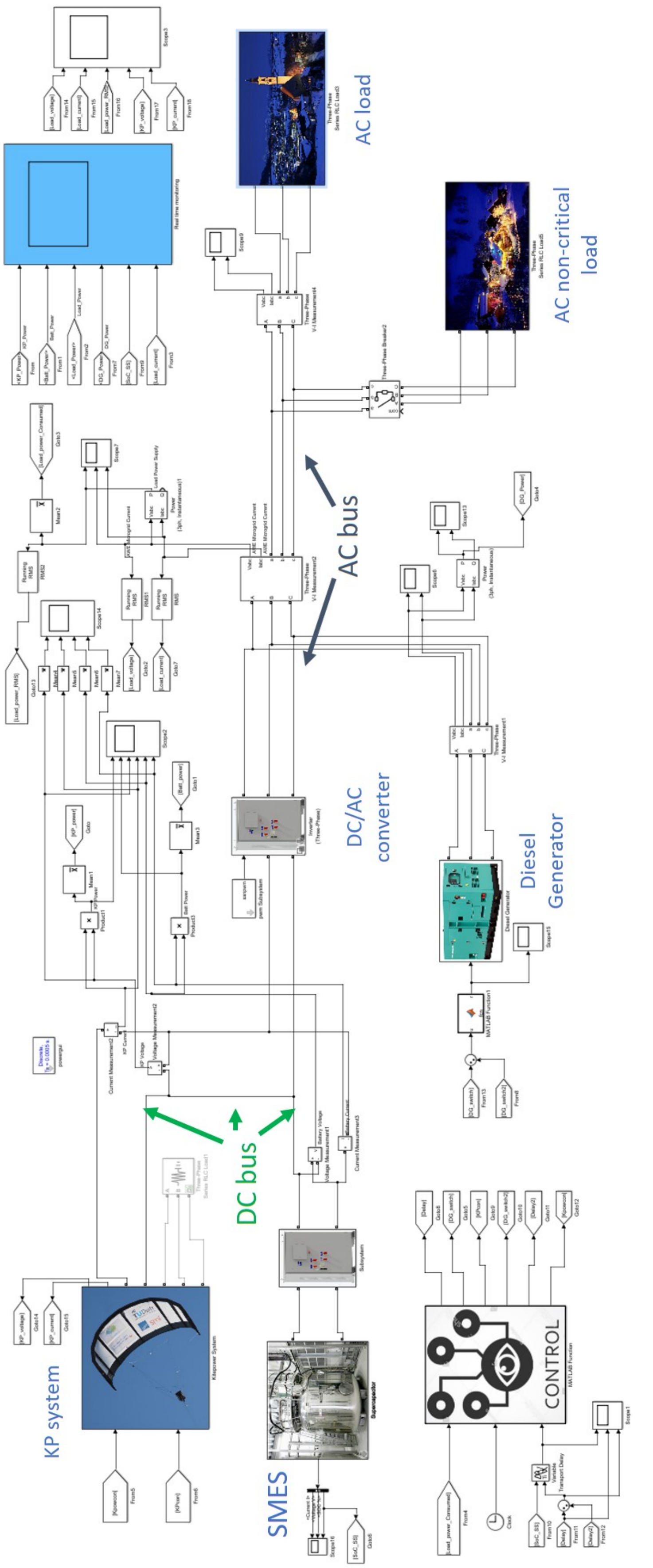


Figure D.3: ***KP Microgrid model***

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