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Analysis of alternative back-up power source for a distribution centre

A Lindex Partille case study

Bachelor thesis in Marine engineering

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Department of Mechanics and Maritime Sciences
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2018

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Abstract

Lindex distribution centre (Lindex DC) in Partille has a back-up power system with a diesel generator to power their servers in case of power failure. Since the servers' power consumption has declined in recent years, their diesel generator is now oversized. An oversized diesel generator will run on low load which puts strain on the diesel engine and may result in problems in the future. In order to solve this problem, this case study compares different alternatives such as; connecting more equipment to the current diesel generator, selling the current generator and investing in a more optimized diesel generator, and selling the current generator and investing in a renewable energy source such as a fuel cell and/or solar power. The solar power could then be used to produce hydrogen gas via an electrolyser. In the latter alternative, the hydrogen is stored in a pressurised tank and can later be used with a fuel cell in case of a power failure. When the storage tank is full, the solar energy will instead provide the building with energy. If there is an overproduction of energy, it may be possible to sell the excess energy to a distributor. By investigating the consumption and documentation at Lindex DC, the consumption for the alternatives could be estimated. In the comparison between the alternatives, the authors chose to investigate availability, economy and environmental impact in order to evaluate the alternatives with a grading system. With these combined aspects, a fuel cell alternative received the highest grade.

Keywords: Fuel cell, UPS, Back-up power, Diesel generator, Electrolyser, Distribution centre, Hydrogen gas, Low load, Solar panel, energy storage.

Sammanfattning

Lindex distributionscenter (Lindex DC) i Partille har en reservkraftlösning med en dieselgenerator för att försörja deras servrar vid ett strömbortfall. Eftersom servrarnas energianvändning har minskat under åren har deras dieselgenerator blivit överdimensionerad. En överdimensionerad dieselgenerator kommer att köras med låg last. Detta är inte bra för dieselmotorn och kan komma att leda till problem i framtiden. För att lösa detta problem, jämför denna fallstudie flera olika alternativ så som; att koppla in ytterligare utrustning till den nuvarande generatorn, sälja den nuvarande generatorn och investera i en mer optimerad storlek på generator, samt sälja den nuvarande generatorn för att istället investera i en förnyelsebar energikälla så som en bränslecell och/eller solpaneler. Solpanelerna kan sedan användas för att producera vätgas via en elektrolysör. I detta alternativ kommer vätgasen att förvaras i en trycksatt tank, och kan sedan användas tillsammans med en bränslecell för att generera elektricitet vid ett strömbortfall. När vätgastanken är full, kommer solenergi från solpaneler istället att användas för att försörja lokalen. Om det sker en överproduktion av solenergi, kan det finnas en möjlighet att få sälja tillbaka överskottet till elleverantören. Genom att undersöka elförbrukare och dokumentation i Lindex DC:s lokal har energikonsumtionen för de olika alternativen kunnat uppskattas. Vid jämförelsen mellan dessa alternativ har författarna valt att titta på tillgänglighet, ekonomi och miljöpåverkan för att på så vis kunna utvärdera alternativen med ett poängsystem. Ett alternativ med bränslecell har visat sig få höga poäng med avseende till dessa aspekter.

Nyckelord: Bränslecell, UPS, reservkraft, Diesel generator, Electrolysör, Distributionscenter, Vätgas, Låg last, Solpanel, Energilagring.

Foreword

The authors would like to thank Leif Almberg for providing the opportunity to perform this project, Mikael Elovsson, and Ingmar Karlsson at Lindex for their time and commitment, and AB Lindex. The authors would like to express additional gratitude towards Gert-Olof (Måns) Holst at PowerCell, Niels-Arne Baden at Green Hydrogen as well as Elon Lövgren, Dick Håkansson, and Mats Hermansson at Coromatic AB for their cooperation and valueble information. The authors would also like to thank their supervisor Jimmy Ehnberg and a final thanks will also be assigned to Maria Jassinskaja who assisted with proofreading.

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Nomenclature

AC	Alternating Current
AEE	Availability, Economy and Environmental impact
DC	Direct Current
DG	Diesel Generator
FC	Fuel Cell
ICE	Internal Combustion Engine
IGBT	Insulated-Gate Bipolar Transistor
kVA	Kilovolt-Ampere
kVAr	Kilovolt-Ampere reactive
kW	Kilowatt
Lindex DC	Lindex Distribution Centre
MTBF	Mean Time Between Failure
PEM	Proton Exchange Membrane
PLC	Programmable Logic Controller
UPS	Uninterruptible Power Supply
VAT	Value-Added Tax

1 Introduction

Lindex distribution centre (Lindex DC) in Partille, outside Gothenburg, is the main hub for all Lindex goods. Clothes, cosmetics and accessories ship by boat from Asia and arrive in Helsingborg, and from there, the products are transported to Partille by truck. In the distribution centre, the goods are repackaged and sent out to Lindex stores all over Europe. Additionally, all of Lindex's online orders are packaged in a neighbouring building on the same street. The Lindex DC also contains the servers for the overall operation, and the online store. Because of this, a power shortage or black-out would be devastating for Lindex, as it would result in a complete stop to all operations, such as taking new orders in the online store, repackaging, and loading trucks. (Leif Almberg, Network technician at Lindex DC, personal communication, January 22, 2018).

Today, the Lindex DC has a diesel back-up generator combined with an uninterruptible power supply (UPS) in order to power the most essential equipment in the case of a power failure. This includes servers, a cooling system for the servers and a few randomly spread out lights. The diesel generator has a power output of 160 kW, but the equipment that it would power in case of a black-out only consumes between 28 – 40 kW. (Leif Almberg, personal communication, January 22, 2018).

According to Leif Almberg at Lindex DC, there are two major problems with the current setup. The first problem is that the current equipment that the diesel generator is able to power is not even nearly enough to put a reasonable load on the back-up generator during test runs. The generator is therefore severely oversized for the current set-up and predictions show an even further decline in the overall energy consumption in the near future. This indicates that the need for replacing the current arrangement will soon become even more pressing. The second problem is that during a black-out, there is additional equipment that should be considered essential, but despite this it is currently not connected to the generator. In case of a shorter black-out, the server hall is the most important part to keep running. Other essential equipment that is not connected today includes; printers and a few computers that are required for the logistic process, and some truck-loading-equipment that is required in order to be able to continue loading trucks during a power interruption.

1.1 Purpose

The main purpose of this case study is to investigate and compare different back-up power options for the Lindex DC in Partille. Further, the study will explore alternative back-up power sources to the diesel generator in order to power the facility and its vital equipment, with a focus on the availability, economy and environmental impact (AEE) aspect. The result of this study should act as a foundation for future decision making concerning Lindex DC's likely change of back-up power due to their upcoming decline in energy usage. Additionally, it will be useful for others who administrate similar facilities and are in the process of selecting or replacing a back-up power source to meet their specific demands.

1.2 Research questions

What is the most beneficial back-up power source with the combined aspects of the availability, economy and environmental impact (AEE)?

Is it possible to improve the AEE of the current diesel generated back-up power source?

Which load types are important to consider when dimensioning a back-up system?

What is required for Lindex distribution centre to be able to keep a part of or all of their operations running, using a back-up power source?

Is a fuel cell combined with an electrolyser and solar panels an AEE-justifiable alternative for back-up power?

1.3 Delimitations

This study is only aimed towards Lindex DC in Partille, outside Gotheburg. This means that the alternatives presented are specifically tailored to this facility and its power consumption only. The core aim of this investigation will be to find an economically feasible alternative that fits Lindex DC's needs, while focusing on the environmental and availability aspect. The environmental investigation will be limited to energy consumed during manufacturing, global warming, and operational carbon dioxide (CO_2) and nitrogen oxide (NO_X) emissions. The economic calculations will only include material costs, i.e labour costs will be excluded. The proton exchange membrane (PEM) fuel cell will be the only type of fuel cell investigated.

2 Technical background

According to the Swedish authority Swedish Civil Contingencies Agency (Myndigheten för samhällssydd och beredskap), a modern society is dependent on electric power to function properly. If the main power grid fails, it will result in serious issues for consumers. The need for a functional back-up power source is a necessity to keep the production in operation and reduce the vulnerability of individual consumers. (Swedish Civil Contingencies Agency, 2015)

According to the electricity act; 1997:857 (Sveriges Riksdag, 2018), an electricity provider shall ensure that interruptions in the transmission of electricity to a customer never exceed twenty-four hours unless the interruption is due to an obstacle beyond the control of the provider. Thus, the interruptions from an electricity network provider will in most cases not exceed twenty-four hours. The back-up power must therefore be able to run continuously for at least that time.

2.1 Availability when the main power grid fails

The need for a reliable back-up power source is in some cases invaluable. Without a back-up power source, the whole system will come to a stop if the main power grid fails (Swedish Civil Contingencies Agency, 2015). Some electrical equipment, like computers and servers, can lose information and take time to restart if the power source is lost and an uninterrupted solution is therefore of the highest necessity. This can be achieved with a UPS system which supplies the equipment with power until the back-up source is up and running. (Platts and Aubyn, 1992, p. 8)

2.1.1 Online UPS

A UPS is used to take over the power supply in case the main power grid fails. Nasiri and Hamidi (2018) explains that, in general, there are two different, commonly used UPS systems; standby UPS and online UPS. A standby UPS, sometimes referred to as offline UPS, uses a static switch in order to supply consumers when there is a power failure, which results in a short delay before the power is restored. An online UPS is instead designed to detect a dip in voltage in the system and automatically supply the consumers without any delay. Since there is no delay, a computer or similar equipment, will not shut down during a power failure. This makes it especially useful from an availability aspect (Nasiri and Hamidi, 2018).

The UPS consists of a battery, a charger with a built-in rectifier, and an inverter. The charger is connected to the main grid and converts the alternating current (AC) to direct current (DC) which is continuously charging the battery. The inverter converts the DC to AC and delivers it to the consumers. (Hordeski, 2005, pp. 84–87)

Figure 1 illustrates an online UPS system powered from the main grid. The green lines illustrate the power source used and how the current flows in this mode.

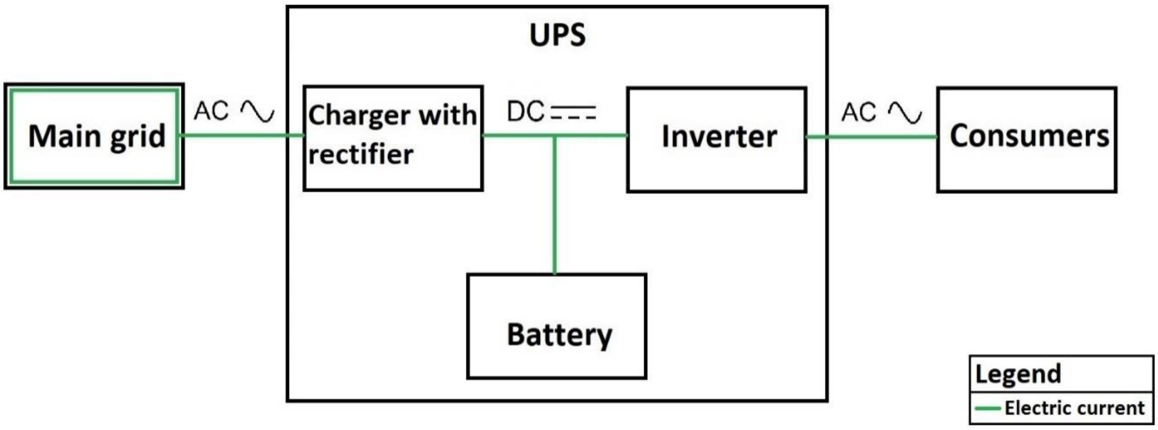

Figure 1*.* Power is delivered from the main grid. The green line illustrates how electric current flows through the UPS and charges the battery. Authors own work based on Nasiri and Hamidi (2018).

Figure 2 illustrates a situation where the main grid fails to deliver power to the consumers. The battery will automatically start to feed the inverter. The green lines illustrate the power source used and how the current runs when the main grid fails.

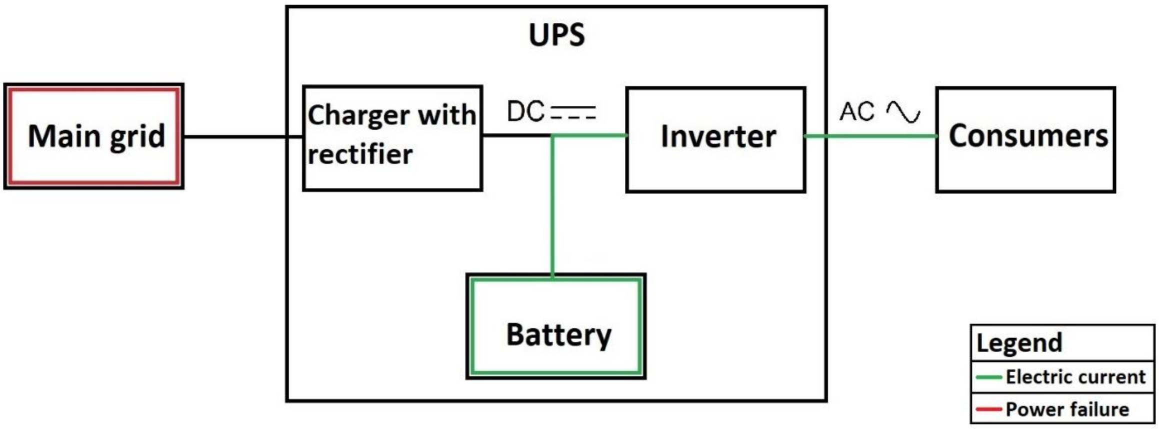

Figure 2. Main grid power failure, the UPS takes over. Red colour illustrates main grid failure, green lines illustrate how the battery deliver power to consumers. Authors own work based on Nasiri and Hamidi (2018).

2.1.2 Online UPS combined with diesel generator

Hordeski (2005, p. 85) writes in his book that a UPS is normally not made to power consumers for a longer period of time. It is instead common to use the UPS as a type of bridge or temporary power source until another long-term alternative for back-up power has connected. For example; a diesel generator will take a few seconds to connect and is unable to deliver power to the consumers immediately after the power from the main grid fails. The UPS will instantly take over the responsibility of delivering power to the consumer until the diesel generator is ready. Figure 3 illustrates a diesel generator in stand-by, ready to connect in case of a main grid power failure.

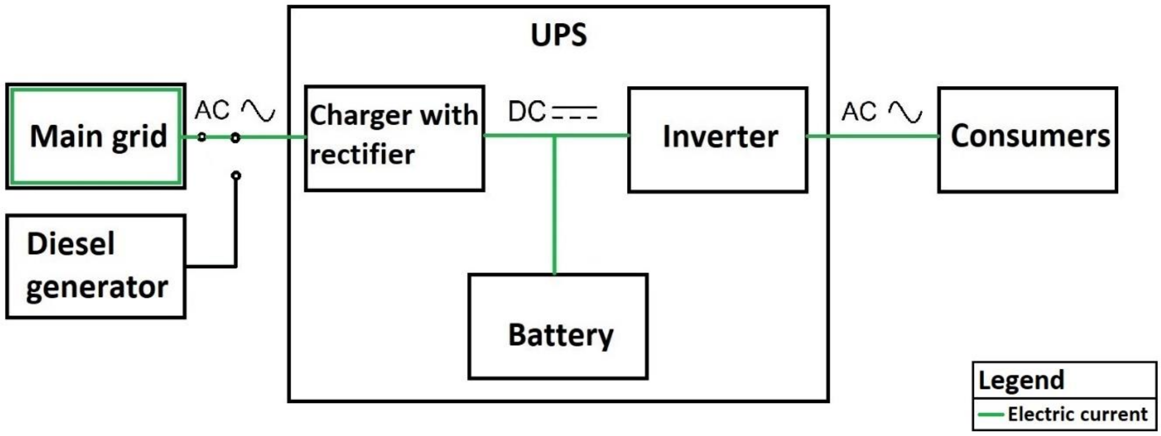

Figure 3. Power from main grid, diesel generator in stand-by. Green lines illustrate how the power runs, both supplying consumer and charging the battery. Authors own work based on Nasiri and Hamidi (2018).

Figure 4 illustrates a few seconds after a main grid power failure. The battery has already started delivering power to the consumers, the yellow colour represents that the diesel generator has received a start command.

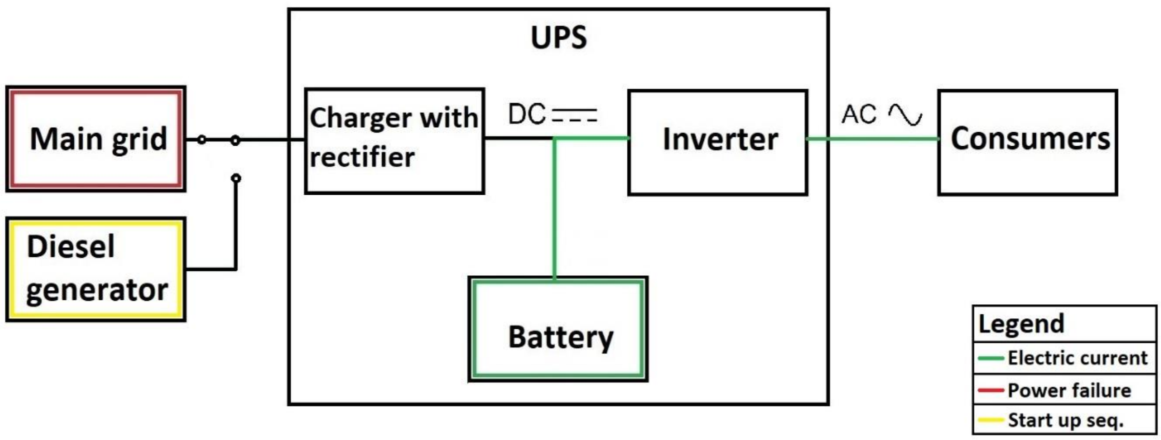

Figure 4. Main grid power failure, battery in UPS takes over, yellow colour illustrates that the diesel generator is in its start-up sequence. Authors own work based on Nasiri and Hamidi (2018).

Figure 5 illustrates the diesel generator when it has reached working-speed and automatically connects to the rectifier, providing the UPS with power. The batteries in the UPS will then recharge.

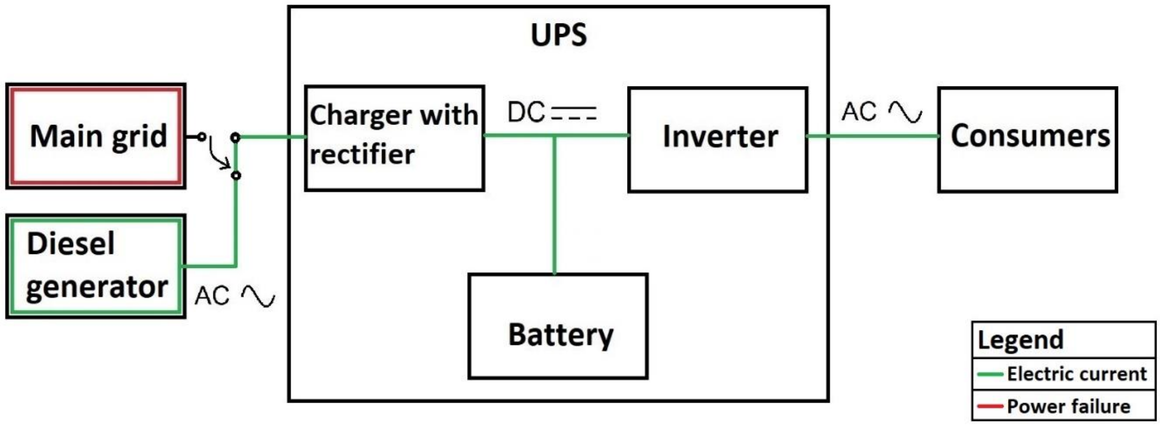

Figure 5. Diesel generator have started and connected to the UPS. Authors own work based on Nasiri and Hamidi (2018).

2.1.3 Online UPS combined with fuel cell

Another alternative is shown in figure 6. This illustrates an arrangement with a fuel-cell as a main back-up power supply instead of a diesel generator.

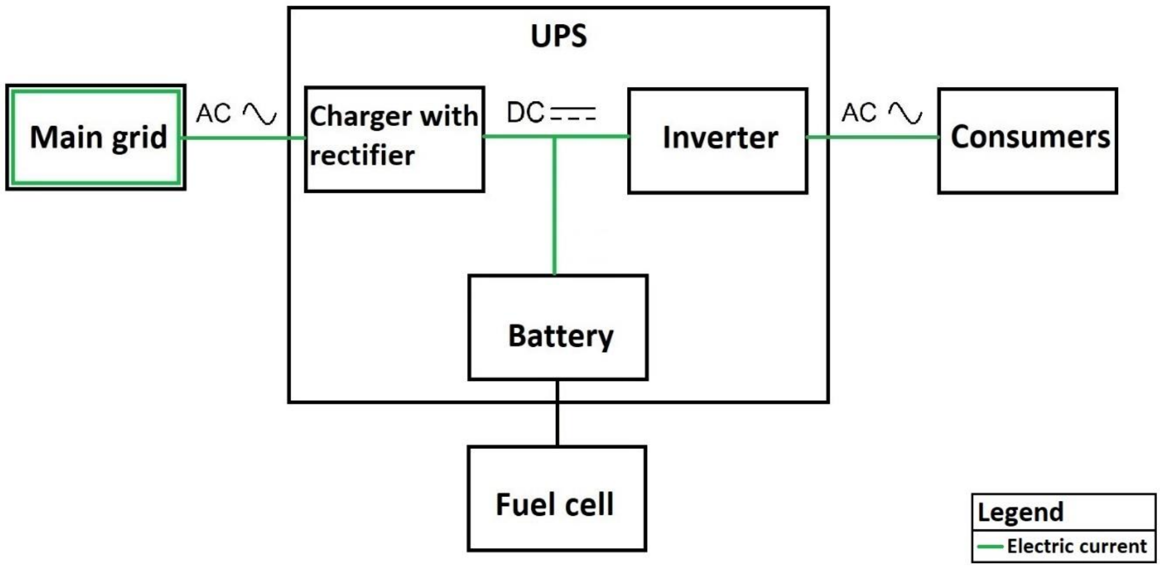

Figure 6. Power from main grid, charging battery. Fuel cell in stand-by. Authors own work based on Nasiri and Hamidi (2018).

Figure 7 illustrates how the fuel cell starts generating electricity in order to charge the battery while it is supplying consumers.

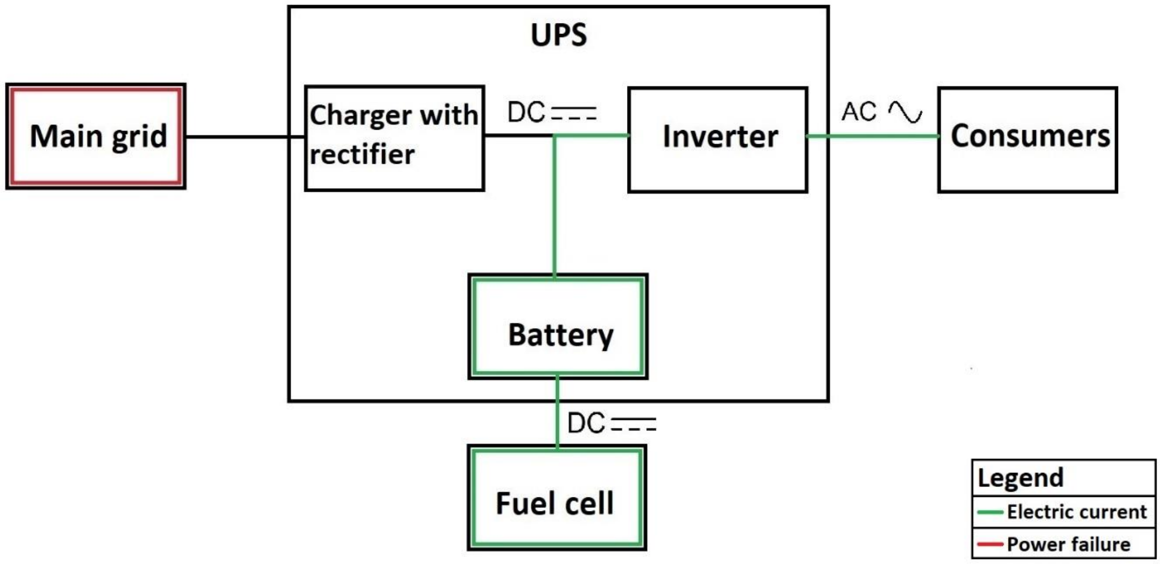

Figure 7. Main grid power failure, battery and fuel cell takes over. Authors own work based on Nasiri and Hamidi (2018).

2.2 Diesel generators for back-up power

A diesel engine is a type of internal combustion engine (ICE) and is a common installation for back-up power. The diesel generator is well-established and frequently used as an emergency/back-up power supply, but it needs continuous maintenance. The planning of maintenance is based on a time schedule and not running hours (Curtis, 2007, p. 53). According to Curtis (2007), this is due to the running hours on an emergency/back-up diesel generator usually being very few. The planned maintenance is one of many important things to consider in order for the diesel generator to function properly when it is running. Curtis (2007) also points at the system design and the choice of surrounding equipment as important aspects for the functionality.

According to Curtis (2007), one problem in back-up diesel generators is that the operator has very few running hours of the engine and therefore limited experience with the equipment in question. The back-up diesel generator is often neglected because of the few running hours. (Curtis, 2007, p. 53)

The diesel generator should have a load of more than 30% of the rated power to function properly (Nordin and Lindemark, 1999). If the load is below 40% of the rated power, the engine is running on low load which puts strain on the diesel generator (Dalsøren Tufte, 2014). According to Dalsøren Tufte (2014) there will be residues from the combustion, such as soot and unburned fuel. Dalsøren Tufte (2014) concludes that this will have a negative effect of the piston rings sealing capability and unburned fuel and soot will pass by the piston. When fuel is mixed with lubricant oil, the viscosity of the oil will become too low and affect the lubrication of the engine's critical parts, such as bearings (Dalsøren Tufte, 2014).

At low engine load, the pressure and temperature in the combustion chamber will be low. Low temperature will lead to inferior combustion of lubricant oil in the combustion chamber. An engine always consumes a small amount of lubricant oil when the engine is running (Design by Initiative, 2012). Design by Initiative also mention that the unburned oil will stick to the exhaust system and turbo charger. This will lead to reduced turbocharger efficiency and may cause fires in the exhaust system.

2.3 Electrical load types

There are different loads to consider when dimensioning a back-up system. The loads can be divided into resistive loads, resistive-inductive loads, resistive-capacitive loads and non-linear loads (Nordin and Lindemark, 1999).

2.3.1 Resistive loads

Resistive loads, or resistors, are loads caused by pure resistance in the flow of electricity. Incandescent light bulbs, toasters and electrical heaters are common examples of resistive loads. When current passes through the wire of a light bulb or a toaster, the resistance converts electrical energy into light energy or heat energy respectively (Logan, 2018). According to King and Knight (2003), a resistive load consumes active power, measured in kilo-watts (kW) and will be the largest load on a generator. Large amounts of active power will cause the diesel generator to drop in speed and the engines must compensate with more fuel in order to keep the speed up (King and Knight, 2003).

2.3.2 Resistive-inductive loads

Electric motors, transformers and other equipment with coils are examples of resistive-inductive loads (Logan, 2018). Reactive power is consumed in the coils and will cause more current in the circuit. This will create more heat in the cables, which leads to an energy loss. Reactive power is measured in kilovolt-ampere reactive (kVAr) and will influence the generators apparent load which is measured in Kilovolt-ampere (KVA) (King and Knight, 2003).

2.3.3 Resistive-capacitive loads

Resistive-Capacitive loads come from components called capacitors, which are commonly used together with electric motors (Logan, 2018) in order to compensate for the reactive power caused by resistive-inductive loads and reduce the apparent load in the circuit (Nordin and Lindemark, 1999, p. 2).

2.3.4 Non-linear loads

Equipment that cause non-linear loads are those that use rectifiers to convert AC to DC. A common example of this is stationary computers and laptop power supplies. According to Nordin and Lindemark (1999, p. 2), it is important to consider that the nonlinear loads may create problems for a small grid. The nonlinear loads disturb the current in the grid, and consequently, the voltage from the generator. Because of this, the nonlinear load in the grid should not exceed 50% of a back-up generator's capacity. (Nordin and Lindemark, 1999, p. 2)

2.4 Fuel cells

Hydrogen gas is a commonly used fuel for a fuel cell. The fuel cell produces a DC current when the reaction process in the cells is on-going. The basic principle of a fuel cell is the conversion of chemically bound energy to electric energy and heat. The fuel cell needs a fuel such as hydrogen and oxygen for the internal reaction. Figure 8 shows a PEM fuel cell which consists of an anode and a cathode, and between them a membrane or electrolyte matrix.

The reaction at the anode inside the fuel cell is shown in reaction 1. (Birnbaum, Linssen and Leifeld, 2008, p. 12)

Anode: $$2H_2 \rightarrow 4H^+ + 4e^- \quad (1)$$

The hydrogen fuel ($2H_2$) is split inside the fuel cell. The four electrons ($4e^-$) cannot pass through the electrolyte matrix shown in Figure 8 and must therefore pass through the electrical connection between the anode and the cathode. (Birnbaum et al., 2008, p12)

The reaction at the cathode inside the fuel cell is shown in reaction 2.

Cathode: $$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \quad (2)$$

When the electrons ($4e^-$) meet the hydrogen ions ($4H^+$) and oxygen (O_2) at the cathode, they react to produce water ($2H_2O$) and heat. (Birnbaum et al., 2008, p12)

Reaction 3 shows the net reaction of a fuel cell.

Total reaction: $$2H_2 + O_2 \rightarrow 2H_2O \quad (3)$$

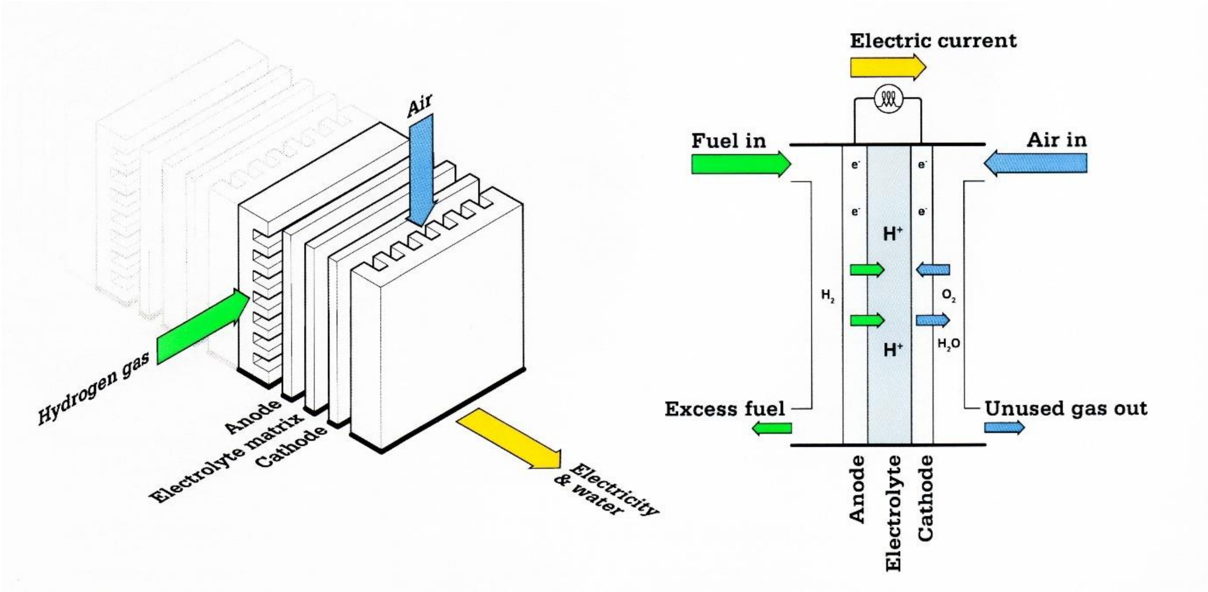

Figure 8. Fuel cell working principle. Hydrogen passes through the electrolyte matrix, electrons are not allowed to pass through. (Powercell Sweden AB, 2018) used with permission.

A DC/DC converter is necessary to stabilize the voltage generated by the fuel cell. The fuel cell combined with an alternator can supply an AC grid with electric power. (Larminie and Dicks, 2003, pp. 331-332).

There are a few different types of fuel cells available on the market which use different technologies to produce electricity and have different advantages and disadvantages. The PEM fuel cell is the most common fuel cell in the automobile industry today. In a near future, this kind of fuel cell will likely also be used in stationary facilities. (Employee at PowerCell, personal communication, March 5, 2018).

According to PowerCell (2018), the fuel cell requires a few minutes to start up and needs a battery to function. PowerCell (2018) also mention that a fuel cell cannot be the only power supply source in a system with large power peaks, as it is very slow at compensating for changes in the load. This issue can be solved with batteries that can withstand the power peaks, resulting in constant load for the fuel cell. When the power peak is over, the fuel cell begins to reload the batteries. The peak load is an important factor to consider when dimensioning the batteries in the system as they must be large enough to handle the starting current for the installed equipment.

An example of a fuel cell system layout is shown in figure 9. The system consists of a circulation pump for hydrogen, cooling water pumps, a heat exchanger/cooler, an air blower, valves, a humidifier, temperature control, a DC/DC converter, and an air filter. The air blower supports the fuel cell with the right amount of air for the power out-take. The amount of air regulates the power production in the fuel cell. In the humidifier, the inlet air is humidified by means of the exhaust air. The reason for this is that the membrane in the fuel cell needs humidified air to function properly. The pressure regulator (v3) in the hydrogen system reduces the inlet pressure from supply to working pressure for the fuel cell. When the fuel cell is running, some nitrogen will escape from the air side to the hydrogen side. The purge solenoid is therefore needed to purge the nitrogen out from the hydrogen side. (Alfredsson and Swenson, 2017, p. 20)

The heat recovery part increases the overall efficiency of the system. However, it is not required for the system and is typically only used in cases where there is a need for heating the building. (Alfredsson and Swenson, 2017, p. 20)

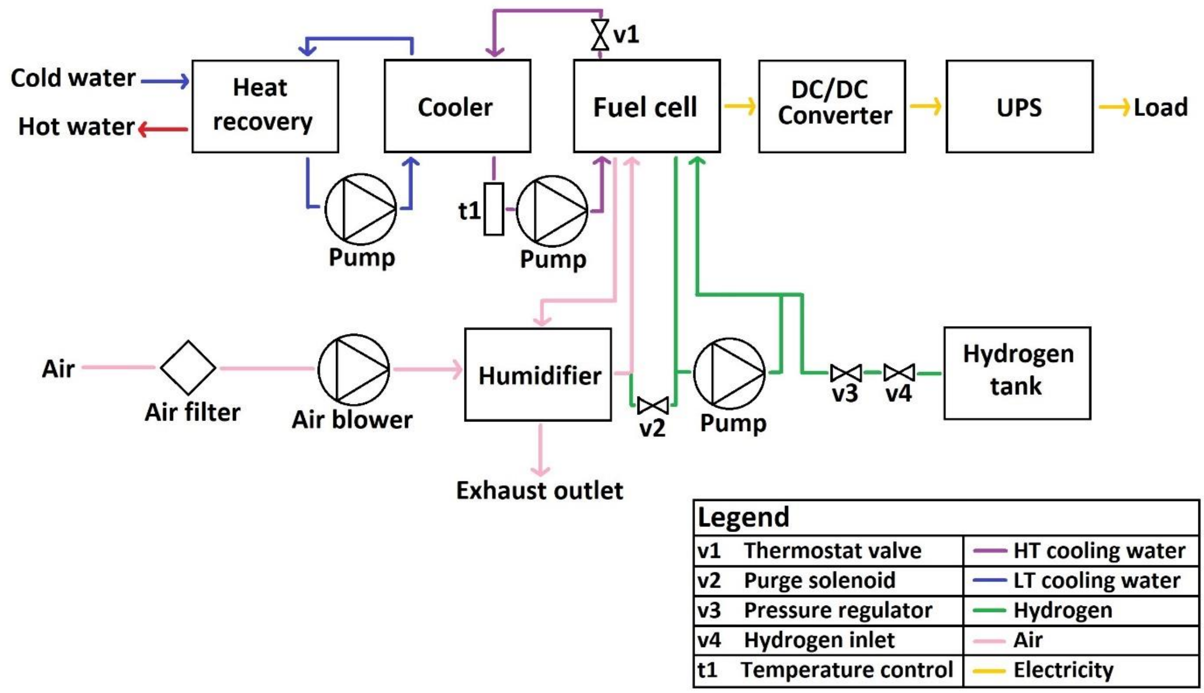

Figure 9. Layout for a fuel cell system. Authors own work based on Alfredsson and Swenson (2017).

2.5 Solar energy

With renewable energy such as solar power, the company can also be an electricity supplier and take additional responsibility for the climate. In recent years, the solar panel efficiency has improved. With a higher efficiency, the power production will be greater compared to old panels with the same panel area. This means that the economical investment will be repaid faster compared to older panels, especially as the cost for a solar panel investment has decreased in recent years. (Swedish authority of energy, 2016)

Most solar cells used for power production are made from silicone crystalline. In general terms, there are two main kinds of solar cells made from this material; poly-/multi-crystalline and monocrystalline silicone. These are the kinds of solar panels that are intended for outside use, such as on roofs. Monocrystalline is made from one whole piece of silicone, which makes it more expensive, but also gives it a slightly higher efficiency compared with polycrystalline. Polycrystalline is, as the name entails, made from many small pieces of silicone (EnergySage, 2018). Since silicone is a non-toxic material, it is easy to recycle and recondition the solar cells, with relatively few ethical problems (Dross, 2012).

2.6 Storing renewable energy

The big challenge with renewable energy is to find a suitable way to store it. When the main power grid fails, the optimal solution, from an environmental standpoint, would be for individual consumers to use stored renewable energy as back-up power. One way to do this is to produce hydrogen gas with an electrolyser using excess energy from a renewable source, such as solar panels. This technique is called electrolysis (Kelly, 2011, p. 170). Figure 10 shows the process of hydrogen production from solar energy. Hydrogen is stored in a tank for later use in a fuel cell to produce electricity when needed. To produce hydrogen gas with electrolysis, electric power and water are needed. The electrolyser splits the water into hydrogen gas (H_2) and oxygen (O_2) (Office of Energy Efficiency and Renewable Energy, 2018). The hydrogen is compressed and stored in tanks. Kelly (2011, pp. 170-171) argues that the electric power needs to come from a renewable energy source to have as little impact on the climate as possible.

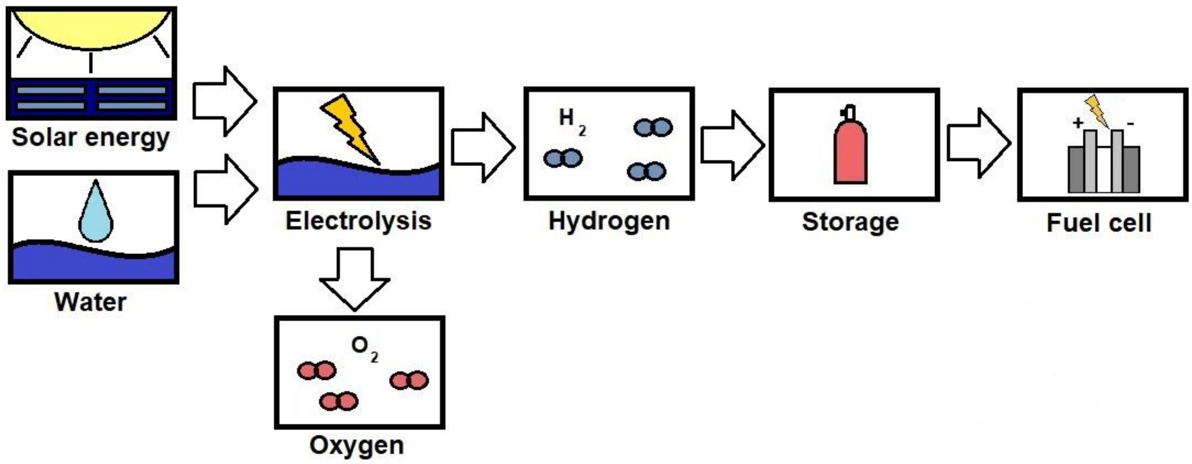

Figure 10. Electrolysis from solar energy and water. By separating water molecules, hydrogen is extracted and stored for later use. The only emission is oxygen. Authors own work.

The hydrogen gas must be stored at high pressure due to its large volume at atmospheric pressure. Nevertheless, the storage volume for hydrogen gas is space-consuming even when stored at high pressure. There is on-going research to find other ways of storing hydrogen with new and stronger materials that will facilitate a decrease in storage volume. (Kelly, 2011, pp. 169-173)

3 Lindex distribution centre case study

When Lindex DC installed the current back-up power source, they were anticipating an increase in power usage as they knew that their need for data storage would grow, and thus assumed that the power consumption would increase accordingly. However, they did not take the development of data storage technology into consideration and since current trends are indicative of further decline in power consumption, the current back-up power source does not fit their needs. Recent development has shown a steady decline in power consumption for data storage equipment. In the future, it is therefore likely that the back-up power source will become even more over-sized and therefore incompatible with their equipment. (Leif Almberg, personal communication, January 22, 2018)

When it comes to selecting a back-up power source, Lindex DC must choose between powering the whole facility, a part of it, or only the most necessary equipment. It is important to investigate the different loads in the grid and calculate the active, reactive, and apparent power (Nordin and Lindemark, 1999). Equipment such as electric motors have eight times higher starting current than their rated current, leading to power peaks in the grid (Alfredsson, Cronqvist, and Abdo-Walldén, 2002, p. 147). It is therefore important that the power source can handle such peaks.

3.1 Back-up power setup at Lindex distribution centre

The current back-up generator is a diesel-powered solution. It is delivered as a complete solution, with an air-cooled radiator, an integrated fuel tank in the foundation, and a generator switch. The generator can deliver a maximum active power output of 160 kW and maximum apparent power of 200 kVA. When the generator is running, it constantly has a load of 28 kW in winter time and peaks at 40 kW on a hot summer day. It supplies the servers, cooling equipment for the server hall, and some lights. The servers are supplied via an online UPS which provides an interference-free transition to the back-up generator when the main grid fails. (Leif Almberg, personal communication, January 22, 2018)

When Lindex DC are in back-up mode, numerous functions in the building cease to work. Alarm systems, passage systems and the support department are examples of important functions that are currently not connected to the back-up system. Additionally, Lindex's online shop building is not supplied via the back-up power source, even though it is considered a very important part of the Lindex corporation. The size of the online department of Lindex will most likely increase in the coming years. (Leif Almberg, personal communication, January 22, 2018)

3.2 Dimensioning an alternative for Lindex distribution centre

When dimensioning a back-up power system, the amount of equipment connected will determine the size of the back-up power source. This study focuses on four different alternatives, with four different levels of back-up powered equipment.

3.2.1 Existing back-up power alternative

In the existing back-up power alternative, Lindex DC keep the same equipment setup as is in place today, i.e. no changes to the equipment connected to the back-up power will be done. This alternative requires a smaller back-up power source than what Lindex DC have today. The back-up power source should be at least 75 kVA.

3.2.2 Improved back-up power alternative

This alternative contains the most important equipment for Lindex DC. The requirement is that the back-up generator should be able to support the data servers, the cooling system for the server hall, the support department, the alarm system, the passage system for the building, and some lights.

The highest possible power consumption in this alternative will act as the norm when dimensioning the back-up power source (Nordin and Lindemark, 1999, p. 3). The back-up power source should be at least 110 kVA.

3.2.3 Skeleton crew back-up power alternative

According to the Cambridge dictionary (2018), a skeleton crew is “the smallest number of people needed to keep a business or organization operating”. In this alternative, the back-up system will supply one robot, one crane, conveyors, packaging robots, some lights, an air compressor and one telescopic belt conveyor in order to avoid interruptions in the production. The distribution centre will run with reduced capacity. In this alternative, a programmable logic controller (PLC) is required to ensure that only one large consumer runs at a time in order to limit the required power for the back-up generator. Large consumers include robots and cranes.

According to Table 1, the back-up power source should be at least 310 kVA. The largest power consumer is the crane, which would represent 20% of the back-up generator's capacity. This load will alternate, but this is acceptable as it only accounts for 20% of the back-up power capacity. The crane has servo electric motors and will therefore not have a high starting current and thus not create power spikes in the grid.

3.2.4 Total back-up power alternative

In this alternative, the back-up generator needs to be large enough to supply all the equipment in the distribution centre. This is the best option for the production. The distribution centre can operate normally within a few seconds of a main grid failure.

The momentary consumption on a working day basis is approximately 420 kW. The measured value for Lindex DC alternates between 250 kW and 330 kW. When manually counting the consumers, the required power adds up to a maximum of 682 kW. It is unlikely that all consumers are running at the same time, which means that it is not necessary for the back-up power system to handle this amount of power. The back-up power source should be approximately 551 kW which is the average mean between 420 kW and 682 kW. With a generator of this size, there will be a limited risk of having an over-sized back-up power source, as is the problem today. Since the total power alternates up to 330 kW, this would result in a 60% load, which is reasonable.

3.2.5 Electric load types at Lindex distribution centre

There are different loads to consider when dimensioning the back-up system for Lindex DC. The loads are resistive loads, resistive-capacitive loads, resistive-inductive loads and non-linear loads. A resistive load does not constitute an issue for a generator as it only requires active power.

Resistive-capacitive and resistive-inductive loads can be found in electric motors and fluorescent lights, respectively. These loads can cause disturbances in a small grid and should constitute a limited part of the back-up power grid. (Nordin and Lindemark, 1999, p. 2)

An example of a non-linear load in the Lindex DC is computers, which can create harmonics in the grid. These loads have different effects on the generator and should be kept within the generator's limitations of 50%. In Lindex DC's case, an online UPS for the servers and computer loads exists. The online UPS has an insulated-gate bipolar transistor (IGBT) rectifier which has resistive load characteristics (Gelman, 2014). This means that the UPS will not affect the generator critically.

Table 1 shows the different alternatives required active, reactive and apparent power. Some of these loads are connected via the UPS and not directly into the diesel generator. The total reactive load connected directly to the current diesel generator at Lindex DC is 4.2 kVAr, while the total reactive power for the existing back-up power at Lindex DC is 13 kVAr.

Table 1. Estimated Power required for the different alternatives

Estimated Power required for the different alternatives	Existing alternative	Improved alternative	Skeleton crew alternative	Total alternative
Active power (kW)	72	108	316	682
Reactive power (kVAr)	13	27	112	345
Apparent power (kVA)	73	111	335	764

3.3 Lindex distribution centre main building

Lindex DC's total power consumption is 1367 MWh/year. The lights in Lindex DC consist of 600 fluorescent lamps of 2x49W per armature and 600 LED armatures of 49W per armature. According to McFadyen (2012) the power factor for fluorescent lamps is 0.93.

According to Ingemar Karlsson, service technician at Lindex, the total available roof area is 12,500 m^2 (Personal communication, February 7, 2018). With the total area covered with solar panels, enough electricity should be produced to cover the total consumption of the building on a yearly basis. A 12,500 m^2 solar power plant will produce roughly 1875 MWh/year in Gothenburg (Göteborg Energi, 2018). For Lindex DC's back-up power demand, the dimensional aspects will be back-up running time and power consumption. It should be able to run for at least twenty-four hours, based on the electricity act; 1997:857 (Sveriges Riksdag, 2018).

4 Method

4.1 Case study

For a project with a natural setting (in this case; Lindex DC) and with multiple sources of information, the case study method is appropriate (Denscombe, 2014, p. 79). This method is widely acknowledged as a useful tool when investigating both single-case and multiple-case solutions. Case study advocates "six sources of evidence", which includes collecting evidence from documents, interviews, direct observations, participant-observations, and physical artefacts (Yin, 1994, p. 53, 63, 78). It has functioned as a guide during the investigation stage and helped increase the overall reliability of the research.

4.2 Data collection

4.2.1 Multiple sources of evidence

When conducting case study research, it is important to use more than one source of evidence in order to strengthen the case. By using several different sources, the quality of a case study is considered higher compared to using a single source for evidence (Yin, 2014 p. 119). By gathering information from both documents and interviews, the result can be confirmed from two different sources, this is called triangulation (Wargo, 2014). For these reasons, the aim was to gather data from a broad range of sources whenever possible.

4.2.2 Interviews

The main form when conducting interviews has been of the so called "open-ended nature" which involves meeting with a person of interest who potentially has the required information. This resulted in receiving information in the form of both solid facts, and the interviewees own opinions about the situation and/or object(s).

4.2.3 Literature based data collection

Substantial time and effort was dedicated to reading articles and books in order to find information that was relevant for the questions related to this study. Relevant information has then been presented in the results and has formed the foundation for the report.

4.2.4 Power consumption (Direct observations)

During a field visit to the Lindex DC, the switchboard for the entire facility was examined. The switchboard contained an electricity meter that showed the actual power consumption in real time. Already here it became evident that the consumption fluctuated intensely because of heavy machinery starting and stopping irregularly. By taking notes of different values over a period of time, a reasonable average of the power consumption at Lindex DC, could be calculated.

In order to calculate the power consumption of separate consumers at Lindex DC, an extensive collection of different data had to be performed. By carefully examining all equipment in the Lindex DC, counting the total amount of fluorescent lights and reviewing instruction manuals, it was possible to compile the power consumption of separate consumers in the table located in appendix. B.

During a test run of the current diesel generator at Lindex DC, the total reactive load connected directly to the diesel generator was observed on the generator display. This aided calculations on the total amount of reactive power.

The online store is located in the neighbouring building, and because of its smaller size, it has a substantially lower power consumption. The service technician at Lindex DC (Ingemar Karlsson, personal communication, February 7, 2018) had performed measurements and compiled the total power consumption for one month (December) in a spreadsheet. This provided sufficient data to do the necessary calculations.

4.3 Estimations

The exact power consumption for some parts of Lindex DC's equipment was impossible to measure without connecting advanced measurement instruments between the grid and the equipment itself for an extensive period of time. Measurements like this were not possible to perform, so qualified estimations were done in some instances.

The power consumption for the office department was estimated by counting lights and computers in the department which represent the largest part of the office power consumption.

It is highly unlikely that all motors are running at the same time, or that they are running at their rated power. Because of this the power consumption of the conveyor belts was estimated to be ¼ of the combined power consumption of the total amount of electric motors.

Norden Solar is a company that provides solar panels for both private consumers and companies. They offer many different packages, which they then can tailor to fit each customer. Their largest package costs approximately 750,000 SEK excluding value-added tax (VAT) and covers an area of 680 m^2 (Norden Solar, 2018). It was calculated that Lindex DC would need 18 of these packages in order to cover their entire roof, and therefore the price was estimated to 13,500,000 SEK excluding VAT.

4.4 Calculations

4.4.1 Efficiency

Calculations for the current diesel generator are based on fuel consumption marked on the diesel generator fuel tank (Appendix. A). Additionally, some measurements have been made when Lindex personnel have performed test-runs. The diesel generator has been run for 30 minutes with 28 kW load, upon which the refuelled volume to the fuel tank has been measured. The efficiency of the actual load for the current diesel generator can then be calculated.

4.4.2 Operational cost

Calculations for the diesel generators operational cost for twenty-four hours is based on the fuel consumption from the product sheet for the specific generator and the diesel fuel price obtained from EcoPar (2018).

Calculations for the fuel cell operational cost is based on the heating value of hydrogen and fuel cell efficiency, received directly from an employee at PowerCell (2018) during an interview and fuel price data from Ny teknik (2015). Fuel consumption is calculated on different loads. The operational cost is subsequently calculated with the heating value, efficiency, fuel price and fuel consumption during twenty-four hours.

4.4.3 Maintenance diesel generator

The cost for test-runs for the diesel generators is calculated with the recommended test-run time, yearly frequency and with a diesel generator load of 50%.

4.4.4 Hydrogen storage tank

The size of the Hydrogen storage tank is based on the amount of consumed fuel at 100% load during twenty-four hours of operation. The size is subsequently calculated with data from Riis, Sandrock, Ulleberg and Vie (2006, p. 21) which concludes that a hydrogen tank with a capacity of 145 litres contains 3 kg of hydrogen at a pressure of 350 bar.

The cost for a hydrogen fuel tank is calculated with data from Riis et al. (2006, p. 21), which states that the estimated price for a hydrogen storage tank is 500 – 600 USD/kg hydrogen.

4.5 Analysing and compiling the data

Yin mentions in his book four general strategies for analysing data. The first strategy out of the four is called *"Relying on theoretical propositions"* (2014, p. 136). According to Yin, this strategy of analysis fits for a case study based on a set of research questions, and where the goal of the study might be to reach a new hypothesis or proposition.

When all data had been collected and summarized, it was compiled for each separate alternative, which were then compared against each other by dividing the data for each alternative according to the AEE standard and compiling different tables. By doing this, it was possible to compare each alternative to each other in all aspects of AEE. This method is described by Yin (2014, pp. 164 – 168) as cross-case synthesis. The final result of the compiled data was carefully valued by giving each possible alternative a grade of 1 - 5 in each aspect of AEE. The grades were added together to form the total grade, which represents how well each alternative score in the total aspect of AEE. In order to get the most accurate grade for each alternative, four aspects were considered; availability, economy, environmental impact and maintenance. The need of maintenance can be seen as a combination of both an economical and an availability aspect.

Availability: Results show that the availability of a fuel cell is slightly higher than that of a diesel generator. However, the difference between them is quite small. Because of this, all diesel generator alternatives receive a grade of 4, while the fuel cell alternatives receive a grade of 5.

Economy: When grading the individual alternatives in the economical aspect, both the actual cost of the system and its installation as well as the possibility of keeping future costs down and even providing a secondary source of income, by e. g. selling excess energy produced from solar panels, were considered. When grading the individual alternatives, the most expensive alternatives receives the lowest grade of 1, while the most economical alternative receives the highest grade of 5. The other alternatives obtain their respective grade of 2-4 depending on the individual price.

Environmental: The least environmental friendly alternatives receive the lowest grade of 1. Alternatives with a fuel cell receives a grade of 4. However, in this subsection, none of the alternatives qualify for the highest grade of 5. The alternatives with solar panels would be able to receive a grade of 5, but due to the high environmental impact from the manufacturing process of the electrolyser and its low running hours, the grade is reduced to 4.

Maintenance: When grading the alternatives need for maintenance, the fuel cell received the highest grade of 5 since it does not require any maintenance or test runs. The alternatives with solar panels require relatively small amounts of maintenance of the panels themselves, such as washing etc. While the diesel generator requires the highest amount of maintenance, as well as test runs once per month, it is not a substantial amount of maintenance, resulting in the diesel generator receiving a grade of 3.

5 Results

The different parts of the results are divided in the AEE aspects, starting with the availability of diesel engines and fuel cells followed by the economical and the environmental aspect. Finally, the result has been compiled in a table, showing the potential of the different alternatives.

5.1 Availability

The availability for the different alternatives is based on their individual system requirements. The online UPS is used in all back-up alternatives and will therefore not be considered in the availability aspect. The electrolyser and solar panels are used as a complement and will not affect the availability of the back-up power and will therefore be excluded in this part of the result.

5.1.1 Diesel generator availability

The most common reason for malfunction in a diesel generator is lack of battery maintenance (Du, Burnett, and Chan, 2002). According to Du, Burnett and Chan (2002), in a diesel generator back-up power installation, the risk of start-up failure is considered small. According to their study in Hong Kong, start-up failures in commercial buildings only occur in 2.4% off all start demands. The mean time between failure (MTBF) is 11,830 hours for commercial buildings. The availability is 97% for a commercial building. (Du et al., 2002).

5.1.2 Fuel cell availability

The availability of a fuel cell system will include all components in the system. A fuel cell does not need maintenance according to PowerCell (Employee at PowerCell, personal communication, March 5, 2018). However, the components in the auxiliary system for the fuel cell have a specific availability expressed in percentage, as it consists of pumps and fans which contain rotating parts that require maintenance. If one component of the auxiliary system needs maintenance or needs to be replaced, the total availability of the back-up power will be affected.

5.2 Economy

The choice of a new generator system will be a determining factor for the economy calculation. As a back-up power system has few running hours, the investment and installation cost of a system represent the largest part in most of the calculations, but calculations on twenty-four hours running time are also presented in this section.

5.2.1 Improved alternative with the current back-up diesel generator

1. installation/rebuilding

In the improved back-up power alternative, the current back-up diesel generator can be kept. The most expensive part in the improvement of the efficiency of the current diesel generator is the rebuilding of the electrical system. The alternative needs new cables and connections in order to put more load on the diesel generator.

2. Operational

The fuel cost for the diesel generator is small for this alternative, due to the low number of running hours. If the load of the diesel generator is 50% of the rated power, the fuel cost increases substantially compared to the current setup, since the efficiency improves. Table 2 shows the estimated fuel consumption and cost for twenty-four hours run time on three steps of load for improved alternative. The current diesel fuel distributor is EcoPar, a company located in Gothenburg. The fuel price is 15.17 SEK/litre if the order exceeds 1,000 litres (Employee at EcoPar, personal communication, April 3, 2018).

Table 2. Estimated fuel consumption and cost during twenty-four hours for Improved alternative

Improved alternative estimated fuel consumption and cost [SEK] for 24 hours	At 50% load	At 75% load	At 100% load
Consumed fuel [Litre]	600	912	1,152
Fuel cost [SEK]	9,102	13,835	17,476

Figure 11 shows the estimated fuel cost for twenty-four hours on different loads for the current diesel generator.

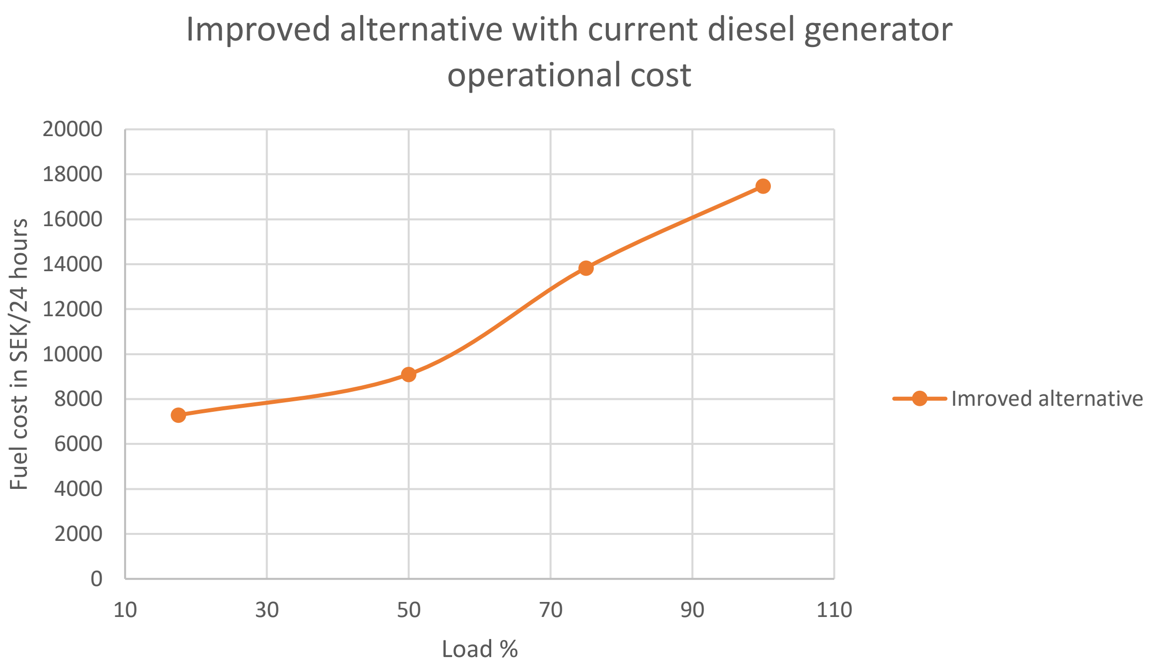

Figure 11. Fuel cost on different loads for the current diesel generator with Improved alternative.

3. Maintenance

The test runs of the diesel generator represent the largest part of the fuel consumption. Maintenance of the engine is included in the diesel generator's maintenance cost and mainly consists of changing filters and lubricating oil one time per year. Test runs of the diesel generator are also a part of the yearly maintenance cost. The estimated fuel cost for all test runs in a year is shown in table 3. The minimal test load is at least 50% of rated power (Dalsøren Tufte, 2014, p.66). Table 3 shows the current load at 19% compared with the desired test load at 50%. The fuel price is 15.17 SEK/litre according to EcoPar (Employee at EcoPar, personal communication, April 3, 2018) and the recommended test time is at least one hour every month according to King and Knight (2003).

Table 3. Estimated fuel cost for test run on recommended time with improved alternative.

Yearly consumed fuel and fuel cost for test runs, one hour every month	At 19% Load	At 50% Load
Consumed fuel [Litre]	240	300
Fuel cost [SEK]	3,640	4,551

5.2.2 Alternatives which requires changing the back-up diesel generator

1. installation/rebuilding

Since there is no need to change the diesel generator in the improved alternative, this alternative will not be included in this chapter. However, replacing the current diesel generator is necessary if the existing, Skeleton crew or total power alternative is chosen. The three alternatives have different installation costs. Buying and installing a new diesel generator and rebuilding of the electrical system are examples of expensive installation costs. Some funds can be recovered by selling the old diesel generator. In the existing back-up power alternative, rebuilding of the electrical system is not necessary. Investment and installation of the new diesel generator is the most expensive part. The Skeleton crew alternative needs a large rebuilding as a new PLC is required for the control of consumers. It is probably the most expensive alternative due to installation costs. In the total power alternative, the diesel generator and its installation will represent a large part of the investment cost. This alternative does not require an extensive rebuilding of the electrical system. Table 4 shows the investment in a new diesel generator for the existing, skeleton crew and total power alternative. The price is only for the diesel generator set (Mats Hermansson at Coromatic, personal communication, April 26, 2018).

Table 4. Diesel generator investment cost for the existing, skeleton crew or total power alternative.

Investment cost for the different alternatives (excluding VAT)	Existing alternative	Skeleton crew alternative	Total power alternative
Diesel generator (excluding installation) [SEK]	100,000	300,000	650,000

2. Operational

The fuel cost for the diesel generator is small for these alternatives due to the low running hours. The different alternatives consume different amount of fuel when they are running. Table 5 shows the estimated fuel consumption for the existing, skeleton crew and total power alternatives and the fuel cost for twenty-four hours run time on three steps of load. The fuel price is 15.17 SEK/litre according to EcoPar (Employee at EcoPar, personal communication, April 3, 2018).

Table 5. Estimated fuel consumption and fuel cost for twenty-four hours for the existing, skeleton crew and total power alternatives at three steps of load.

Estimated fuel consumption and cost for 24 hours	Existing alternative	Skeleton crew alternative	Total power alternative
At 50% load [Litre (SEK)]	204 (3,095)	802 (12,166)	1,512 (22,937)
At 75% load [Litre (SEK)]	288 (4,369)	1159 (17,585)	2,268 (34,406)
At 100% load [Litre (SEK)]	384 (5,825)	1514 (22,973)	3,072 (46,602)

Figure 12 illustrates a comparison of fuel cost depending on load between the existing, skeleton crew and total power alternatives.

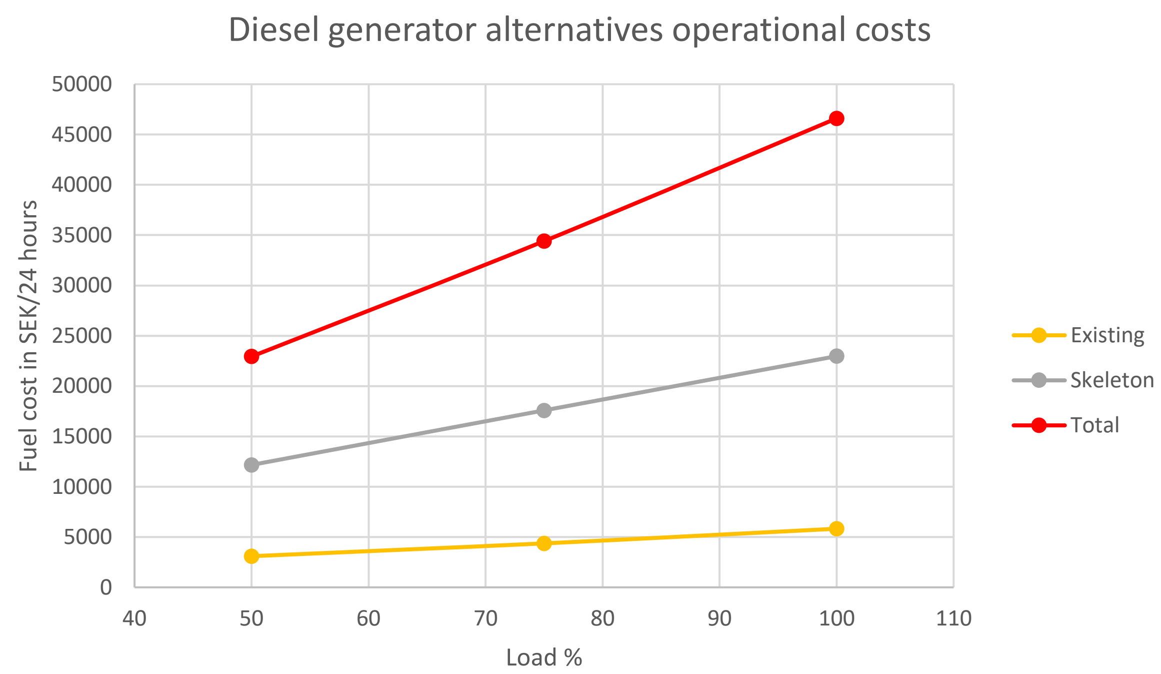

Figure 12. Operational costs for different diesel generator alternatives.

3. Maintenance

Maintenance of the generator is included in the diesel generator cost. The maintenance cost for a diesel generator mainly consists of changing filters and lubricating oil one time per year. The yearly maintenance cost includes the test runs of the generator. The estimated fuel consumption and fuel cost for all test runs in a year is shown in table 6. The fuel price is 15.17 SEK/litre according to EcoPar (Employee at EcoPar, personal communication, April 3, 2018) and according to King and Knight (2003) the recommended test time is at least one hour every month. The minimal test load is at least 50% of rated power (Dalsøren Tufte, 2014, p.66).

Table 6. Estimated fuel consumption and fuel cost for the existing, skeleton crew and total power alternatives for test run on recommended time.

Yearly fuel consumption and fuel cost for test runs, one hour every month at 50% load	Existing alternative	Skeleton crew alternative	Total power alternative
Consumed fuel [Litre]	102	401	756
Fuel cost [SEK]	1,547	6,083	11,469

5.2.3 Fuel cell, electrolyser and solar panels

In the alternatives with a fuel cell, it is necessary to change the UPS. The new UPS must be larger than the current one in order to supply all equipment that needs to be backed-up in the different alternatives.

1. Installation/rebuilding

For a fuel cell system, PowerCell have a container concept that can be placed outside the building. The hydrogen storage tanks are not included in the container solution and will need to be placed separately. The estimated price for a fuel cell is approximately $70 USD/kW (Alfredsson and Swenson, 2017, p. 20), which corresponds to approximately 590 SEK (see appendix. C).

An electrolyser from Green Hydrogen in Denmark with a power consumption of 5.5 kW will cost 36,700 EUR (381,096 SEK, see appendix. C) excluding VAT and installation. Green Hydrogen also provide a larger electrolyser model, which can produce hydrogen dynamically between 15-100%. The electrolyser has a maximum power consumption of 270 kW at 100% including auxiliary system. The container solution costs 430,000 EUR (4,465,163 SEK, see appendix. C) excluding VAT and installation. (Niels-Arne Baden at Green Hydrogen, personal communication, April 9, 2018)

According to Norden Solar (2018), a solar panel investment on the entire roof area costs approximately 13,500,000 SEK excluding VAT and installation material such as inverters. With a roof area of 12,500 m^2 the total installed solar panel power is 1.8 MW (Norden Solar, 2018). Table 7 compiles the equipment's total investment cost in the different back-up power alternatives. The fuel cell price is based on $70 USD/kW (Alfredsson and Swenson, 2017, p. 20). The UPS price is provided by Dick Håkansson at Coromatic (personal communication, April 26, 2018). The price for electrolysers is obtained from Niels-Arne Baden at Green Hydrogen (personal communication, April 9, 2018) and the solar panel price from Norden solar (2018).

Table 7. Summary of the investment cost for the equipment in the different back-up power alternatives.

Investment cost [SEK] for the different alternatives (excluding VAT)	Existing alternative	Improved alternative	Skeleton crew alternative	Total power alternative
Fuel cell (excluding auxiliary system)	43,300	65,700	183,100	407,300
UPS including batteries (30-minute run time)	500,000	750,000	1,750,00	3,000,000
Electrolyser	381,096		4,465,163	
Solar panels and installation materials	13,500,000			

Riis et al. (2006, p. 21) concludes in their report that the estimated price for a hydrogen storage tank is 500 – 600 USD/kg hydrogen (4,207 – 5,048 SEK, see appendix. C). According to Riis et al. (2006), a gas tank with a volume of 145 litres and a pressure of 350 bar contains 3 kg of hydrogen. Table 8 show the calculated hydrogen storage tank capacity and investment cost in the different alternatives.

Table 8. Hydrogen storage tank capacity in the different alternatives with 350 bar.

Hydrogen storage tank 350 bar	Existing alternative	Improved alternative	Skeleton crew alternative	Total power alternative
Estimated hydrogen gas tank size	4.9 m^3	14.1 m^3	21.1 m^3	49.2 m^3
Estimated hydrogen gas tank price [SEK]	429,000-515,000	1,224,000-1,469,000	1,834,000-2,201,000	4,282,000-5,139,000

Table 9 shows the investment cost for a fuel cell and a UPS in all alternatives, assuming the highest price for a storage tank, combined with an electrolyser and solar panels.

Table 9. Summary of the investment cost for the fuel cell alternatives**.**

Summarised investment cost [SEK] for the different alternatives (excluding VAT)	Existing alternative	Improved alternative	Skeleton crew alternative	Total power alternative
Fuel cell and UPS	1,058,300	2,284,700	4,134,100	8,546,300
Including electrolyser and solar panels	14,960,165	16,186,565	22,099,263	26,511,463

2. Operational

According to PowerCell (Employee at PowerCell, personal communication, March 5, 2018), one kilogram of hydrogen contains 33 kWh of energy, and their fuel cells have an efficiency of 50%. Table 9 shows the calculated hydrogen fuel consumption in twenty-four hours in the different back-up power alternatives. The fuel price for hydrogen in the comparison is assumed to be 80 SEK/kg based on the hydrogen price at hydrogen fuel stations for cars (Ny Teknik, 2015).

Table 10. Estimated fuel consumption and cost [SEK] for twenty-four hours.

Fuel consumption and cost for 24 hours	Existing alternative	Improved alternative	Skeleton crew alternative	Total power alternative
At 50% load [kg (SEK)]	51 (4,080)	145 (11,600)	218 (17,440)	509 (40,720)
At 75% load [kg (SEK)]	76 (6,080)	218 (17,440)	327 (26,160)	764 (61,120)
At 100% load [kg (SEK)]	102 (8,160)	291 (23,280)	436 (34,880)	1018 (81,440)

Figure 13 shows a comparison of operational cost for the fuel cell alternatives with hydrogen gas from a distributor.

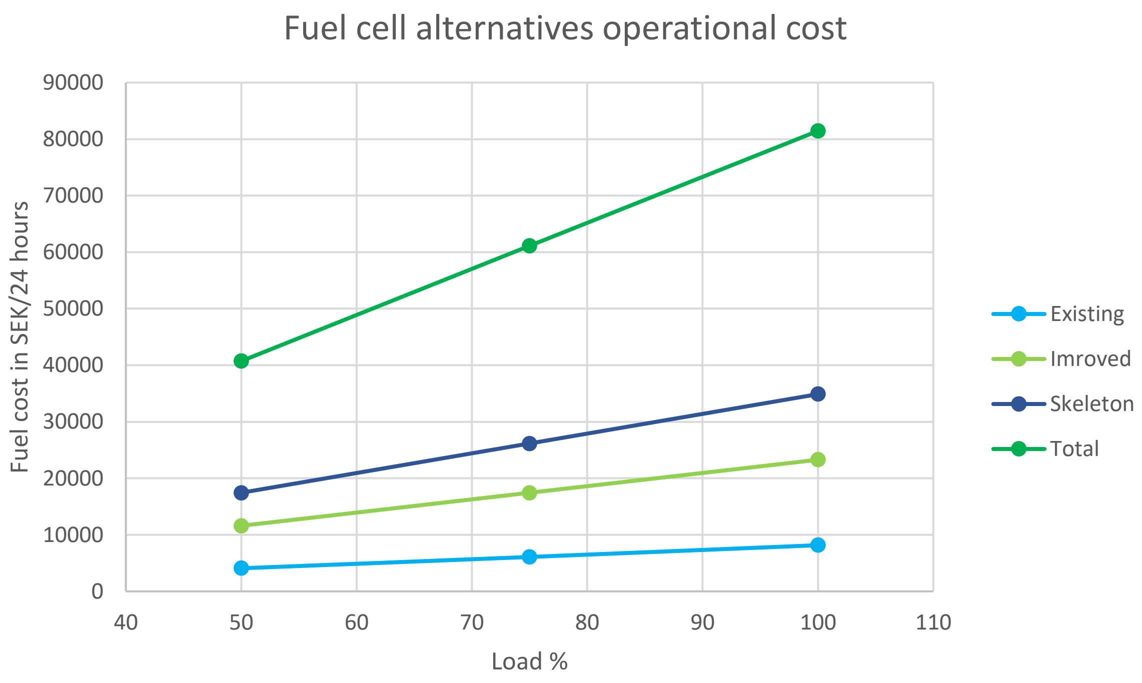

Figure 13. Operational costs for different fuel cell alternatives.

With a fuel cell alternative combined with an electrolyser and solar panels, the fuel cost for hydrogen is zero. The main cost is the equipment, such as the electrolyser, hydrogen storage tank, fuel cell and auxiliary systems.

When the hydrogen storage tank is full it is possible to sell excess energy produced with solar panels, although most companies have considerable limitations in this aspect. The maximum input power is limited, and it is not possible to sell more energy than what is used in total during one year (Vattenfall, 2018). Today, only one electricity provider in Sweden is willing to buy larger amounts of electricity without the previously mentioned limitations (Bixia, 2018).

3. Maintenance

According to PowerCell (Employee at PowerCell, personal communication, March 5, 2018), the fuel cell does not require maintenance. However, the auxiliary system may need some maintenance. The fans and circulation pumps require maintenance or a change of unit after achieved operating hours.

5.3 Environmental impacts

The environmental impact is presented in this chapter, and the different back-up sources differ from each other due to the diverse operational and manufacturing processes.

5.3.1 Diesel generator environmental impact

1. Operational/maintenance

The main environmental impact of a diesel generator comes from the exhaust gases. The exhaust gases contain CO_2 and NO_X (Shah et al., 2006). NO_X has a negative impact of the environment and contributes to the eutrophication of land and sea (Jaworski, Howarth, and Hetling, 1997). CO_2 is a greenhouse gas and thus affects global warming (Schmithüsen et al., 2015).

According to the website Ecoscore (2018), 1 litre of diesel weighs 835 grams and contains 720 grams of carbon. When combusting this carbon, 1,920 grams of oxygen is required, and the sum is 2,640 grams of CO_2/litre diesel. Table 10 shows how many kilograms of CO_2 the different diesel generator alternatives emit during 10 years of test running at Lindex DC.

Table 11. The diesel generator alternatives fuel consumption and CO_2 emissions during 10 years of operation.

Diesel generator operation	Existing alternative	Improved alternative	Skeleton crew alternative	Total power alternative
Diesel consumption 10 years of operation [Litre]	1,020	3,000	4,010	7,560
CO_2 emissions during 10 years of operation [kg]	2,693	7,920	10,586	19,958

According to EcoPar, their diesel fuel reduces the NO_X content in the exhaust gas by 50% and particles by 25%, compared with standard diesel. Their diesel fuel is made from 100% natural gas which means that the environmental impact from NO_X will be reduced compared with exhaust gases from traditional diesel fuel. (Employee at EcoPar, personal communication, April 3, 2018)

2. Manufacturing

The manufacturing of an ICE has been perfected during several decenniums. This, combined with the fact that the main materials are cheap and easily obtained (steel and copper), has resulted in a relatively low environmental impact from this process, especially compared with the impact of operation (Mori, Jensterle, Mržljak, and Drobnič, 2014). According to Mori et al. (2014), the energy needed to manufacture an ICE, with a power output of 6 kW, adds up to 2,300 kWh.

5.3.2 Fuel cell, electrolyser and solar panels environmental impact

1. Operational/maintenance

Since there is no maintenance required for a fuel cell (Employee at PowerCell, personal communication, March 5, 2018) the environmental impact of operation/maintenance will be reduced. However, when using a fuel cell and/or an electrolyser, the pollutant from operation is hydrogen gas that might leak from the system and enter the atmosphere. Research has shown that hydrogen can have secondary effects on the ozone layer as some hydrogen may react with the ozone and together form water (Barnes et al., 2003).

The environmental impact of using solar panels usually consists of local effects for plants and animals that might lose part of their habitat to a solar power plant. Some larger solar power plants might use water for cooling turbine generators and cleaning solar panels which will consume large amounts of water. (U.S. energy information administration, 2017)

2. Manufacturing

The manufacturing phase represents the main part of the environmental impact in the hydrogen fuel cell systems life cycle. When producing electricity, if hydrogen produced from a renewable energy source is used, the hydrogen fuel cell is almost completely environmentally neutral (Mori et al. 2014). During their research, Mori et al. (2014, p. 1815) used a fuel cell and an electrolyser with a capability to produce a total of 9.84×10^5 kWh in ten years. The fuel cell had an output power of 6 kW. When considering the systems life cycle during ten years of operation, as shown in figure 14, the manufacturing process of the components (electrolyser, storage tank for hydrogen, and fuel cell) represent 97% of the total global warming impact, while the transportation and the 10 years of operation represent only 2% and 1%, respectively. The manufacturing process of the electrolyser has the largest impact, as it alone represents 76% of the total global warming impact of the whole fuel cell system (Mori et al. 2014).

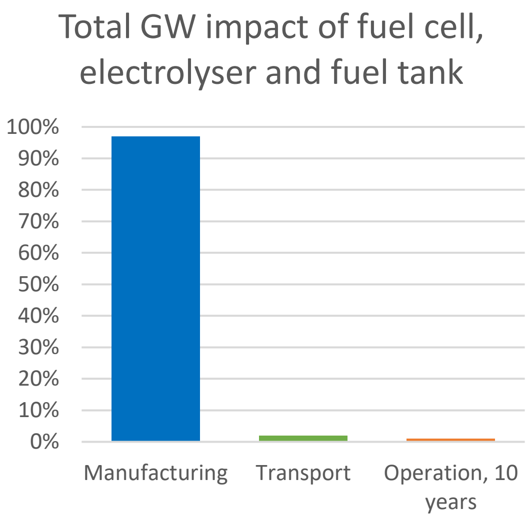

Figure 14. Comparison of GW Impact of a fuel cell, electrolyser and hydrogen storage tank in percentage.

Solar cells made from both mono- and poly-crystalline silicone have been shown to have a relatively small environmental impact during the manufacturing process. When manufacturing mono-crystalline solar cells, only the texturing-process differs compared to poly-crystalline. Other parts of the manufacturing are usually the same for both types and only differ in the equipment used during the process. (Schmidt, Hottenroth, Schottler, Fetzer, and Schlüter, 2012, p. 138)

According to Schmidt et al. (2012), the largest part of the climate impact comes from waste treatment and energy used during the manufacturing process. Their investigations show that direct emissions of greenhouse gases from this process represents 6% of the total effect in climate change, while the energy consumption represents 75%.

When manufacturing solar panels, Schmidt et al. (2012) conclude that the energy needed is 6250 kWh/m2 for poly-crystalline silicone while the capacity for the same kind of panels is 0.13 kW/m2 of generated power.

5.4 Comparison of Diesel generator and Fuel cell alternatives

5.4.1 Comparison of fuel economy

In figure 15, the fuel economy for the current diesel generator is better at high loads than the improved fuel cell alternative running on hydrogen acquired from a distributor. The fuel price for hydrogen in the comparison is 80 SEK/kg according to Ny Teknik (2015). The fuel price is 15.17 SEK/litre according to EcoPar (Employee at EcoPar, personal communication, April 3, 2018).

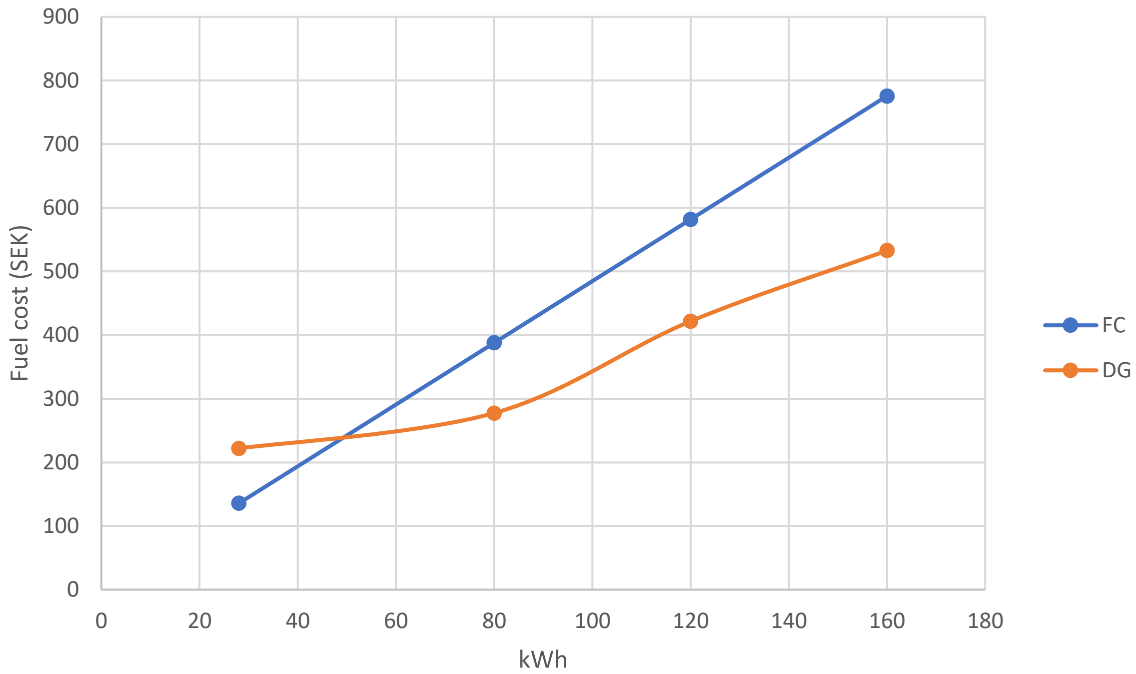

Figure 15. Comparison of fuel cost and kWh between a fuel cell (FC) and a diesel generator (DG).

Figure 16 shows a comparison between the alternatives with a diesel generator and a fuel cell with hydrogen from a distributor. The fuel price for hydrogen in the comparison is 80 SEK/kg according to Ny Teknik (2015). The fuel price is 15.17 SEK/litre according to EcoPar (Employee at EcoPar, personal communication, April 3, 2018). *Skeleton DG* (grey line) and *Improved FC* (light green line) have a similar cost/twenty-four hours, resulting in *Skeleton DG* being covered up by *Improved FC* in figure 16.

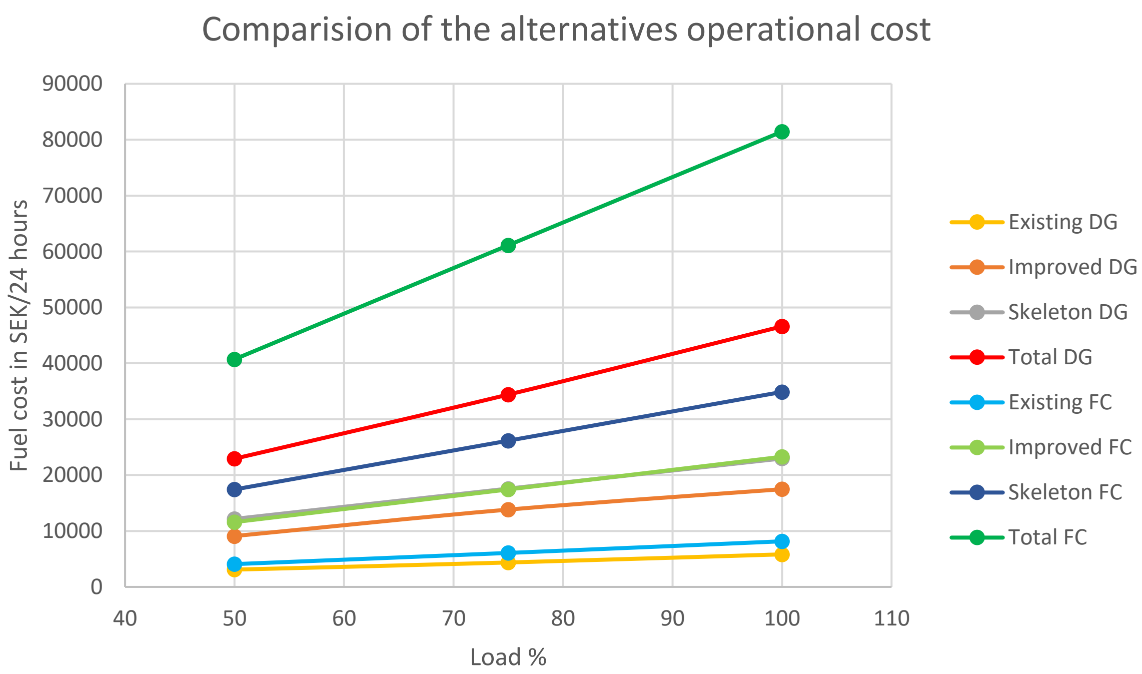

Figure 16. Comparison of the operational costs for the different alternatives.

5.4.2 Comparison of Manufacturing a fuel cell and an ICE

When comparing the environmental impact of an ICE running on a non-renewable energy source with a fuel cell, the manufacturing process represents a smaller part of the total environmental impact after 10 years of operation. Instead, the combustion of carbohydrates has the largest impact.

Figure 17 illustrates the difference between the kWh needed to manufacture solar panels, an electrolyser and a fuel cell, and an ICE. The solar panels, fuel cell and ICE all have the same power output of 6 kW. Manufacturing solar panels costs 288.000 kWh, an electrolyser and a fuel cell cost 676.200 kWh, whereas an ICE only costs 2,300 kWh. FC, electrolyser and ICE data from Mori et al. (2014) and solar panel data from Schmidt et al. (2012).

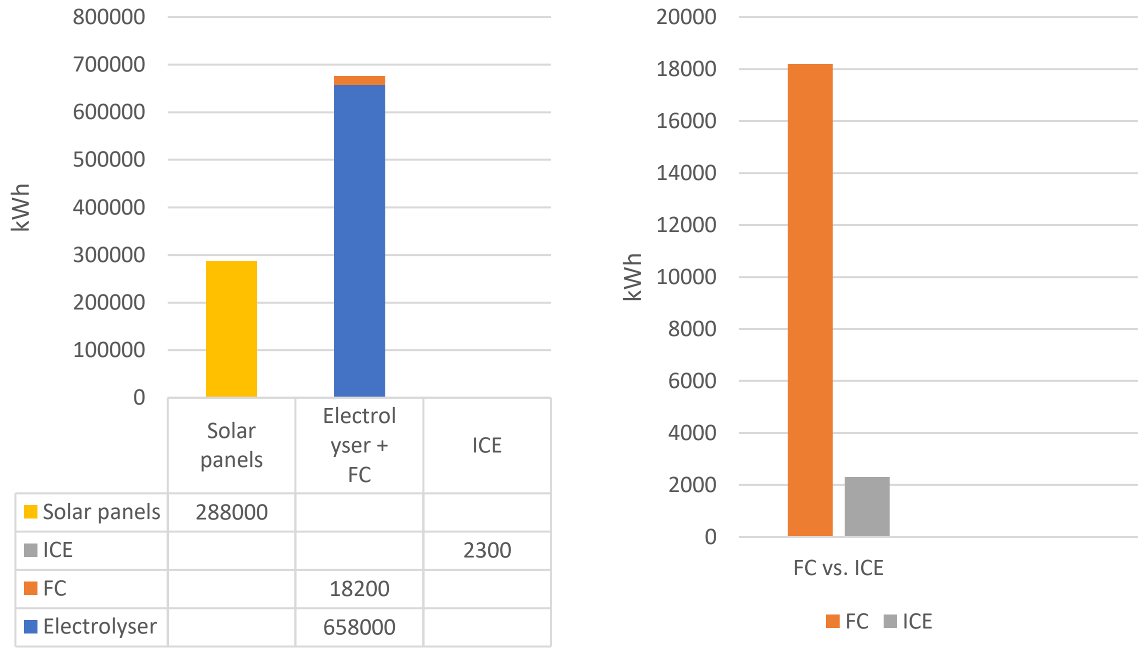

Figure 17. Solar panels, electrolyser, FC, and ICE energy usage during manufacturing.

Mori et. Al. (2014) concludes that 0.357 CO_2 eq. per 1 kWh is produced when using a fuel cell, while 1,190 CO_2 eq. per 1 kWh is produced when using an ICE, although this is based on a system that produces 9.84×10^5 kWh in 10 years.

5.4.3 Comparison of back-up alternatives

A comparison between the different alternatives is presented in table 11. The scale goes between 1 – 5, where 5 is the best grade. For example; if the alternative is expensive, the economical grade will be a lower number, and if the need for maintenance is high, the maintenance grade will be a lower number. All grades are summed up and presented in the total grade column.

Table 12. Comparison between different back-up power alternatives

Comparison alternatives	Availability	Economy	Environmental friendly	Maintenance need	Total grade
Existing power alternative DG	4	5	2	3	14
Improved power alternative DG	4	4	2	3	13
Skeleton power alternative DG	4	1	1	3	9
Total power alternative DG	4	3	1	3	11
Existing power alternative FC	5	4	4	5	18
Improved power alternative FC	5	3	4	5	17
Skeleton power alternative FC	5	1	4	5	15
Total power alternative FC	5	1	4	5	15
Existing power alternative FC, electrolyser & solar panels	5	4	4	4	17
Improved power alternative FC, electrolyser & solar panels	5	4	4	4	17
Skeleton power alternative FC, electrolyser & solar panels	5	1	4	4	14
Total power alternative FC, electrolyser & solar panels	5	2	4	4	15

6 Discussion

The results of our investigation have proven to be quite complex. All the different variations of back-up power investigated in this case study have their own advantages in different areas and situations. Some have shown to be a large and expensive investment to start with, although depending on the life span of the system they may decrease in cost over a longer period of time. For the environmental part, the results are quite similar for all alternatives. One alternative has shown to have a bigger environmental impact at the manufacturing stage, while the electricity production itself had little or none environmental impact, while another alternative has shown the opposite, a small impact from manufacturing but large impact when producing power. This makes the comparison between the different alternatives difficult, but nonetheless interesting.

6.1 Result discussion

6.1.1 Availability

Comparing the availability of a diesel generator and a fuel cell has proved to be a difficult task, mainly because information about the availability of a fuel cell is scarce. Although the result shows somewhat of an advantage for the fuel cell, since it demands little to zero maintenance, it should be noted that a diesel generators availability, when used for back-up power, is still satisfactory. This means that a potential decision to change from a diesel generator to a fuel cell as a back-up power alternative should not be made on the availability aspect alone.

6.1.2 Economy

Existing alterative: From an economical point of view, this alternative is a beneficial choice. The existing alternative does not require rebuilding of the electrical system, but the problem with the lack of desired equipment during a main grid failure, would remain unsolved.

With a fuel cell alternative, the current UPS set-up can be kept if Lindex DC reduces the back-up energy consumption, for example by replacing one of the air conditioning units with a smaller one. Keeping the current UPS setup would be highly beneficial from an economical perspective. In the comparison between the power alternatives, the existing alternative combined with a fuel cell received the highest grade.

Improved alterative: With this alternative, the only alteration needed is rebuilding of the electrical system and connection of additional equipment in order to raise the load on the current diesel generator and gain extra functions during a power failure. According to the investigation performed in this study, this alternative is one of the cheaper alternatives, and it also improves the total AEE aspect.

When combining this alternative with a fuel cell, a high grade of the AEE aspect is achieved. However, this alternative is based on what the current diesel generator needs to reach 50% load. With a fuel cell, the equipment can be reduced to only connect the critical and desired equipment. This will result in a substantially lower load, and a smaller UPS and fuel cell can be selected which would make this alternative more economically beneficial.

Skeleton crew alternative: This is a large rebuilding project of the electrical system and thus the installation cost is high for this alternative. The skeleton crew alternative has shown to be the least preferable alternative in the economical aspect. It is likely the most expensive alternative because of the extensive alterations needed. It requires a new, larger diesel generator as well as comprehensive alterations to the electrical system and installation of a PLC to prevent large consumers, such as cranes, from starting at the same time.

This alternative is unreasonable due to the large rebuilding cost compared with the few running hours. This alternative combined with a fuel cell requires a new UPS and a large storage tank, which results in an even higher investment cost, on top of the rebuilding cost.

Total power alternative: The installation cost for rebuilding is less than the skeleton crew alternative and the improved alternative since there is no need to implement any PLC system or connect individual equipment. However, the diesel generator itself is the most expensive one compared with the other diesel generators, and because of its size, it is also the most expensive one to run.

The total power alternative with a fuel cell is the most expensive alternative. This alternative has an expensive tank, fuel cell and UPS making it irrational due to the large investment cost contra the few running hours. The operational cost for this alternative, if the hydrogen gas is bought from a distributor, has proven to be the most expensive one.

Comparison between diesel generator and fuel cell: With a diesel generator, the maintenance cost will be greater than the maintenance for a fuel cell system, mainly due to the test runs of the diesel generator. A fuel cell does not require any test runs or maintenance and is therefore hard to compete with in this area. However, a fuel cell is considerably more expensive since a storage tank and a new UPS is required in order for the fuel cell alternative to function.

Solar panels: The number of solar panels in the alternative produces more electricity during one year than what Lindex DC consumes, which means that Lindex will have to sell excess electricity in the summer. In the winter, when the solar panels fail to produce enough electricity, Lindex have to buy the electricity back. The return on the investment of solar panels depends on the price for the produced electricity. If Lindex sell all the solar energy, it will take 10 years to repay the investment at an electricity price of 0.72 SEK/kWh.

The alternatives presented in the result all have the maximum number of solar panels that are able to fit on the roof. Another alternative could be to invest in solar panels that just cover the power consumption of the electrolyser. This would result in a substantially smaller investment cost. One reason for covering the entire roof with solar panels is that the investment is expected to be repaid in the future.

6.1.3 Environmental impact

The environmental impact of a diesel generator is mainly derived from operation, while the impact from the manufacturing of a diesel generator is relatively small. A fuel cell has proven to be the opposite; high environmental impact from manufacturing and basically zero impact from operation. Even if this alternative is considerably more expensive, the environmental impact is reduced substantially. If the fuel cell were to be manufactured with electricity from a renewable energy source, the environmental impact could be reduced even further.

In the research conducted by Mori et al. (2014), the system produced 9.84×10^5 kWh in 10 years. If Lindex uses a fuel cell as a back-up generator they will not produce this amount, which means that the CO_2 equivalent per 1 kWh, in the Lindex DC case study, will be considerably higher for the fuel cell since all of the CO_2 comes from the manufacturing process. However, compared with the diesel generator alternative, the total environmental impact will decrease over time, since a fuel cell does not require any test runs.

Both the energy produced, and the energy needed to manufacture an electrolyser and a fuel cell is expected to improve through different EU research programs (Mori et al., 2014, p. 1821), which means that the potential to lower this system's total environmental impact looks promising. The diesel generators environmental impact, however, mainly comes from burning carbohydrates, and will thus likely not be lowered to the same extent.

The impact of solar panels on the environment usually comes from large solar power plants being built in an area where plants and animals habitat is affected, and the large amount of water used for cooling and cleaning. In this case study, the solar panels would not use any water for cooling and would be installed on a roof. Thus, animals and plants would not be affected in any substantial way. Instead, an investment in solar panels seems to be a preferable choice from an environmental aspect.

6.1.4 Improving the AEE of the current back-up power source

The actual load on Lindex DC's diesel generator is 19%, which is below the critical level. According to efficiency calculations on different loads on the diesel generator, the efficiency would be higher with more load. With a generator load of 50% or more, the efficiency would rise from the current 17% to 31% efficiency. The total AEE would improve at the same time, since the amount of fuel would not increase significantly, even if more load is added to the generator. According to Dalsøren Tufte (2014) the amount of soot, residue and unburned fuel is also reduced with a higher load. The total fuel cost for the monthly test runs of the generator rises with less than 1,000 SEK per year which is negligible considering that the total life span of the generator is expected to increase with a heavier load.

6.1.5 Alternatives for an uninterrupted operation

To keep an uninterrupted operation during a main grid failure, Lindex need to change the current back-up generator to a larger one. If a skeleton crew setup is desired, a PLC is required in order to run one large consumers at a time. The total power alternative is considerably easier to install since there is no need for an extensive rebuilding of the electrical system.

If there is a power failure after working hours, when lighting, robots and cranes are turned off, a diesel generator would be running with almost no load. This could not only damage the generator, but is also unnecessarily expensive, due to the low efficiency of the generator at low load. With a fuel cell, this problem would be avoided, since the efficiency of the fuel cell appears to be higher with lower load (Alfredsson and Swenson, 2017, p. 20). From this point of view, a fuel cell is more suitable as a back-up power source for maintaining uninterrupted operation. However, it is unreasonably expensive due to the price of the UPS and hydrogen storage tank.

6.1.6 AEE aspect of fuel cell, electrolyser and solar panels.

Our investigation has shown that a fuel cell combined with an electrolyser and solar panels is an exceptional choice from a purely environmental perspective. It is possible to produce hydrogen gas on site with nothing but solar energy, and subsequently removing the dependency on a fuel provider all together. Although it is a large economic investment, in the long run it aids development towards lowering Lindex DC's environmental impact substantially.

The economical aspect has proven to be more complex to analyse, due to the lack of available information about the selling of solar energy and the fluctuating energy market. If Lindex would decide to sell excess energy produced with the solar panels, it would be a significantly more interesting option, both from an economical and an environmental stand point. Since it also raises the total amount of renewable energy available on the market, this alternative will also contribute to a more environmentally neutral society.

According to Vattenfall, a large electricity provider in Gothenburg, a company is able to sell some of the energy produced with solar panels and become a "micro producer". However, there are a few big flaws in their current agreement. For example, the maximum input power from a company cannot exceed 43.5 kW, and a company cannot sell more energy than what they use in total during a whole year. This means that the purpose of the agreement today is to enable a company to reduce the size of their current electricity bill, and not to allow a company to earn money by producing electricity using solar panels (Vattenfall, 2018). This the case for almost every electricity provider in Sweden today (Solkollen, 2018), although there is one known electricity provider that is willing to buy larger amounts of electricity from companies planning to become micro producers. Their agreements only limitation is that the company need to produce more electricity valued at more than 100 SEK in one month in order to receive payment (Bixia, 2018).

6.1.7 Load types to consider when dimensioning a back-up system

The reactive power connected to the current diesel generator at Lindex DC was measured to 4.2 kVAr, while the total reactive power in the existing back-up power grid at Lindex DC is 13 kVAr according to this study. If Lindex decides to add load on the current diesel generator, the ratio of load types may change. If they connect the lights in the building directly to the back-up generator, the resistive load will constitute a large part of the generator load as it is today. The reactive power is not a problem in the alternatives, but it results in heat losses in the cables.

Sensitive equipment that produces a non-linear load exists at Lindex DC, but is not a large part of the generator load. According to Curtis (2007, pp. 54-55) a back-up diesel generator is not a sufficiently high-quality power source to meet the demands of sensitive equipment.

However, if the equipment is connected via the UPS these problems can be avoided. Equipment that makes up a pure resistive and reactive load can be connected directly to the diesel generator. When using a fuel cell for back-up power this would not constitute a problem at all, since all equipment in the back-up power system would be connected to the UPS.

6.2 Method discussion

The method used in this investigation has proven to be more useful than originally expected. The book written by Robert K. Yin, "*Case study research, design and methods*", provided valuable methods for collecting and analyzing data, and some useful tips for compiling the result and writing the report. The book contained many examples of previously performed case studies, and even though these were mainly sociological case studies, it was still possible to apply the same methods to our research.

In this case study some estimations were done. A more robust method would have been to make real measurements and log the values over a period of time. Measuring the power consumption for each consumer was not possible since it is problematic to connect the measuring equipment, and the equipment needed was not easily available. However, our estimations can be considered good enough to receive reliable results on which calculations can be made.

The pricing for equipment in the report is only from one distributor/manufacturer. No comparison has been made between manufacturers to investigate whether the price differs between them. This might make the rates used in this study one-sided in some instances. However, the costs are not expected to be higher than what is presented in the report.

6.3 Ethical aspects

Solar panel manufacturing is considered to have few ethical problems. Dross (2012) made this conclusion based on that silicone is a non-toxic material. However, one would need to consider additional aspects before coming to a conclusion on a topic this extensive. Other aspects might be; how was the electricity produced? In which country was it produced? What were the working conditions for the people who work with manufacturing?

In this investigation the main focus has been to compare the different alternatives environmental impact by investigating the energy used during manufacturing and emissions during operation. However, there are many more factors that have an equally large impact on the environment. Those factors could consist of eutrophication, acidification or abiotic depletion.

7 Conclusions

Based on the data received from Lindex and previously performed research, the future for fuel cells combined with a UPS as a back-up power alternative looks bright. A fuel cell large enough to cover the existing consumers connected to the back-up power seems to be the best alternative from an AEE aspect. Since there is no need to invest in a larger UPS, this is the cheapest and easiest way to take a substantial step towards becoming environmentally neutral. Today, the price of a fuel cell is relatively high, but as fuel cells becomes more common in other, larger industries, such as cars and boats, fuel cells would be manufactured at a greater extent and the price would decline, rendering it even more attractive as a back-up power source.

If combined with an electrolyser and solar panels, Lindex DC would be able to lower their climate impact to levels that few other companies are even close to. This is something that is not only positive for the society as a whole, but it can also work as a way to strengthen their brand and push the industry to take more responsibility for the environment.

7.1 Future investigations

With the amount of energy used and the environmental impact from manufacturing a fuel cell, and most of all an electrolyser, the system will not come to full use, since the electrolyser only produces hydrogen when the storage tank is anything less than full. Due to the low running hours on the equipment, it is probable to assume that the electrolyser would produce hydrogen once or twice in a decade, which would be a waste of energy and resources. In order to get the most out of the electrolyser, one would need to find a secondary usage for it at Lindex DC. One interesting option would be to investigate if it would be possible and profitable for Lindex to use hydrogen-fuel-cell cars as their company vehicles and produce their own fuel on site. Depending on the size of the electrolyser, it may also be possible to sell hydrogen to employees or any other person who has a hydrogen-fuel-cell car. This way Lindex would get a larger capital return on their investment and reduce their environmental foot print even further.

7.2 Recommendations to Lindex

The main problems that Lindex has today include an oversized diesel generator and some crucial equipment that is currently not connected to the back-up diesel generator. The way the diesel generator is loaded today is not preferable and may result in a breakdown earlier than what could be expected if it had a heavier load. It would seem that the easiest way to solve both of these problems is to connect the desired equipment to the back-up power, resulting in both a heavier load on the diesel generator and access to the crucial equipment during a power failure.

In order to include smaller electrical consumers such as computers and printers intended for loading documents, it might be wiser to purchase a second, smaller UPS specifically for them. This would likely be much cheaper than connecting them to the main UPS located on the other side of Lindex DC.

Lindex should consider investigating the impact that a potential investment in solar panels and/or a fuel cell could have on their brand and its reputation in the industry and the society as a whole. This might be a valuable selling point as it may give them the opportunity to market their products as environmentally friendly.

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Appendix

Appendix. A

Appendix. B

In the table for consumers the power factor is assumed to be 0.8 for electric motors and 0.93 for fluorescent lights.

Consumers for Lindex DC main building	**Active power (kW)**	**Reactive power (kVAR)**
Fluorescent lights total	60	23.7
Air condition for servers (1)	30	11.3
Free cooling (1)	2.2	1.7
UPS for Servers (1)	2x20	-
LED armatures tot. (2)	30	11.8
Helpdesk (2)	2	-
Passage & Alarm system (2)	2	-
1 x Telescopic belt conveyors (2)	5.7	4.3
Lights office department (3)	10	-
Computers and printers (3)	8	-
1 x Cranes (total 4) (3)	64	48
1 x Robots (total 4) (3)	22	16.5
1 x Conveyors (total 4) (3)	400	80
Air compressor (3)	22	16.5
Truck charger	11	-
Total fan power	15	3
Existing back-up alternative (1)	72.2	13
Improved back-up Alternative (1,2)	108	27.3
Skeleton crew back-up alternative (1,2,3)	316	112
Total back-up alternative	682	345

Appendix. C Exchange rate (The Riksbank, 2018)

Exchange rate	SEK
$1 USD	8.4133
€1 EUR	10.3841