MASTER'S THESIS ACEX30

Managerial guidelines for microgrids in an urban context

Demonstration at Karlastaden

Master's Thesis in the Master's Programme Design and Construction Project Management

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Göteborg, Sweden 2023

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ABSTRACT

In 2050, the goal is to achieve net-zero emissions globally thus investments in renewable energy sources are speeding up to reach this goal. However, renewable energy sources face many challenges where the intermittency problem is one of the main concerns. Microgrids have the potential to reduce this problem and additionally increase the value streams for the real estate owner. The aim of the thesis is to conceptually design managerial guidelines for evaluating the financial feasibility of microgrids. The definition of microgrids in this thesis is an external grid connected low-voltage grid with energy production and storage technologies in a local urban area. In this thesis, PV cells, wind turbines, battery storage systems and hydrogen gas are evaluated technologies in the microgrid context. Project or business developers can decide how to evaluate important factors and the financial feasibility for a specific project through these guidelines. The guidelines and financial evaluation model are developed based on a qualitative strategy with abductive approach through a literature review and interview study. The guidelines are tested and applied at an urban project in Gothenburg, Sweden, called Karlastaden. Predictions on costs and revenue variants were analysed separately for this regional context. The levelized cost of energy (LCOE) estimations were based on gathered data and compared with Karlastaden's own initial evaluation. For electricity production, the revenue is dependent on sharing electricity freely without energy tax and electricity transmitting fees thus increasing the marginal revenue per kilowatt hour. Whereas electricity storage has three main revenue streams from peak shaving, spot price arbitrage and ancillary services. Prediction on revenue is based on compound annual growth rate (CAGR) for spot price, expected inflation rate and a logarithmic transformed linear equation specifically for ancillary services. The data is analysed by importing data into a MATLAB script and varying the compound annual growth rate in three different cases with varying discount rates. The net present value for every revenue variant is calculated, by reducing the discounted revenue with LCOE, to estimate the profitability of Karlastaden's microgrid potential. The test at Karlastaden implied that wind turbines, PV cells and battery storage with FCR-D down ancillary services are the most profitable revenue variants determined by highest net present value. However, all revenue variants in the MG are profitable investments except peak shaving and spot price arbitrage. To conclude, the managerial guidelines give the project or business developer tools for evaluating the important factors to consider when designing a profitable MG. Whereas, the test at Karlastaden can be viewed as a demonstration of how to use the guidelines.

Keywords: microgrid, investment, renewable energy, management, guidelines, property development

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Preface

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Notations

BES	Battery energy storage
CAGR	Compound annual growth rate
CapEx	Capital expenditures
DG	Decision gate
EI	The Swedish Energy Markets Inspectorate
ESS	Energy storage system
FCF	Free cash flow
HAWT	Horizontal-axis wind turbine
IKN	Exception to the grid monopoly (sv. Icke-koncessionspliktigt-nät)
IRR	Internal rate of return
LCOE	Levelized cost of energy
MG	Microgrid
NPV	Net present value
Opex	Operating expenses
PEM	Polymer electrolyte membrane
PV	Photovoltaic
RER	Renewable energy sources
ROI	Return on investment
SES	Solar energy systems
SvK	Svenska Kraftnät
VAWT	Vertical-axis wind turbine

1 Introduction

The twenty-first century is probably going to be the hottest in the Anthropocene (Birol, 2022). It is estimated that the average global temperature will rise 1.5 degree Celsius relative to pre-industrial era measures if no actions are taken (Birol, 2022). During this time the human society has seen tremendous technical and economical evolution, a transition from using simple tools to advanced technology. This technological shift has required accessible, cheap, and reliant energy. The energy requirements for the transition were made possible due to high energy dense fossil fuels from the ground in the form of coal, oil, and natural gas. However, at the expense of the environment since burning hydrocarbons emit greenhouse gases which speed up the rise in global temperature (Manabe & Wetherland, 1975). Today there is a massive surge in investments in renewables and clean energy technology to reduce the demand of fossil fuels which are needed to achieve net-zero emissions by 2050 (Birol, 2022).

The rapid increase in global energy demand is the main driver to increased emission of greenhouse gases impacting the environment negative (Fahad et al., 2018). During the past year of 2022, Europe and most of the industrialised world have experienced a global energy crisis with surging electricity prices. This is the result of supply shocks such as the war in Ukraine (Birol, 2022). In the nineteenth-seventies, a similar crisis struck the world with negative supply shocks initiated by the OPEC countries (Smil, 2017). The results of this crisis were more efficient cars and technological advancement in nuclear electricity production. Even batteries might have benefited from the same crisis when consumers tried to replace the petroleum (Li et al., 2018). To complete the shift towards sustainable electricity production without impacting the environment negative, renewable energy sources are becoming more ubiquitous in the world (Fahad et al., 2018).

1.1 Definition of microgrids

According to Eriksson and Gray (2017), sustainable electricity production is the major solution to lower greenhouse gas emissions. Sustainable electricity production can be generated from a renewable energy resource (RER), that is from sources which are naturally occurring and does not diminish when extracted (EERE, n.d.a.). Important RERs to reduce the impact on the environment are solar, wind, biomass, hydropower, and tidal power (Eriksson & Gray, 2017). In 2016 the total global capacity of installed RERs amounted to 921 GW with China, USA and Germany in the lead. Wind and solar power combined amounted to almost 800 GW and are therefore the main source of renewable energy. The IEA (2021) estimates that installed RERs will increase to 1800 GW in 2026 and dominate the global investments in installed effect. China, Europe and USA are still expected to lead this development and remain to be dominant in terms of installed effect. However, it is not only a positive development since RERs are vulnerable to external factors for producing energy, for example windy or sunny weather. This is referred to as the intermittency problem, which is where energy storage become important. Breeze (2019) states that in 2017 the total global capacity of installed energy storage amounted to 193 GW where pumped-storage hydropower represented 95 percent and battery storage only 1.5 percent. The IEA (2022) reports that in 2020 the total global installed storage capacity was only 160GW compared to Breeze (2019) estimation of 193GW in 2017. Albeit investments in energy storage are increasing (IEA, 2022; Breeze, 2019) and battery storage installation is estimated to grow by 4400 percent to reach net-zero carbon emission goals in a nine-year period from 2022 (IEA, 2022). When production and storage of energy are increasing, the distribution of energy and energy management systems also begins to become at least as important. In directive (EU) 2018/2002 issued by the European Parliament, member states in the European Union should encourage the development of the electricity sharing and increased energy efficiency. This directive implies that regulations for transmitting and distributing electricity should not be based on granting monopolies to system operators, rather it should be based on organising the market for electricity to become more flexible and to integrate more actors in additional and smaller grids.

Local and small grids with a combination of energy production and storage for a geographically bound area with low voltage are called microgrids (MG) (Fahad et al., 2018) and will likely increase in the future (Farzan et al.., 2014). In general, MGs can reduce transmission losses due to energy being stored and produced at the same area (Stadler et al., 2016), and distribute stored energy production surplus therefore solving the intermittency problem with RERs. A MG can be designed to operate off-grid or as grid-connected. Off-grid MGs purposes are to achieve self-sufficiency capability and thus are generally over dimensioned in terms of energy storage (Ferrario et al., 2021). Conversely, grid-connected MGs purposes are to increase the overall efficiency of energy usage from different sources (Ferrario et al., 2021). These MGs can trade electricity with the external grid thus having the potential to flatten out the peak load and create new value streams (Stadler et al., 2016). Adding new value streams are important since investments in RERs and energy storage can be capital intensive and thus require more incitements than only reducing the emission of greenhouse gases (Hatziargyriou et al., 2006). Since the definition of a MG vary dependent on the purpose, this thesis definition of a MG is presented in figure 1 as an off-grid or external-grid-connected low-voltage-grid with energy production and storage for a local area.

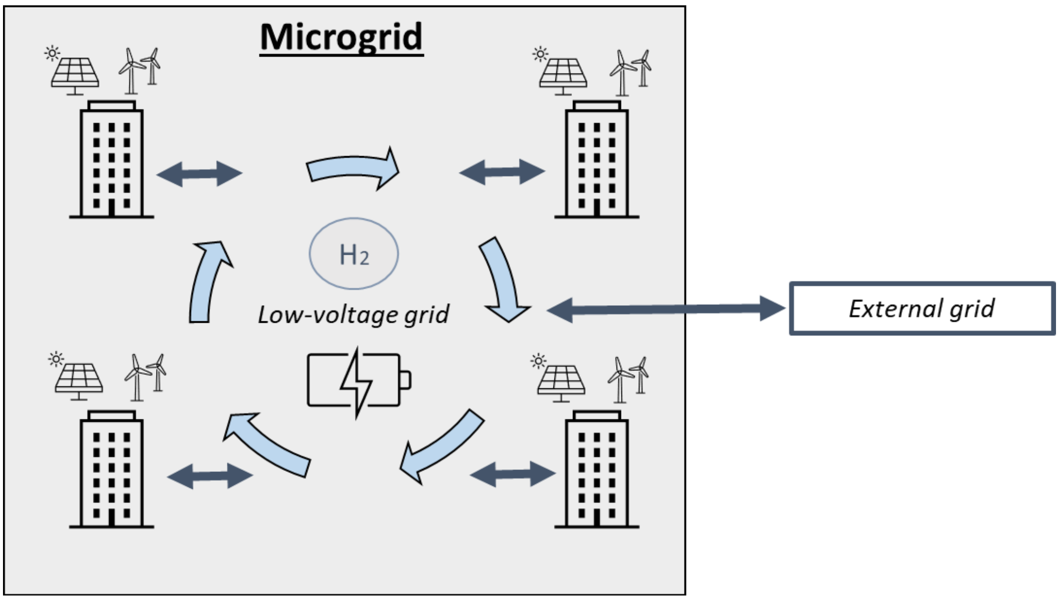


Figure 1. This thesis definition of MG in an urban context. Electricity production technologies on or besides buildings are connected to electricity storage by a low-voltage grid and to the external grid. The external grid is not part of the MG.

1.2 Introduction to Karlastaden

Gothenburg is the second largest city in Sweden in 2022 by population (Statistics Sweden, n.d.). Serneke in collaboration with Balder are developers for Karlastaden in Gothenburg. The project is approximately 275,000 square meter above the ground and is therefore according to Serneke one of the largest urban districts being developed in Sweden currently. It will include the tallest building in Scandinavia at 246 meters named Karlatornet. See figure 2 for illustration of the urban district. Serneke aspire to use innovative solutions and ideas in Karlastaden. They want to steer the area to become sustainable and create new business opportunities for the real estate owner. Serneke has already started the design of a MG and has initially considered components such as photovoltaic (PV) cells, wind turbines, batteries, and hydrogen gas to be included. To investigate the possibility of a sustainable MG, Serneke has identified three topics: finance, design, and technology to be the most important topics to address. They also want to the see the full potential of a widespread MG in Karlastaden.

Figure 2. Karlastaden in Gothenburg, Sweden when completed (Serneke, n.d.)

1.3 Problem statement

Today, the European building stock is responsible for 40 percent of the energy consumed and 36 percent of greenhouse gas emissions related to energy (European Commission, 2021). In Sweden, the construction and real estate sector is responsible for 21 percent of the domestic greenhouse gas emissions whereas energy consumption is representing 34 percent of this amount (Boverket, 2021a). One half of the energy related emissions are linked to the heating of buildings (Boverket, 2021b). Furthermore, the European Commission has introduced a renewable energy directive (Directive (EU) 2018/2002) which aims at increasing the percentage of RER in the energy mix, establishing incentives for electrification, and encouraging energy efficiency and circularity initiatives.

Spiking electricity prices and spiking electricity demand are increasing the amount of greenhouse gas emissions. Sustainable electricity production could mitigate this issue with reduction of energy use and emissions of greenhouse gases in the building sector

(Eriksson & Gray, 2017) but does suffer from an intermittency problem. The intermittency problem is generic for RERs but also dependent on the location of the resources (Bazilian et al., 2013; Stadler, 2016; Soshinskaya et al., 2014). MGs, per definition in this thesis, address the intermittency problem by storing electricity production surplus, hence no waste of produced electricity.

Birol (2022) states that there is a massive surge in investments for RERs today, independent of the intermittency problem, since it is necessary to reduce the negative environmental impact. However, investment is generally only undertaken if there is a financial benefit associated with the investment which makes the financial evaluation of a MG vital (Graham, 2003). The financial evaluation of MGs and RER systems have been approached in various ways where it is most common to estimate the levelized cost of energy (LCOE) (Hernández-Moro & Martínez-Duart, 2013. LCOE is defined by EIA (2022) as "the estimated revenue required to build and operate a generator over a specified cost recovery period" (p.1). That is, by assuming the technical life of an energy project it is possible to estimate the required average revenue per unit of energy generated to cover overall costs. The financial evaluation of a MG is complex and therefore there is a gain in developing guidelines which property developers could utilize to evaluate if an MG is profitable.

1.4 Aim and research questions

This thesis aims to conceptually develop managerial guidelines for evaluating the financial feasibility of MGs in an urban context from a real estate perspective. Furthermore, the guidelines are tested at Karlastaden to demonstrate and evaluate the financial feasibility of such a MG. Therefore, the following research questions are addressed:

- What factors need to be evaluated to construct a MG in an urban context?
- How could the financial feasibility of a MG be evaluated?

1.5 Delimitations

The energy production resources are delimited to PV cells and wind turbines, while storage resources are delimited to batteries and hydrogen. Energy produced and stored is assumed to be fully consumed with no saturation point since it can be sold to an external grid if not consumed within the MG. The revenue from electricity certificates have been neglected. No laws and regulations except the electricity law of Sweden will be considered.

2 Background

This chapter present the previous research obtained from literature that will be used when analysing empirical data, constructing the guidelines and when establishing the financial evaluation model. It consists of theory regarding RERs and storage technology, design of a MG, Swedish laws and regulations affecting MG as well as financial evaluation aspects. As mentioned earlier, these were the topics that Serneke had identified as important to consider when doing an evaluation of MGs.

2.1 Energy production and storage technology

To design an efficient and profitable MG both energy production and storage technologies can be utilised (Ferrario et al., 2021). Energy production has the obvious characteristics of creating new electricity while the storage technology can be used to optimise the usage of energy. Walker (2013) also found that solar energy systems (SESs) could reduce operating expenses (Opex) for buildings and increase value. Furthermore, the IEA (n.d.) argues that SESs are preferable when compared to other RERs due to better cost performance and capacity. In comparison to this, there exists few successful urban wind energy projects and the Opex for a wind turbine is substantial at approximately 1.5 – 3 percent (Sunderland et al., 2016). Furthermore, the introduction of an energy storage system (ESS) has a broad set of applications in MGs. An ESS in a MG creates advantages such as the possibility to achieve energy arbitrage, peak shaving, voltage support, frequency regulation, power quality, power reliability (Faisal et al., 2018; Breeze, 2019). The system could either be aggregated with one main energy storage connected to a system of RERs or distributed with one energy storage directly connected to each RER (Faisal et al., 2018). Furthermore, combining different ESSs into a hybridized ESS is beneficial since characteristics from multiple storage technologies can be utilised which could lead to better performance (Faisal et al., 2018; Ferrario et al., 2021). A hybridized ESS could consist of hydrogen for long-term storage and battery storage for short-term storage (Zhang et al., 2017; Breeze, 2019).

2.1.1 Photovoltaic cells

According to Walker (2013), SESs generate electricity or thermal energy from irradiation. Because of high investment cost and risk of equipment failure these have not yet been widely implemented. Walker (2013) states that "solar energy may be viewed as one key strategy to reduce air pollution and associated climate change" (p. 4) where Tyagi et al. (2020) shares a similar view arguing that it will help the global green energy transition. Walker (2013) conducted a study on the promotion of green buildings, where it was found that SESs could reduce property Opex and increase value in addition to being environmentally friendly. More recently IEA (n.d.) argued that solar PV cells are the most beneficial in terms of electricity capacity and cost compared to other RERs. In short term, the manufacturing cost seems to be increasing due to various disturbances in the global market and supply chain, but it has been steadily declining the last 40 years. In fact, solar PV energy production amounted to 179TWh in 2021 which is an increase of 22% year over year.

PV cells are created with materials called semiconductors with variants such as silicon, phosphorous and boron (Walker, 2013). These materials have properties to enable electricity production in PV cells. Energy contained in photons emitted by the sun can be captured by the valance electrons in semiconductors. The valance electron then uses this energy to advance from the valance band to the conduction band, which is a higher energy level for the atom. All semiconductor materials have different specific amount of energy for this electron advancement, which is called 'band gap'. Considering that materials have different band gaps it is possible to increase efficiency for PV cells by combining materials which is done in many PV modules today.

The creation of solar panels implies stacking PV cells together to create PV modules, then mount the PV modules on to arrays and wire them together. For a building, the modules can be assembled on racks at the roof or integrated in the façade as curtain walls. The PV cells properties is the solar panels properties. There are several PV cells which all have different characteristics. Types differentiate each other by cost, efficiency, and lifetime. There are different types of PV cells where the most common one is silicon-based, which in 2013, represented 90 percent of the PV cell market (Walker, 2013; Tyagi et al., 2020). The reason for using silicon is because it relatively abundant and cheap. The efficiency of PV modules is defined as measuring the energy produced and then divide that by the maximum solar irradiance on the same surface area. Recently, France et al. (2022) achieved an efficiency of 39.5 percent, which they claim to be the record. A normal efficiency for commercialised PV cells in 2022 ranges from 15-25 percent. According to Walker (2013) the theoretical maximum efficiency for PV cells is 86 percent.

Choosing the optimal PV modules for buildings can be difficult (Walker, 2013). First, the structural load increases with 20 to 30 kg per square meter. Secondly, it is necessary to not only review the PV modules specific characteristics but also the cost of installation and design parameters. If there is limited amount of space it might be lucrative to choose a PV module with higher efficiency. Thirdly, PV modules are also dependent on the ambient temperature, where the efficiency reduces with increasing temperature. King et al. (1997) argue that the relation between efficiency and temperature is positive and linear with a coefficient of approximately –0.46 percent per degree Celsius. However, that it is only correct for a reasonable temperature interval. At temperatures higher than 40 degrees Celsius the reduction tends to speed up. Sun et al. (2022) also show that rising the temperature reduces the lifetime of PV cells. Furthermore, it is necessary to review the angle of the mounted arrays where, according to Walker (2013), the zenith angle is the most beneficial in terms of energy production. This is the angle for where the surface area points directly at the sun when it is at the highest point during the day. For horizontal surfaces it is easy to achieve this compared to the façade which only has one option if totally integrated. This is the reason why façade mounted PV modules are less efficient and not as preferable compared with roof mounted.

2.1.2 Wind turbines

Wind turbines turn kinetic energy into mechanical torque which drives a generator (Tan et al., 2022; Ishugah et al., 2014; Sunderland et al., 2016). The output power from a wind turbine is related to the sweep area of the rotor blades and the wind velocities. Small-scale wind turbines could be classified into four categories, where the rotor diameter is the determining factor (Aravindhan et al., 2022).

- Micro wind turbine – 0,25 m – 1,4 m
- Mini wind turbine – 1,5 m – 3 m
- Household wind turbine – 3,1 m – 10 m

- Small commercial wind turbine – 10,1 m – 20 m

Wind turbine applications in urban areas have been extensively researched but still there exists a lot of uncertainties and issues to achieve good performance of such installations (Aravindhan et al., 2022; Ishugah et al., 2014). The issues are generic and independent of the size of the wind turbines. For example, the urban environment creates a complex and rough diverse landscape in the atmospheric boundary layer, i.e., wind characteristics since buildings creates wakes, flow disorders etc (Aravindhan et al., 2022; Škvorc & Kozmar, 2021; Ishugah et al., 2014; Sunderland et al., 2016). Due to this, it is difficult to assess the wind inflow to the turbines. There exist three types of atmospheric boundary layer profiles: rural, sub-urban and urban. The urban atmospheric boundary layer has the lowest mean wind velocities and highest turbulence intensities, which is not preferable since wind turbines have the greatest efficiency when the wind velocity is high and constant with low turbulence (Škvorc & Kozmar, 2021; Sunderland et al., 2016). Wind velocities increase with height and the turbulence decrease. Therefore, the geometry and height of buildings influence the energy harnessing potential and wind turbines should not be placed in the lower regions of buildings due to high turbulence and low mean wind velocities. Wind turbines on tall buildings have the biggest potential since the location of wind turbines on the roof is less sensitive than on lower buildings where corners of the roof are most preferable (Škvorc & Kozmar, 2021). If there is a prevalent wind direction, then wind turbines have the best productivity if they are located on the leeward side of the roof. If there is no prevalent wind direction, then wind turbines should be placed in the center of the roof. Furthermore, rooftop turbines should at least be installed at a height above the ground corresponding to 1.3 times the height of the building and 1.51 to 1.79 times the height of the building for better performance (Aravindhan et al., 2022). The rooftop angle should also be designed to be perpendicular with the wind flow and the installation of a diffuser increases the performance significantly. Other factors such as vibrations and absence of amplification of natural wind speeds makes the performance optimisation of wind turbines in the urban environment an even more complex endeavour (Aravindhan et al., 2022). Another notable issue with wind turbines in the urban environment is the noise pollution that they emit (Aravindhan et al., 2022; Ishugah et al., 2014).

The vertical-axis wind turbine (VAWT) and the horizontal-axis wind turbine (HAWT) are mainly used in urban environments whereas HAWTs is currently most common (Škvorc & Kozmar, 2021; Ishugah et al., 2014). There are two common variants of the VAWTs known as Savonius and Darrieus wind turbines (Tan et al., 2022; Škvorc & Kozmar, 2021). The Savonius wind turbine generate electricity by utilizing the aerodynamic drag force and the Darrieus wind turbines utilizes the aerodynamic lift force (Škvorc & Kozmar, 2021). The variants are illustrated in figure 3. HAWTs utilises the shafts rotational energy when wind inflow is directed towards the blades and converts the energy into electricity (Ishugah et al., 2014). Sunderland et al. (2016) argues that a conventional HAWT has an overall efficiency around 30%. See figure 3 for an illustration of a HAWT and Ishugah et al. (2014) for further information regarding variants of HAWTs.

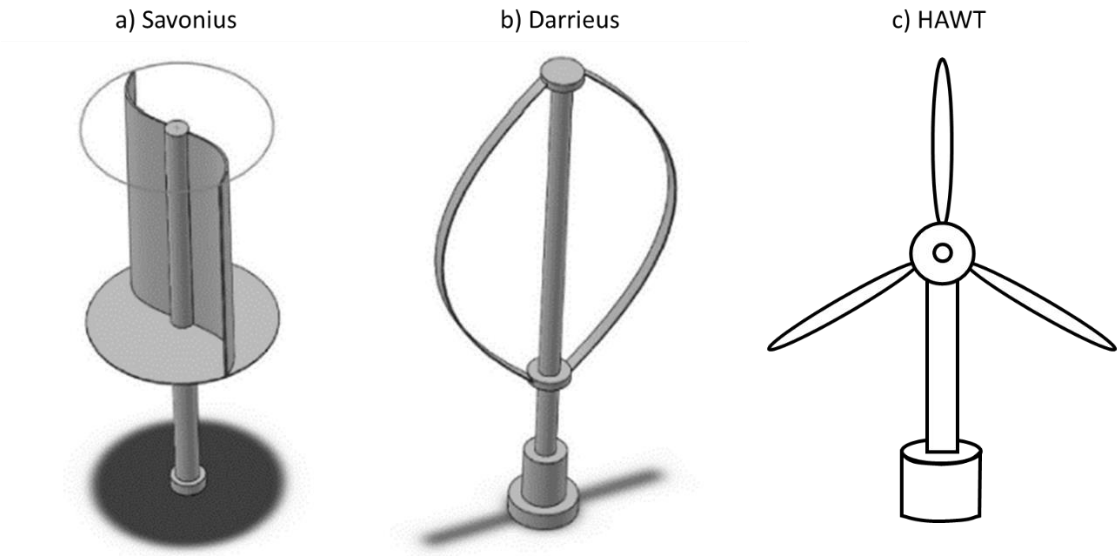


Figure 3. Illustration of the VAWT variants; Savonius (a) and Darrieus (b) (Škvorc & Kozmar, 2021) and HAWT.

VAWTs are declared to be more suitable in urban environments and it is unclear why HAWTs are most common since both HAWTs and VAWTs have their respective benefits and drawbacks (Škvorc & Kozmar, 2021). VAWTs are preferable in an urban environment due to their omni-directional feature, which means that VAWTs can harness wind energy independent on the wind direction (Škvorc & Kozmar, 2021; Ishugah et al., 2014; Wilke et al., 2021). They are also less sensitive to turbulence which is a ubiquitous characteristic in the urban environment. VAWTs also have lower Opex compared to HAWTs since the generator is placed at the base of the rotor and not at the top of the turbine (Škvorc & Kozmar, 2021; Ishugah et al., 2014). Furthermore, the blades of a HAWT becomes a limiting factor since the building will interfere with the blades if they are too long. However, VAWTs does experience fluctuating forces on the blades due to their design and centripetal force due to the turbulent characteristic of the urban environment, which leads to fatigue loading (Škvorc & Kozmar, 2021). The fatigue loading on VAWTs entails increased Opex. They also produce less energy compared to HAWTs (Ishugah et al., 2014). However, Ishugah et al. (2014) argues that VAWTs will dominate the market in a couple of decades since VAWTs have the potential to produce more energy per used area.

Ishugah et al. (2014) argue that approximately 75% of the total cost for wind energy is related to the initial costs which includes turbine cost, installation costs etc. The Opex make up a great share of the remaining costs of the system. Sunderland et al. (2016) argues however that the annual Opex of a wind turbine is estimated to equal 1.5 – 3% of the turbine cost. A wind energy investment often pays off during the lifetime of the system but is greatly affected by the wind speeds, which makes this an important factor to investigate. This is in line with the conclusion by Škvorc and Kozmar (2021) which means that there are few examples of successful urban wind energy projects today and that the two most important factors for success are that the building is designed to harness energy and that the wind resource assessment is performed thoroughly. Wilke et al. (2021) investigated how much energy small-scale household VAWTs could produce if applied to all buildings in Berlin with a height of more than 10m and less than 40m. Their result suggest that small wind turbines are barely profitable if the energy produced are sold to the external grid but are profitable if the energy is selfconsumed. Sunderland et al. (2016) investigated LCOE for small-scale micro HAWTs in Sri Lanka, Ireland and UK and found that LCOE of a micro wind turbine were 3-4 times as large for urban production than for rural production. They also concluded that urban wind energy production is not feasible in any of the countries.

2.1.3 Battery storage

Batteries have been used for over a century and are today used in myriad applications from small-scale devices to aiding large-scale power plants. Dunn et al. (2011) highlight lucrative implementations on the electricity grid, such as regulation of frequency, peak shaving, and different types of load shifting caused for example by RERs. In a battery cell, electricity is not stored as pure electricity, instead it is converted into electrochemical energy by chemical reactions (Breeze, 2019). Hence, a battery is controlling the output from reactions induced by an electrochemical cell. This is achieved by using two half reactions at the cathode and anode. Reactants at each side would react spontaneously but between these two an electrolyte is placed which will force the electrons to move across a wire which generates electricity. Depending on the reversibility of the reactions captured by the electrolyte, batteries are classified as primary and secondary cells (Breeze, 2019). Compared to the primary cells, secondary cells can reverse the reaction and are therefore rechargeable. Furthermore, the secondary cells can be divided into traditional and flow cells. The most notable design difference is that flow cells batteries have external storage of reactants while the traditional batteries do not (Dunn et al., 2011). Depending on the reactants used, traditional batteries have different characteristics (Breeze, 2019). For utility purposes, the most common material is lead-acid which is widely used in vehicle batteries. Nickel and cadmium are also used but these are more common in smaller portable applications, such as mobile phones. In grid energy storage systems, lead-acid, nickel-cadmium, lithium-ion or sodium sulphur are most suitable. The lead-acid battery can achieve efficiencies ranging from 75 to 85 percent and lifetimes from 15 to 30 years. This battery is sensitive to temperature differences and is heavy compared to its storage capacity. On the contrary, nickel-cadmium can store more energy per weight and is not as sensitive to temperature differences but is usually more expensive and achieves approximately the same efficiency ranging from 70 to 85 percent at a notably shorter lifetime from 10 to 15 years. Lithium-ion batteries used for frequency regulation can achieve lifetimes of 8.5 to 13.5 years (Stroe et al., 2016) compared to Zhang et al. (2017) estimate of 15 years with regular use, and efficiencies up to 99 percent. Sodium sulphur batteries need a temperature of 300 degrees Celsius to operate and can obtain efficiency of approximately 85 percent and a lifetime of 15 years.

In contrast to traditional batteries explained above, flow batteries are also interesting for grid energy storage systems (Breeze, 2019). However, these have not yet been implemented commercially (Hassan et al., 2021; Breeze, 2019). Flow batteries are still in an early development phase, but they are interesting since they have longer lifetime, higher efficiency and better seasonal storage capacities compared to traditional batteries because of their design. Thus, they can be preferable in large-scale grid connected energy storage. Notably, Faisal et al. (2018) identified the short lifetime of batteries as one of the main drawbacks with implementing batteries in energy storage systems. The traditional battery lifetime is determined by how many times it can be recharged which is called cycles. Therefore, the lifetime is affected by how the battery operates (Stroe et al., 2016). A drawback with flow batteries is that they have significantly longer response time, approximately 100 ms compared to 5 ms for traditional batteries

(Breeze, 2019). When only considering the traditional batteries, the lithium-ion battery is outperforming the rest due to higher efficiency and lifetime (Zhang et al., 2017; Stroe et al., 2016). But lithium is very flammable (Breeze, 2019) which affects the safety aspect of lithium-ion batteries when implemented commercially (Bandhauer et al., 2011; Choudhury, 2022).

2.1.4 Hydrogen storage

Hydrogen is produced via electrolysis which converts electricity into hydrogen (Hassan et al., 2021; Breeze, 2019). Electrolysis is the process where voltage is applied to water by using two electrodes and electricity, which sparks a chemical reaction that harnesses hydrogen gas at one electrode and oxygen at the other (Breeze, 2019). Hydrogen could also be produced via a thermochemical process by using fossil fuels which is the main method to create hydrogen globally today (Abohamzeh et al., 2021). After the hydrogen has been produced, it is stored either as a compressed gas, liquid or as a solid. Today, the preferred storage solution is to store the hydrogen as a compressed gas in a steel or composite tank since storage of liquified hydrogen demands cryogenic equipment, which is expensive, and storage of hydrogen in solid state becomes too heavy for many applications. Hydrogen in solid state becomes viable if alloys are used that absorb the hydrogen. Hydrogen could either be converted to electricity via a fuel cell or burnt to be converted into thermal energy. See figure 4 for a schematic overview of the process.

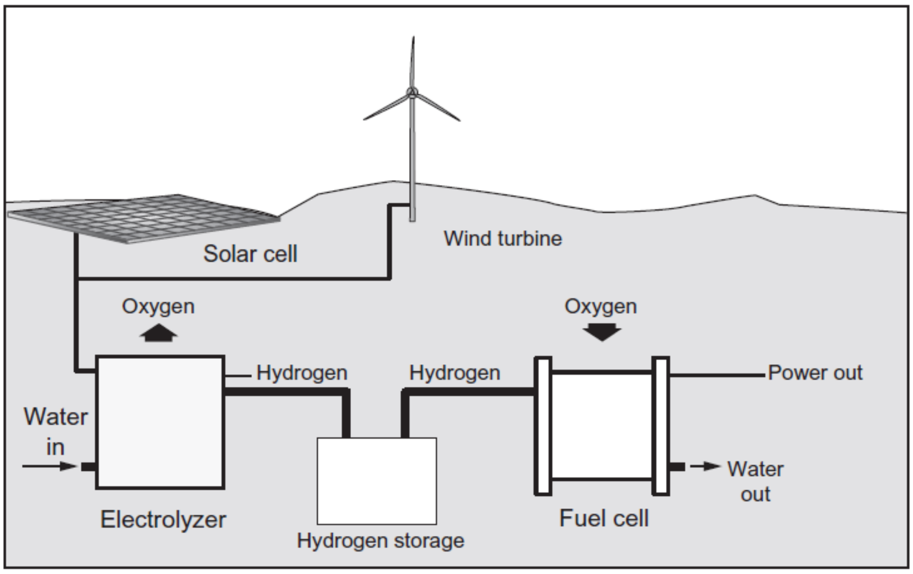


Figure 4. Schematic overview for the process of producing renewable hydrogen, store it, and convert it back to electricity (Breeze, 2019).

A fuel cell is an electrochemical device which utilizes the reversed order of the electrolysis to produce electricity (Breeze, 2019). A traditional battery is constructed on the same principle but encloses the reactants in the battery compared to the fuel cell which gets supplied with reactants from an external source similar to the flow battery. The fuel cell has the attractive feature of being able to reach high efficiency with the theoretical maximum of 83 percent. However, the best fuel cell available today is the alkaline fuel cell which has an efficiency of 60 percent, which could be compared to the best heat engine, the diesel engine, which has an efficiency of 50 percent. Additional advantages of the fuel cell are that it does not have any moving parts, which reduces Opex. Its main drawback is the cost of the fuel cell since it has been proven difficult to produce affordable fuel cells and its relatively low round-trip efficiency. Furthermore, in the context of production of hydrogen from RERs, Herrmann et al. (2019) found that this production was the most expensive compared to other energy supply concepts.

For a polymer electrolyte membrane (PEM) fuel cell, which is used as an example, the hydrogen reacts with the anode and is split into electrons and hydrogen ions (Breeze, 2019). The electrolyte filters the reactants, so it does not mix directly, and therefore controls the process, i.e., allowing the hydrogen ions to pass through the filter and react with oxygen molecules. The oxygen molecules will split into oxygen atoms when adhering to the cathode. However, oxygen atoms need electrons to form oxygen ions which they only can receive from the anode. The electrons cannot pass through the electrolyte so if a connecting wire is applied between the anode and cathode, the electrons will travel from the anode to the cathode and an electrical current is created. When the electrons have reached the cathode, the hydrogen ions can react with the oxygen ions and build water molecules. See figure 5 for an illustration of the process of a PEM fuel cell.

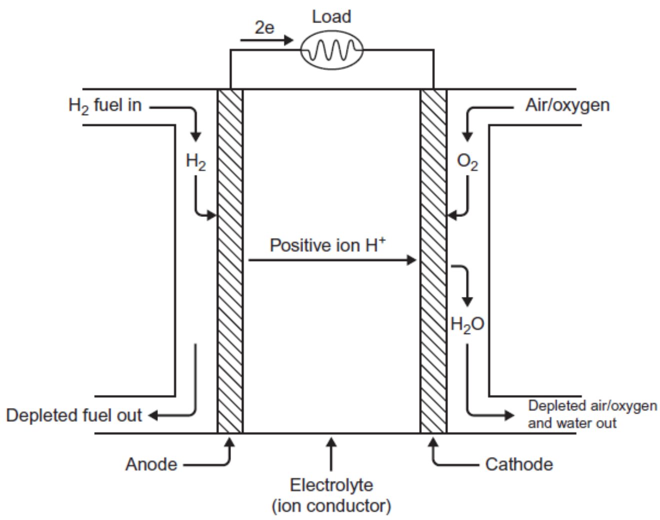


Figure 5. Illustration over the electrochemical process of a PEM fuel cell (Breeze, 2019).

Since it is the electrolyte that controls the process, the fuel cell is often identified through which electrolyte is being used. Faisal et al. (2018) argue that alkaline, PEM and high-temperature solid oxide electrolyte technologies are available techniques currently. The alkaline, PEM and high-temperature solid oxide electrolyte allows hydrogen ions, hydroxide ions and oxygen ions to pass through the membrane respectively (Breeze, 2019). More technologies than these three are, however, being researched.

Hydrogen production could possibly achieve a 94 percent efficiency using a PEM electrolyte or 90 percent by the more available alkaline electrolyte. The energy density of hydrogen is increased through pressurization of the gas which consumes energy (Hassan et al., 2021). For gas-compressed storage, an energy consumption up to 15 percent of the energy content of the hydrogen is consumed and for liquefied storage up to 35 percent of the energy content is consumed. Liquefied hydrogen is only applicable for certain purposes, e.g., aerospace, if not cryo-compressed. However, energy consumption is not considered for round-trip efficiency. The efficiency of the fuel cell is, as previously mentioned, dependent on the electrolyte that is used and efficiencies for the three available electrolytes are presented in table 1 (Breeze, 2019). However, if accounting for a hybrid system which also utilizes the heat generated from the process, a fuel cell could reach 70-75 percent efficiency. Herrmann et al. (2019) found that a combined heat and power plant fuel cell could reach 95 percent efficiency. Breeze (2019) argues that the round-trip efficiency, with accessible techniques, is at best 54 percent by using the alkaline electrolyte for both the hydrogen production by electrolysis and fuel cell. Zhang et al. (2017) argue that the round-trip efficiency is around 35 percent and Ferrario et al. (2021) argue that it is around 35 to 40 percent. Hydrogen storage is suitable for long-term storage due to seasonal mismatching of RERs production and load (Zhang et al., 2017). Hydrogen also benefits from its low discharge rate and flexibility. Hydrogen storage is flexible since the charge power, discharge power and storage capacity consist of three independent components. The electrolysis system determines the charge power, the fuel cell determines the discharge power, and the storage container/medium determines the storage capacity.

2.2 Design of the microgrid

Design of the MG differentiates based on the technology and if it is connected to the external grid. In prior studies the focus has been to find a solution to different electricity production profiles. But that can be hard due to regulations restricting the possible designs.

2.2.1 Microgrid design in prior studies

Depending on the evaluation parameters of MG there are myriads of prior studies considering the design. All the prior studies reviewed were conducted during the last 20 years and considered the integration of RERs into the external grid through MG. Common drawbacks such as RERs being an intermittent power source, what components should be included, and trading with the external electricity grid in the operation phase were considered by scholars.

Bahmani-Firouzi and Azizipanah-Abarghooee (2014) emphasize the intermittent characteristic of RERs as a particular important reason for designing MGs. Therefore, they studied optimal design of MGs with energy storage potential such as RERs and battery energy storage (BES) for residential, commercial, and industrial load. The frequency of designs that implements BES into MGs are increasing as the ratio of RERs increase in the general energy mix. Conclusions from their study suggest that designing a hybrid MG could reduce the total cost by trading or storing electricity when it is most profitable and reduce energy losses in the system. An optimal size BES for a specific MG have the potential to reduce the annual Opex by 40 percent.

Eriksson and Gray (2017) also studied the integrating of a hybrid system which complements the RERs intermittent problem with electricity storage but by means of hydrogen. They concluded that such systems need comprehensive software and energy management optimization to function properly. They argued that few studies go beyond the design of technological components, thus, they consider four dimensions regarding technical, economic, environmental and socio-political factors to reach the optimal design and purpose. In their view, it is only possible to create an optimal design by reviewing all factors. Obviously, the optimal design depends on the purpose and factors evaluated. However, by incorporating hydrogen in the MG design, Eriksson and Gray (2017) argue that complexity increases since an energy carrier besides electricity is used. Adametz et al. (2017) also conclude similar results when they compared batteries with hydrogen. Although, hydrogen may be more complex to operate it enables larger electricity storage potential. Adametz et al. (2017) studied the design of an energy storage system with PV cells and storage through hydrogen tanks for a residential building connected to the grid. The hydrogen storage was used for periods of time, seasonality, when the PV production potential was lower than the demand. They reached between 38 to 60 percent self-sufficiency rates depending on single- or multifamily household.

On the other hand, not being able to use energy storage could be solved by trading electricity with the grid. Zhang et al. (2013) studied MGs potential to reduce the volatility in demand and supply of RERs electricity production. They traded energy with the external grid and thus maintained the supply-demand balance. They introduced an energy management system which can provide means to combat the intermittent energy production of renewables. In connection to this, Mizani and Yazdani (2009) studied the optimal design and operation for grid-connected MGs with components such as diesel-generator, boiler, battery, PV cell, wind turbine and natural gas to reduce the intermittent problem. They discussed that an optimal designed MG with both production and storage technology could reduce both costs and emissions during the life cycle. However, a system that trades with the external power grid could be complex and the energy management system is not easily implemented with success due to regulations and energy taxes, in this case at a university in Ontario Canada (Mizani & Yazdani, 2009). Mengelkamp et al. (2018) did, besides emphasizing the intermittent problem and volatility in demand-supply, try to determine an efficient design and operation through blockchain-based MG energy markets to locally be able to trade electricity without disturbance. They study a large residential MG in Brooklyn which is connected to the grid and produce electricity with PV cells. Seven components are identified as necessary for an operable electricity market such as MG design, energy management system and pricing mechanisms, highlighting the complexity of trading with electricity.

Hafez and Bhattacharya (2012) studied the design, planning, size and operation for a hybrid MG. Their MG design is evaluated through four scenarios with different components in the MG. Components considered in their design are wind turbines, PV cells, battery, hydro turbines and diesel generators. The renewable scenario included wind turbines, hydro turbines, PV cells and batteries. Wind turbines had the greatest contribution to electricity production of 89 percent followed by PV cells at nine percent and hydro turbines at two percent. They concluded that RERs are competitive both at an economic and electricity supply point of view when designed with an energy storage system. They also discussed that the most favourable option is a MG connected to an external grid.

To conclude, by studying MGs in prior studies it is possible to identify general questions regarding the design. These questions could vary from what technologies that should be included, if the MG should have both production and storage, if the grid should be self-sufficient or not, and how much complexity that could be handled due to the introduction of energy management systems and electricity markets.

2.2.2 Implications of grid connectivity and electricity sharing in Sweden

In previous sections, the argument and desire of grid-connected MG is due to the ability of trading electricity between buildings or between buildings and the external grid. The technology seems to have come far and can make this possible. However, Sweden's regulations may endanger this ability. In Sweden, electricity transmission within a geographical area, under the definition local grid, is regulated by the Swedish Energy Markets Inspectorate (EI) (EI, n.d.a). EI is responsible to regulate electricity distribution and operators fee for local grids. The regulation gives a company monopoly (sv. 'nätkoncession') for distributing electricity in that local grid. However, there are exceptions to this regulation which remove the monopoly of grid owners to distributing electricity.

EI (n.d.a) states that the most common way to find exceptions to this regulation is if the grid is an internal grid, which allows the grid owner to ignore the monopoly when transmitting electricity on the internal grid. A grid that is allowed to ignore the monopoly is called 'icke-koncessionspliktigt-nät' (IKN) in Swedish. EI (n.d.b.) introduce several possible ways to achieve an IKN. However, it is not straight-forward what is considered an exception and what is not. Similarly, the regulations are changing rapidly, and the prejudices of cases provided in the regulations as examples are outdated. Today, it is possible to achieve IKN according to EI (n.d.b.) by the following paragraphs in the law of electricity (1997:857) under IKN-regulation (2007:215):

- 5 § if it is an internal grid for the same building. Underground transmission, for example an underground culvert, is not considered an internal grid. Furthermore, no exception is made for buildings which have PV cells and want to transmit electricity between the buildings.
- 6 § if an internal grid, and the transmission is between a building and a facility close by, for example electricity storage facilities. Close by means that the internal grid reaches it and does not pass under a public or municipality owned road nor transmitted via power lines in the air.
- 22a § if it is a compound which is not accessible by the public and share connection to the external grid. For example, an airport, solar cell park or wind park.
- 22c § if it is an internal low-voltage grid that distribute electricity from production or storage sources within the grid owner's property boundary and between buildings which do not share the same connecting to the external grid nor transmitted via power lines in the air.

In Sweden, there also exists an energy tax regulated in the law of tax on energy (1994:1776) which in chapter 11 applies when:

- 1 § if the electricity is consumed the tax apply, if not regulated by 2 §.
- 2 § if consumed to generate electricity. If the electricity is not transferred to an external grid operator with monopoly. However, if the electricity is produced by a collected top load from wind of 250 kW or 500 kW from solar it is subjected to energy taxation. If the electricity is produced from several sources the collected top loads are summarised.

2.3 Finance and risk

The theory in this section is used to analyse the collected data and results in one part of the investment decision tool. This section consists of results from previous studies that have investigated investment in MG's, cost and revenue estimation framework, and tools and description to perform risk and sensitivity analysis.

2.3.1 Microgrid investments in prior studies

Energy projects are today commonly associated with reducing the emissions of greenhouse gases (Aussel et al., 2018). There are several indicators for determining environmental impacts, however, ubiquitous definitions for financial feasibility of energy projects are absent. This reduces the possibility to compare projects and thus risk aversion plays a bigger role for investors. Aussel et al. (2018) provide financial parameters to investors for distinguishing projects. If MG is grid-connected or not is important to consider since being connected means that the MG can trade electricity, thus, increasing the chances of additional revenue streams. Designing MGs that are not connected to external grids can be expensive and problematic (Fioriti et al., 2020). Ergo, it is convenient to find a method to determine if the designed MG can be financially beneficial. Fioriti et al. (2020) studied common financial indicators such as net presented value (NPV), discounted payback period and LCOE. Considering only one of these indicators is not enough for evaluating the financial feasibility since there are drawbacks with NPV that need to be considered. For example, it is difficult to analyse the size of the investment and capital expenses (CapEx). By studying an off-grid hybrid MG in Uganda, they were able to provide a guideline for increasing the financial profitability of the MG using different designs. Furthermore, they combined their study with a sensitivity analysis and concluded that predictive scenarios could help boost profitability by providing operating strategies. Fioriti et al. (2020) argue that there are three distinct expenditures for a MG. First being initial investment expenditure, second being the CapEx, and third the Opex. They also argue for the recovery value since it affects the investment decision.

Bahmani-Firouzi and Azizipanah-Abarghooee (2014) suggest that the demand for an optimal design of RERs and BES has increased due the intermittency problem with RERs. Considering financial evaluation parameters, it is possible to find several benefits in their system such as short-term power supply, energy quality enhancements, integrating intermittent RERs, backup system and trading with the external grid. Soshinskaya et al. (2014) argue that the optimal MG design and mix vary, and are dependent on several factors such as technical or financial barriers and specific location. According to them, technical barriers are the alternation between being connected to the main grid or not, quality and control of the energy, and protection. While financial barriers are the relatively high investment expenditure and CapEx. Stadler et al. (2016) explain that MG is more complex compared to the traditional power grid which is one source of the higher investment expenditure. The problem with high investment expenditure is related to the low global adoption rate of MGs. However, they further elaborate that this initial investment can be profitable since the MG can create value streams. To understand what value streams investments in MGs enable, Stadler et al. (2016) conducted a literature review on the matter. Stadler et al. (2016) conclusion yield four value stream categories:

1. Demand response
2. Power exports
3. Resilience against power shortages
4. Local energy market

Furthermore, they conclude that MGs have the potential to be lucrative investments if considering all value streams. But that it is specific to location, local regulations, and tariffs. Giving investors the right tool to study the financial feasibility is important because technical feasibility is not enough for the energy project to be undertaken. This view is shared by Aussel et al. (2018).

2.3.2 Net Present Value (NPV)

There exist many different types of investment decision rules and models, but one ubiquitous is the NPV investment rule (Berk & DeMarzo, 2014; Wetekamp, 2011). The aggregation and estimation of cash flows and uncertainties regarding assets lifespan are creating needs to investigate if adjustments to the NPV calculations are needed. However, Sereg (2021) has investigated the errors stemming from three types of NPV calculations, included the 'textbook' variant described below, and found that other variants of NPV calculations are not needed in the general case due to relatively small improvements in result. The NPV rule states that when NPV is positive, the investment should be undertaken and the investment with the highest NPV should be prioritised (Berk & DeMarzo, 2014). There are however other aspects that needs to be considered but the totally rational investor will undertake a project if the NPV is positive. The NPV calculation consists of two parts: the initial investment (I) and discounted future free cash flows (FCF) generated from the investment during the lifetime (N) (Eq. 1).

$$NPV = -I + \sum_{n=1}^{N} \frac{FCF_n}{(1+r)^n} \qquad \text{(Eq.1)}$$

The FCF is the available cash generated from an investment, which is forecasted in an NPV calculation (Berk & DeMarzo, 2014). The FCF is calculated by taking the unlevered net income and adjusting for depreciation tax shield effects (t_c*Dep), additional CapEx and changes in net working capital (ΔNWC), see Eq. 2.

$$\text{Free cash flow } (FCF) = EBIT*(1-t_c)+(t_c*Dep)-CapEx-\Delta NWC \qquad \text{(Eq.2)}$$

T_c is the corporate tax; Dep is the depreciation and EBIT is earnings before interest and taxes.

The time perspective of an investment is accounted for by dividing and summing up each annual cash flows with a discount rate and raised to the power of years for when the cash flow occurs ($(1+r)^n$). The discount rate (r) equals the rate of return on available investments which are similar in risk and terms or the cost of capital (Berk & DeMarzo, 2014). Therefore, the free cash flows are often either discounted by the risk-free interest rate, with or without the risk premium, or the cost of capital. The discount rate is chosen by the company that performs the investment calculation and is therefore somewhat of a subjective chosen value since risk often needs to be accounted for (Virlics, 2013). Brealey et al. (2011) argue that most companies determine their discount rate by starting with their cost of capital on a company level, and afterwards analyses if their project have higher or lower risk than the company itself. If the project has higher risk than the company, then the discount rate will be larger than the cost of capital on the company level and vice versa.

2.3.3 Cost evaluation of electricity production projects

Bazilian et al. (2013) argue that three common methods are used to analyse the economics of PV investments. These are price-per-watt (peak) capital cost of PV modules [cost/W], LCOE [cost/kWh] and grid parity. Hernàndez-Moro and Martínez-Duart (2013) means that the most common method to determine economic feasibility in electricity production technologies is by using LCOE. However, Bazilian et al. (2013) argue that return on investment (ROI) or internal rate of return (IRR) are most typical economic feasibility measurement applied for energy production projects. Marchioni and Magni (2018) stress that the coherence of different measures and NPV are important, and they conclude that ROI is strongly coherent while IRR is not. The incoherence between NPV and IRR is not neglectable since the wrong investment decision could be made. Bazilian et al. (2013) mean that the price-per-watt, LCOE and grid parity methods could be adjusted in numerous ways. It exists a general confusion of results when these methods have been applied since scholars are not transparent with the adjustments made.

The price-per-watt (peak) capital cost of PV modules have the advantage of being easy to apply because of its simplicity and that data is available in the correct format (Bazilian et al., 2013). The price-per-watt (peak) capital cost is calculated as dividing the capital cost with the peak power output. However, the results give no indication of the costs of a fully installed system. Yields depending on peak and average price can vary depending on technology and there is not clear if the costs are the manufacturers costs or the wholesale costs. LCOE and grid parity requires more assumptions than the price-per-watt. They also vary more since the results are depending on location, return requirements from investors and requires a wider dataset for estimation. Therefore, LCOE and grid parity requires a sensitivity analysis, which is in general not performed by scholars.

LCOE considers the entire lifetime of the project which provides the investor with a more detailed approximation of the total costs (Bazilian et al., 2013). Because the entire lifetime of the project is considered, a valuable insight regarding the performance of the system is presented, which demands a context-specific investigation. LCOE is the calculated price at which energy must at least be sold to break-even due to the relationship with NPV (Darling et al., 2011; Sunderland et al., 2016). Standardized definitions of the LCOE method have been suggested, but the method is rather straightforward, and it is instead a question of being transparent with cost uncertainty and assumptions that are needed to present more convergent results (Bazilian et al., 2013; Darling et al., 2011). Grid parity is essentially only a comparison between an LCOE of an electricity production project compared to another alternative wholesale electricity production project (Bazilian et al., 2013).

The most basic formulation of LCOE is to divide the discounted aggregated costs of the system over its lifecycle with the total electricity production of the systems lifetime, see Eq.3 (Lotfi & Khodaei, 2016; Darling et al., 2011; Pawel, 2014).

$$LCOE = \frac{\text{Discounted aggregated lifecycle costs}}{\text{Total lifetime energy production}} \qquad \text{(Eq.3)}$$

Alterations to this basic equation could involve various things to increase the detail level. Darling et al. (2011) presented an equation which involved capital structure parameters to consider tax shield effects and amortization expenditure. They also performed a Monte Carlo simulation which is a common technique to mitigate errors and uncertainty factors in the LCOE calculation by scenario analysis of probabilities and randomisation of outcomes (Berk & DeMarzo, 2014). This approach is beneficial since the simulation provides the investor with measures that describe the uncertainty of the assumptions and calculation itself. Lotfi and Khodaei (2016) altered the equation to consider an entire MG with multiple energy generation technologies and a storage system. Pawel (2014) extended the equation to consider a PV plant and a storage system. For the case of only investigating LCOE for an electricity production project with no storage, equation 3 could be used. To further describe the involved parameters for such a calculation, equation 3 is elaborated and presented in equation 4. This equation is based on Darling et al.'s (2011) description of an equation taking financial considerations into account but adapted to be generalized and configured to fit with the FCF equation. RV stands for residual value and is the remaining value in the end of the evaluation period. kWh produced is the production for the production technologies and SDR is the degradation of the technologies over the evaluation period.

$$LCOE_{prod} = \frac{I - \sum_{n=1}^{N} \frac{Dep}{(1+r)^n} * t_c + \sum_{n=1}^{N} \frac{Opex}{(1+r)^n} * (1 - t_c) + \sum_{n=1}^{N} \frac{CapEx}{(1+r)^n} - \frac{RV}{(1+r)^N}}{\sum_{n=1}^{N} \frac{kWh\ produced * (1-SDR)^n}{(1+r)^n}} \quad \text{(Eq.4)}$$

Since a storage system does not produce electricity, the LCOE equation needs to be configured to account for purchasing of electricity which later will be stored (Pawel, 2014). Pawel assumes that the stored electricity is purchased, either via an internal purchase between the electricity production part of the MG, or from the external grid. Pawel (2014) also assumes that prices will increase which is considered by adding a price increase factor. Hoppmann et al. (2014) used compound annual growth rate (CAGR) specifically for this price increase factor. Therefore, these methods are combined in Eq.5.

$$LCOE_{St} = \frac{I - \sum_{n=1}^{N} \frac{Dep}{(1+r)^n} * t_c + \sum_{n=1}^{N} \frac{Opex}{(1+r)^n} * (1 - t_c) + \sum_{n=1}^{N} \frac{CapEx}{(1+r)^n} - \frac{RV}{(1+r)^n}}{\sum_{n=1}^{N} \frac{kWh_{out} * (1-SDR)^n}{(1+r)^n}} + \frac{(1+CAGR)^N * p_{r,0}}{\eta_{st}} \quad \text{(Eq.5)}$$

kWh_{out} is the production after the round-trip in systems. The kWh_{out} gets smaller for hydrogen and battery storage due to the poor efficiency of these systems (Breeze, 2019). $P_{r,0}$ is the initial retail price in the evaluation period and η_{st} is the efficiency of the technology. Both equation 4 and 5 describes the LCOE of one technology, e.g., PV energy production or battery energy storage, but since several hybrid MG designs are evaluated, each with multiple technologies included, a contribution factor of the technologies is relevant to establish, in the same manner as Lotfi and Khodaei (2016). Two different approaches to determine the contribution factor are presented in Eq. 6.

$$\beta_i = \frac{E_k}{\sum_{k=1}^{K} E_k} = \frac{\eta_k * P_{k,rated}}{\sum_{k=1}^{K} \eta_k * P_{k,rated}} \quad \text{(Eq.6)}$$

In Eq.6, the produced electricity per technology is divided by the total produced electricity. The same result could be achieved by multiplying the capacity factor (η) per technology (k) with the rated power of that technology and then divide it with the sum of the multiplications for all technologies (K) in the MG. By utilizing the contribution factor, equation 4, and 5, it is possible to establish equation 7 for the combined system.

$$LCOE_{MG} = \frac{\sum_{k=1}^{K} LCOE_k * E_k}{\sum_{k=1}^{K} E_k} = \sum_{k=1}^{K} \beta_k * LCOE_k \quad \text{(Eq.7)}$$

2.3.4 Revenue evaluation of electricity projects

The revenue stream stemming from the production of electricity can be evaluated based on electricity prices which consists in general of two components called spot price and grid fee (Zhang et al., 2017). Spot price is the cost for consumed electricity which have been transmitted from the producer to the consumer and vary on hourly basis. Grid fee is the fixed or moving price consumers pay to the external grid owners to get allowance of transmitting electricity on their grid. In Gothenburg, the grid fee has three components (Göteborg Energi, n.d.). First component, electricity transmitting fee which is the price for transmitting energy on the grid. Second component, subscription fee to get allowance to use the grid. Third component, maximum load fee where the highest load for three hours at different days each month results in a fee. Zhang et al. (2017) explain that the revenue from production of electricity can be evaluated based on if the consumer is part of the MG or if the electricity is sold to the external grid. Selling electricity to an external grid infers that grid fee will be applied which decreases the revenue. However, if the producer consumes or sells the energy on a MG it is possible to gain a financial benefit by removing the grid fee, thus increasing the revenue. Similarly, to production, energy storage can decrease the peak load and therefore be used to decrease the fee (Stadler et al., 2016).

Since one part of the revenue will depend on electricity spot prices, a method for predicting these prices is needed. Hoppmann et al. (2014) used CAGR to create scenarios, which they used to predict future electricity spot prices. The equation for calculating CAGR is presented in equation 8. Due to the uncertainty of the electricity price development, Hoppmann et al. (2014) describe this method as the most suiting. Farzan et al. (2014) argue that historical data and insights are generally a main driver for financial investments which aligns with Hoppmann et al.'s approach. Ziel and Steinert (2018) argues that there exist very few statistical methods for predicting electricity spot prices in the long run, where the long run equals a period longer than one year. They do recognize that the long-term period is not well anchored in the literature, but they assumed this period after their literature review. Ziel and Steinert (2018) managed to develop a statistical model which allowed prediction of electricity prices for up to three years. However, since investment lifetimes of MGs are assumed to be at approximately 30 years (Hunter et al., 2021; NREL, 2022), three-year prediction is insufficient for this type of evaluation. Therefore, prediction method used by Hoppmann et al. (2014) based on CAGR is most suitable and should be configured to the regional context. CAGR is the geometrical average of the annual growth (Berk & DeMarzo, 2014) and is calculated according to equation 8.

$$Cumulative\ annual\ growth\ rate\ (CAGR) = \left(\frac{End\ value}{Initial\ value}^{(1/t)}\right) - 1 \quad \text{(Eq.8)}$$

t is the period that is evaluated, i.e., years since it is the annual growth rate. Could instead be month or another period.

Energy arbitrage is described as trading energy with the external grid and utilising the storage of energy (Kadri & Raahemifar, 2019; Dagget et al., 2017). The revenue is evaluated by purchasing energy at a low price at low demands and selling it to a higher price at high demands. This revenue is therefore based on the price volatility of electricity spot prices through optimising the storage and discharge of energy. Dagget et al. (2017) show that it is possible to make energy storage with batteries financially feasible through electricity arbitrage. But to create even bigger financial benefits, they also show that a combination of arbitrage and ancillary services is desirable. In comparison, ancillary services have larger revenue streams at lower initial costs and increases the lifetime of batteries.

Ancillary services are a method to stabilise the demand and supply on the electricity grid (Rebours et al., 2007; Stadler et al., 2016, Zakeri & Syri, 2016). The method creates a market for bidders to gain a revenue by selling available load to the external grid and discharge electricity whenever it is necessary (Stadler et al., 2016). Globally the revenue can take many forms, but it usually includes the following:

- fixed allowance
- availability price
- utilization payment
- compensation for a possible opportunity cost

In Sweden this market is a tendering process which is operated and regulated by Svenska Kraftnät (SvK). The renumeration is based on availability, SEK/MW/h, and utilisation, SEK/MWh (Rebours et al., 2007). The market involves several primary frequency controls which is summarised in table 1. There are minimum requirements to enter the market which involves size and technology. SvKs' (2021) goal is to balance electricity demand and supply which implies a steady frequency. If the consumption rises above the production level, the frequency decreases and vice versa. Frequency is therefore a measurement of how well balanced the grid is, where a stable frequency is 50 Hz. If the electricity consumption increases or decreases below 50 Hz the grid needs help from primary frequency control. SvK (2021) also predicts that ancillary services will increase with more RERs entering the energy mix until 2026 due to large differences in production profile. Cho et al. (2015) argue that electricity storage, in particular battery technologies, can be useful for solving the intermittency problem of RERs. The system store energy when production is high and distribute when production is low which generates a revenue stream by selling the services of balancing the grid.

Table 1. Ancillary services by primary frequency control (SvK, n.d.a.).

Fast Frequency Reserve (FRR)	**Frequency Containment Reserve-Normal (FCR-N)**	**Frequency Containment Reserve – Disturbance (FCR-D Up)**	**Frequency Containment Reserve – Disturbance (FCR-D Down)**	**Automatic Frequency Restoration Reserve (aFRR)**	**Manual Frequency Restoration Reserve (mFRR)**
Minimum bid 0.1MW and required response time 0.7 sec. Activates automatically when estimated frequency disturbances. Endurance range 5 – 30 seconds.	Minimum bid 0.1 MW and required response time 60 sec. Activated for disturbances between 49.90-50.10 Hz. Endurance 1 hour.	Minimum bid 0.1 MW and required response time 5 sec. Activated for disturbances between 49.50-49.90 Hz. Endurance at least 20 minutes.	Minimum bid 0.1 MW and required response time 5 sec. Activated for disturbances between 50.10-50.50 Hz. Endurance at least 20 minutes.	Minimum bid 1 MW and required response time 5 min. Activated for disturbances at 50 Hz. Endurance 1 hour.	Minimum bid 10 (5 in SE4) MW and required response time 15 min. Activated manually by SvK. Endurance 1 hour.
2022 demand 100 MW	2022 demand 230 MW	2022 demand 556 MW	2022 demand 530 MW	2022 demand 140 MW	2022 demand Not available

2.3.5 Sensitivity analysis

A sensitivity analysis is an important capital budgeting tool (Berk & DeMarzo, 2014). The sensitivity analysis tests the assumptions made in project evaluation models individually. By varying the values of the assumptions with a given rate, the factors that creates the biggest effect should be further investigated before an investment decision is made. Hoppmann et al. (2014), in their evaluation of PV modules and battery storage solutions in a three-person housing, found that the nominal discount rate, battery investment cost decrease and battery investment cost were the three most sensitive factors in their model. Hèrnandez-Moro and Martínez-Duart (2013) found available solar resources, irradiation and discount rate to be the most sensitive factors in their study of PV and concentrating solar power technologies. Bazilian et al. (2013) criticise scholars since sensitivity analysis are normally not presented but very important. Furthermore, load factor variations, variations in construction costs and discount rate were found to be the top three sensitive factors when installing PV modules. Abdelhady (2021) investigated the optimal solar power technology to be applied in an area in Egyptian western desert where collector (reflector system) cost, and real discount rate were found to be the most sensitive factors. All reviewed prior studies have found that discount rate is among the top three sensitive factors in their model.

2.3.6 Risk is closely related to investment decision

The riskier an investment is, the higher premium the investors desire (Berk & DeMarzo, 2014). Hence, determination of the riskiness of an investment is needed. From an economic perspective, risk is understood as how the decision maker decide with imperfect information (Virlics, 2013). Risk is dependent on the reversibility of an investment, where an investor will be more risk-averse to an investment when it is irreversible. To mitigate this, the investor should be flexible and value new information that have the potential to change the estimated outcome of an investment. However, the future can be predicted to a higher or lower degree, and to reduce the uncertainty a deep understanding of the affecting variables is needed. Because the future is uncertain, the risk factor is introduced. Therefore, a risk analysis is important to conduct, and an investment decision should not be taken before such an analysis is performed. This is in line with Wetekamp (2011), which argues that being able to identify and managing risks in advance is a great advantage for investors.

The most common way to define and determine risk is by using probability distributions, either by using the probability to calculate the expected return or to calculate the variance and standard deviation of the investment (Berk & DeMarzo, 2014; Hirshleifer, 1965) where investors like to have high expected returns and low variance/standard deviations (Hirshleifer, 1965). However, Hirsleifer (1965) argues that decision-makers does not always seek the lowest variability of investment predictions, if they find that they can undertake risky investments at fair odds, with higher marginal utility. This means that investors can be inclined to undertake risks even if the probable monetary gain is equal, but the marginal utility is higher with the risky investment than with the other.

Abba et al. (2022) argue that risk management of RER investments is a complex endeavour since there is many factors that are interdependent and affects the system at the same time. The complexity leads to general oversight of:

- The need for a multidisciplinary approach,
- Interactions and interdependencies between factors,
- The neurological and behavioural nature in decision-making,
- The contextual and dynamic properties of risks, and
- The need for a holistic approach when considering risks when investing in RERs.

The most common methods for identifying risks, in the current body of literature, are by performing literature reviews, expert interviews/surveys or a combination of the activities (Abba et al., 2022). Regarding analysis and evaluation, myriad of approaches was found, where various established decision support analysis tools, dynamic system tools, structured interviews, or analysis of cash flow with Monte Carlo simulation and sensitivity analysis were the general common approaches. Mitigation was dealt with the same way as with analysis and evaluation, excluding decision support analysis tools and including agent-based modelling.

The Monte Carlo simulation approach was used by Darling et al. (2011) to mitigate the effect that assumptions of input parameters have on the LCOE-values, which is a risk mitigation approach according to Abba et al. (2022). Input parameters are computed together with probability distributions in a so-called Monte Carlo simulation which makes the result more robust. Farzan et al. (2014) also used the Monte Carlo simulation approach but to analyse and evaluate risk. They argue that there in some cases, especially regarding larger infrastructure projects, exists a need to make investments over a long period. Investments are common to combined with a time factor, whereas the long-term uncertainties such as interest rate, market and capital cost often are incorporated in the evaluation models. However, short-term uncertainties such as volatility in spot prices, electricity demand, solar intensity and wind speed is not. Short-term uncertainties in the long-term investment model greatly affects the profitability and investment decisions. Therefore, short-term uncertainties become important to consider and act upon when faced during the construction of a system. Short-term uncertainties do also change the optimal investment decision in the long run, which makes predictions and evaluations of a system in the long-run more sensitive to uncertainties. Abba et al. (2022) confirms that the time factor of risks is important to consider and that there generally is a lack of consideration regarding this aspect.

3 Method

The method is based on five steps including background, interview study, development of guidelines, development of financial evaluation model and, testing of guidelines and financial evaluation model.

3.1 Research strategy

The research strategy applied for this study was mainly qualitative with an abductive approach. Since there is a need to create estimations of future outcomes during the development of a financial evaluation model, quantitative analysis was briefly utilised. However, the findings from the quantitative analysis were evaluated based on a qualitative strategy. For this thesis there exists a need to combine the inductive and deductive approach which is referred to as an abductive approach (Bell et al., 2022). This approach entails that findings from an interview study or empirical data collection is iteratively compared with literature to establish consensus. The abductive approach is appropriate since it globally exists a large field of research about MG but not in the Swedish context. The choice of abductive approach is further motivated since the development of guidelines including a financial evaluation model is tested, which involves using the developed guidelines and model to evaluate specific cases or scenarios. This allowed determination of the effectiveness and validity of the approach and discuss any necessary adjustments or improvements.

In figure 6, an illustration of the research design is presented in five steps. In the first step, a literature review was performed to gather understanding of the current state of knowledge and identify gaps or areas for further study. The second step was an interview study, in which interviews were conducted with experts and other relevant individuals to gather information and insights on the topic. These interviews provided valuable first-hand accounts and perspectives that helped to understand the issue. The literature review and interview study were performed as an iterative process since the steps individually introduced new topics and questions which needed to be further explored. The findings from steps 1 and 2 were used in steps 3 and 4 to develop guidelines and a financial evaluation model. To show the potential and gain further understanding, a demonstrative test was performed with the financial evaluation model.

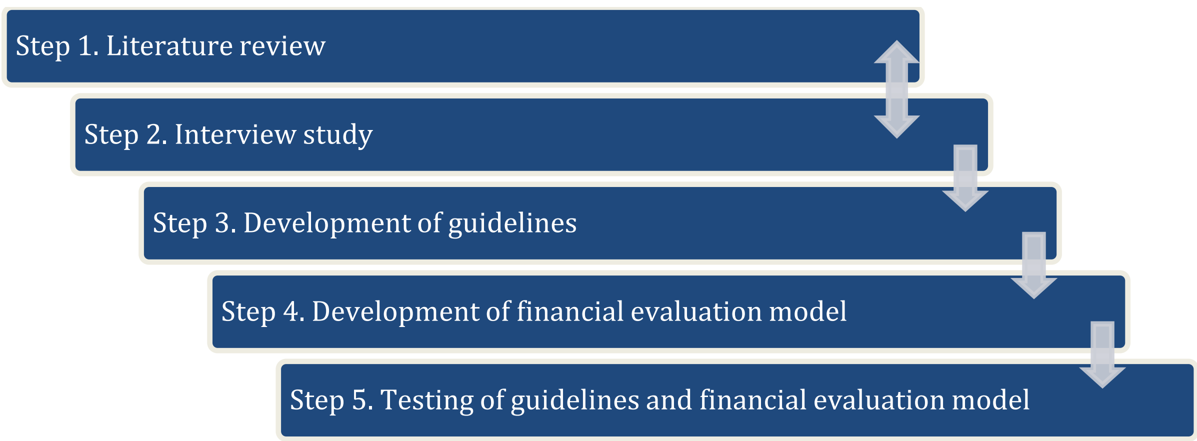


Figure 6. A principal overview of the research design in five steps.

3.2 Literature review

The abductive approach entails a need for enquiring theory in different periods and with different keywords due to input from interviews. Therefore, keywords and literature selections were changed over time and led to a wider scope of investigated literature. The main database used for finding and selecting academics articles were Scopus, Google Scholar and the Chalmers University's in addition to snowballing references. Reports and publications from authorities and relevant associations was included in the literature review when relevant. Bell et al. (2022) argue that academics journals can take long time to become published and therefore reports and publications from authorities and associations can cover more recent developments and events. However, academic articles are the dominant source of knowledge and were therefore primarily used. Selecting criteria for literature was that it should be as current as possible and there was a preference for literature which had been extensively cited. The keywords used were dominantly "Microgrid", "investment", "management", "LCOE", "NPV" and "renewable energy".

3.3 Interview study

The interview study was conducted to gain more insights and thorough explanations of topics relevant for MG evaluations. Since the literature coverage of MGs are large, difficult to interpret and hard to find in the Swedish context, there was a need to acquire contextual knowledge. Therefore, interviews with a qualitative strategy are applied which focused on questions that provided generalization of the vast literature pool. Performing interviews with a qualitative strategy are not as bound to the predetermined structure of questions and are therefore more flexible (Bell et al., 2022). This suited this thesis since it has an abductive approach. However, the interview guide was not changed during the research process, but follow-up questions became more detailed over time. The interview guide is presented in appendix A.

There are two common types of qualitative interview studies: the unstructured and semi-structured interview (Bryman et al., 2022). Differentiating these two types are how well-prepared the researcher is with predetermined questions. In both types, the flexibility is high relative to the structured interview, but a semi-structured interview usually has some specific topics that the researcher wants to cover. The semi-structured interview is preferable for this thesis since the topics; finance, design, and technology were predetermined by Serneke. Hence, the interview guide was based on these. Before the interviews, interviewees were given the choice to read the interview guide as preparation and during the interview, the topics were selected based on the interviewee's experience.

In total, eight interviews were conducted during approximately one month. The goal when selecting interviewees was to find a diversified pool of interviewees, that is knowledge or experiences from all three main topics which implied selecting different roles in the field. In table 2, all interviewees are presented with date, role, topics covered, if the interview was recorded, and argument for the interview.

Table 2. Eight interviews were conducted based on three topics: finance, design and technology.

Interviewee (acronym)	Interview date	Present role	Topic(s) covered	Recorded interview?	Argument for the interview
Peder Zandén Kjellén (PZ)	2022-10-03	Researcher in environmental science	Finance, design, technology	Yes	A researcher but has previously been a project manager at a MG project which gave broad insights to all topics
Magdalena Nääs (MN)	2022-10-05	Property Developer at construction company	Design	Yes	Part of a construction company which developed a residential project with solar energy and battery storage which gave insights of designing MGs
Nicklas Bäcker (NB)	2022-10-07	Strategy Chief Officer at battery supplier company	Finance, design, technology	Yes	Knowledge about battery technology and financial evaluation of including it in MG
Edvin Guéry (EG)	2022-10-11	Product Manager at battery storage systems company	Finance, design	Yes	Experience on the complexity of designing and operating energy management system to generate financial benefits
Tommy Magnusson (TM)	2022-10-13	Hydrogen Consultant	Design, technology	Yes	Expert knowledge of the hydrogen technology and how to adapt it into the urban context which no other interviewee shared.
David Steen (DS)	2022-10-19	Researcher in electrical engineering	Technology	No	Insights of necessary technology components and general structure of the Swedish electricity market
Magnus Olsson Brolin (MOB)	2022-10-21	Electricity market strategist at Svenska Kraftnät	Finance	Yes	Determine how the electricity market will evolve over time and experiences of locally traded energy to evaluate predictions for financial evaluation
Peter Lindström (PL)	2022-11-14	Electricity strategist at real estate company	Finance, design	Yes	The real estate owners view at one of the largest Swedish commercial real estate owner

During the interviews, the interviewees were asked about their role, experience, and knowledge of MGs to establish trustworthiness of the empirical data collected. Interviewees one, two and seven had specific case experiences and thus were asked to elaborate about these. Every interviewee was asked if they wanted to be anonymous and if it was allowed to record the interview. All interviewees accepted the publicity and therefore all interviewees are referred to by name. Most of the interviews were conducted digitally, recorded, and lasted about one hour each. All recorded interviews were transcribed which enhanced the analysis with the thematic approach that was used (Bell et al., 2022). This is common for qualitative data sets and relates to finding topics that reappear throughout the study (Bell et al., 2022). Results of the interview study were coded where similar topics from different interviews were summarised in the same categories.

3.4 Development of guidelines

The guidelines are the result from information gathered in the literature review and interview study. They were developed through a workshop format with the authors of this thesis as participants. First, an initial generation of factors that needs consideration when evaluating a MG were established. These factors were then grouped into more holistic categories with the factors as sub-bullets. When the holistic categories and factors were established, the causality between the categories was determined. The causality was of great importance for the guidelines since it is what determines the process order. The categories were then arranged to follow a logical path according to the causality and the guidelines were designed.

3.5 Development of a financial evaluation model

The development of a financial evaluation model was based on the findings in the literature study. Previous research with the aim of developing a similar model was used to set the basis. In general, the model is constructed by estimated costs and revenues through a discounted cash flow analysis. The costs were developed by LCOE calculation and revenues with a NPV calculation.

3.6 Development of guidelines and testing of financial evaluation model

In addition to develop the guidelines, the financial evaluation model was tested as Karlastaden in Gothenburg. The contractor and developer, Serneke, wanted to understand the full potential of implementing MGs which led to that the financial evaluation model was tested. Serneke provided information about the site and other input data related to Karlastaden to perform test of the financial evaluation model. Additional data such as the electricity spot prices, electricity load, frequency regulation, and some technology costs estimations were collected from public data, organizational documents, and media outputs. It was difficult to find reliable data in Swedish currency, hence, exchange rates EUR/SEK and USD/SEK were downloaded from Yahoo Finance (n.d.). Furthermore, the testing is geographically bound to Karlastaden and therefore a regional context was applied in the data gathering process.

The data collected were first reshaped in Excel to fit the financial evaluation model and to decrease the complexity. This was done by calculating average values and reviewing potential outliers that could affect the result. Since it is difficult to predict the future and for it to be applicable in future studies, the financial model was created with the purpose to run different input parameters, the complete script can be viewed in appendix B, C and D.

3.7 Validity and reliability

A qualitative study often experiences difficulties in reaching high levels of validity and reliability due to changing social conditions and relationships (Bell et al., 2022). This thesis has, for instance, presented a couple of aspects that could be considered as aggravating circumstances for construction of MGs. However, these factors may not be seen as aggravating in the future, or the social construct have changed the viewpoint of these factors into seeing them as something necessary or beneficial.

The validity of a qualitative study is determined based on sample sizes and duration of observations (Bell et al., 2022). The goal for qualitative studies is to reach a theoretical saturation which requires large sample sizes. Due to time boundaries for this thesis, observations over a long period are not possible. However, this might not be as important for this thesis since evaluations of MGs are likely to change in the future due to rapid changes in technology, legislation, and costs. Therefore, sample sizes become more important than duration of observations. Largest possible sample size until theoretical saturation have been strived for. A good sample size bearing in mind the limitations for this thesis have been achieved.

The reliability of qualitative studies is dependent on multiple aspects whereas sample size is one. (Bell et al., 2022). This thesis has pursued high reliability by transcribing all recorded interviews to ensure valid interpretation of the interviews. To reach even higher reliability, all interviewees were giving the opportunity to validate their statements by reading the interpretation after the interview was performed (Bell et al., 2022). This means that the finished results are shared with the interviewees and that they had the possibility to change or reject their statements if the results had been understood incorrectly. This method led to more reliable results since the interviewees agrees on their statements in two separate periods and settings. Additionally, both authors of this thesis were present in all interviews except the one with Peter Lindström due to sickness. Since two persons interprets the result of each interview, it is more probable that alternative interpretations are captured.

4 Result from interview study

The results from the interviews were decoded according to technology, design, and financial subjects. However, several topics affect all subjects and is therefore described from multiple perspectives.

4.1 Energy production and storage technology evaluation

In general, the interviewees are positive towards implementing PV cells and batteries, while hesitant towards implementing hydrogen and wind turbines. This is also true for the real estate context (PL). Wind turbines are a good energy source with low cost per produced kWh for large scale farms, but which makes it inappropriate in the urban context (EG, NB, MOB). MOB indicates that the economy of wind power scales in a non-linear relationship with size, which means that larger wind power plants produce a lot more than smaller plants to a lower cost.

> *To be profitable with wind energy you must build a rather large plant since you have a wind power scale on approximately raised to the power of three on swept area of the turbine [...] while you do not have any scale on solar power. Therefore, solar power is rather suiting in an urban context – MOB*

NB and PL explain that wind turbines in the urban context creates a lot of vibrations and disturbances, EG argue that it is not efficient as large wind turbines. Furthermore, EG explains that wind turbines have higher Opex since the turbines have moving parts and estimates that this expenditure is around 2 percent of the investment initial cost. PZ and MN do however mention that MGs have low Opex in general. MOB argue that wind might suffer from aesthetic aspects which potentially could hamper approval processes. In comparison, PV cells are better in smaller scale, for example the urban context (MOB, NB) where PL estimate that their buildings can produce up to 10 percent of the electricity demand. PV cells are especially interesting for PL since the production profile is matching the consumption for commercial buildings, that is high during the day. NB explain that installation of PV cells is not particularly good from a business perspective due to high costs per produced kWh and that it rather focuses on achieving tax benefits and greener profile on buildings. An owner of PV cells does not need to pay taxes on produced electricity up to a certain amount of installed capacity and therefore PV cells comes with tax benefits (NB). MOB argue that irradiation could be easier to predict than wind and that this aspect would be preferable, especially if the MG strives to be self-sufficient to some degree. Furthermore, it will be easier to plan the amount of energy that needs to be purchased and how the energy storage should be used (MOB). But MOB also argue that it could exists some sort of benefit with a hybrid RER system from an energy production perspective.

RERs intermittency problem is discussed by a multitude of interviewees. The main issue with intermittency is that a lot of energy is produced at the same time during certain conditions, for example windy or sunny weather (NB, PL). This production profile does therefore not match the consumption profile of energy which leads to larger spot price volatility and supply issues in certain periods. PZ extends the discussion by arguing an increased risk with having RERs close to each other, which is the case for an MG. If RERs are located far away from each other, they will not have the same production profile since the weather conditions will differ. This results in a combined production profile that matches the consumption profile better. NB and PZ believe that the intermittency problem could be mitigated with the introduction of ESSs since the production profile therefore could be matched with the consumption profile. PZ argues that backup power is necessary in off-grid MGs due to the intermittency of RERs and therefore supports NBs statement. TM elaborates the discussion by arguing that plannable energy sources, the opposite of intermittent energy sources, should not have been dismantled so quickly in Sweden since plannable energy sources contributed with frequency stabilisation in the Swedish energy system. PZ does however argue that frequency stabilization could be achieved by introducing ESSs in the energy system.

The main difference between hydrogen and batteries as storage technologies is that hydrogen is used in the long-term and batteries in the short-term (PZ, TM, NB, MOB, EG, PL). Batteries have an optimal storage time of a couple of hours and hydrogen for longer periods than that (EG, MOB). Hydrogen suffers from a low roundtrip efficiency (PL) around 30% (PZ, NB) to 25% (TM) but have lower cost per stored unit of energy (PZ). This means that the system could store larger amounts of energy to a lower cost compared with batteries since the components itself are cheaper. Therefore, hydrogen storage has a lower marginal cost and is suitable for storage of large amounts energy (PZ). Furthermore, PZ, PL and MOB argue that the business case and utility of hydrogen storage could be better if the heat from the fuel cell combustion is recovered. This heat could then be distributed in the buildings through a local heat network and is important since a lot of energy from the fuel cell process is otherwise wasted in the form of heat. MOB further argues that hydrogen is a necessity today if a MG should be self-sufficient to any degree.

NB argues that batteries are today superior to hydrogen since they are more commercially available but there is probably only a matter of time until the costs and efficiencies for hydrogen systems are competitive with batteries (EG, NB). Furthermore, EG argues that batteries are used for most applications today but believes that a multitude of technologies, going beyond hydrogen and batteries, will be used in the future depending on requirements and purposes for the ESS. However, batteries are creating the possibility to achieve other revenue streams and have higher roundtrip efficiency (NB). PZ discuss that reuse of batteries from electrical vehicles could decrease the high, marginal, cost with batteries. However, old batteries have more safety risks that need to be addressed. In the comparison of safety between hydrogen and batteries, interviewees argued that hydrogen and batteries have sort of the same risk profile (NB, TM). TM argue that the only reason that there exists a scepsis towards hydrogen is because it is not as commonly used, i.e., it is a new and emerging technology. This means that there is a lack of knowledge and regulations of such installations which creates hesitance towards applying it. NB argued that there is a similar risk profile for both storage technologies but where hydrogen is a bit more complex to handle. An interesting extension of the discussion is that TM argued that flow batteries is almost risk-free from a safety perspective which could mitigate the hesitance experienced of the other technologies. Nowadays, lead and lithium-ion are the most common for storage (EG, TM) whereas lead batteries are mostly used for background processes during shorter periods (EG). In the real estate context PL explains that batteries require buildings to be dimensioned for increase fire and structural load. Similarly, hydrogen is explosive and needs large space to be interesting as storage technology. This is a problem for buildings in high density urban areas but not for logistics hub outside of the city.

4.2 Regulatory and risk aspects of design

The interviewees highlight regulatory issues concerning the design of MG which are connected to property boundaries and the ability to distribute electricity. The Swedish power regulation did previously tax all power that were transmitted over the property bound (PZ). This meant that if electricity were produced in one property and were transmitted to another property, e.g., for storage, then that power was taxed even if it had not been consumed yet. Lately, a partial solution to this was released whereas the double taxed electricity will be repaid when tax is declared (PZ). The tax issue is still paramount and is often the decisive factor for designing MG setup (PZ, MOB). Furthermore, other issues with property bounds exists due to establishing ownership of revenues and costs (NB, MN) and the allowance to build an internal grid between buildings, which is a necessity for MGs (MOB, EG, PL). It just recently got allowed to construct an internal grid for electricity sharing in Sweden but is still only allowed on a small scale with one owner (EG). Electricity sharing in larger areas and with more owners involved is still only tested in pilot projects (EG) or allowed in certain contexts such as airports or universities (MOB). According to MOB, heat does not require this allowance for sharing and is viewed completely differently than for sharing electricity. The ownership of revenues and cost becomes important to establish when considering design since it otherwise is hard to evaluate the feasibility of an investment in an MG (NB).

The reliability of supply also becomes an important aspect to consider in the design of an MG. As previously mentioned, the intermittency of RERs constitute a problem that cannot be neglected. If the MG is grid-connected, then it is important to ensure that the system functions properly and that electricity is transmitted from the distribution grid if needed (PZ). Furthermore, measures to mitigate the intermittency could be applied, such as the installation of batteries (PZ, NB). If the MG have the ambition to either be partly islanded, i.e., no connection or distribution from the external grid, or to have an improved resilience, then there is a need for backup energy (PZ, EG, MOB) and handling the intermittency problem (PL). Backup energy can be in the form of diesel generators, which is the traditional approach, or as battery/hydrogen storage (PZ, TM, EG). However, the adaptations that need to be implemented for increased resilience is complicated (EG). For example, EG mentions that a BESS needs to have an additional battery for rebooting purposes and a smart inverter to assure stabile frequency on the grid if the MG should be able to island itself. Furthermore, if there exists an ambition to be self-sufficient for a longer period, then hydrogen storage is a necessity (TM, MOB).

The safety risks with batteries and hydrogen constitutes a real problem for the design of MGs (MN, TM, NB). Since batteries are traditional and commonly applied in various context, it becomes a comfortable choice for storage (TM). However, there are similar safety risks for both batteries and hydrogen and therefore it exists a need to implement significant precautions for both technologies (TM, NB). TM explain that the lack of regulations in a building context creates a large hindrance in the adoption of hydrogen, but also mentions that such regulations and standards are under development. In the case of hydrogen fuel stations, there is a need to have a minimum of two metres in horizontal distance between the tank and people. Another precaution under consideration is to design hydrogen storage located on the roof since the potential explosion then can be directed to non-hazardous areas. TM believes that it is too early to locate a hydrogen storage inside a building since the risks are too high. However, safety also needs to be considered regarding implementation of batteries, but these precautions are more standardized today (TM).

4.3 Five financial benefits of MG

The interviewees have identified five possible uses for an MG that either creates revenues or that reduces costs. The most frequent financial benefit mentioned by the interviewees is the self-consumption of electricity and in that way reduce the amount of purchased electricity (DS, PZ, NB, MN, EG, MOB). MN and MOB argues that the cost savings due to the self-consumption of produced electricity is more important than potential revenues that a MG can generate. MOB elaborates that this is especially important since there is taxational benefits with the self-consumption of electricity due to a netting of consumption behind buildings in a MG. The taxation problem has been mentioned before but is of paramount importance to make a MG financially feasible (PZ, MOB, NB, MN). Furthermore, connected to the taxation problem and mentioned briefly earlier, NB means that the determination of ownership of different parts of the MG is important to enable a financial evaluation. This is often a rather complex issue and something that needs to be solved to stimulate investments in MGs.

The second most frequent financial benefit mentioned by interviewees was spot price arbitrage. An ESS, which is part of an MG, allows the owner to purchase electricity when its cheap and sell it when it is more expensive hence creating a revenue (EG, DS, NB, MOB, PZ, PL). This use of the system has become more relevant in recent times due to high volatility on the spot price market (PZ, TM, MOB, NB, EG). However, this will probably also lead to the introduction of more agents on the market hence creating a lower arbitrage potential in the long run. PZ, NB and EG argue that when investments in locally produced and stored electricity becomes more lucrative than buying from the external grid, then more agents will enter the market. The introduction of agents will create greater competition hence reducing the possibility of spot price arbitrage and could be considered as a tipping point.

> *When you create market models which is extremely complex, then you need to consider that other people also perform an optimization on the variation. If everyone performs an optimization on the variation, then the variation will decrease – PZ*

The third most frequent financial benefit mentioned by the interviewees are the ancillary service markets (EG, MOB, DS, NB, PZ). SvK have rather strict demands on suppliers if they should be able to participate on the FCR market and therefore it is common to use an aggregator service (EG, MOB). SvK demands a relatively high power capacity, and the aggregator therefore combines the capacity from multiple energy storages to accumulate enough power. The prices on this market are currently extreme and EG mentions a pay-back time for a battery investment of three years with revenues backtracked between 2020 to 2022. The potential of this market is however ambiguous. The FCR market is dimensioned after the largest energy production facility in the Nordics since a potential disconnection from this facility would cause the biggest disturbance on the external grid (NB, EG). Therefore, the power volumes of this market are fixed. This means that when more agents enter this market, the prices will go down and the power volume will be fixed which leads to a contracting market volume (NB, EG). However, other interviewees argue that the market volume will increase in the future due to introduction of intermittent RERs (MOB, EG). EG argues that the increased proportional size of RERs in the energy mix will create more instability on the transmission grid hence leading to more demand for ancillary services.

> *The more intermittent production you introduce you will not get a more stable grid, but you will only get production which could go up and down. But you will have the same inertia on the grid which leads to that it could get much more instable and then ancillary services will be needed to maintain a stable electricity production – EG*

Therefore, EG summarize this by arguing that on one hand, the increased supply from the expected entrance of new agents on the market will reduce the prices hence reduce the market volume. On the other hand, increased demand for services due to increase proportional size of RERs in the energy mix will increase market volumes and therefore the estimation of the size of this market in the future is complex.

The fourth and fifth most frequent financial benefits mentioned by the interviewees are the local-flex market and power peak cutting (EG, DS, MOB). The local-flex market is still under development but will work as a FCR market but only on a local scale. Today, the market has been tested in Stockholm and will be launched in Gothenburg soon. The power peak cutting aims at reducing power peaks which is possible with the use of an ESS (EG). Power peak cutting is especially important for some property owners since they will pay the price when the power is peaking. There are only some property owners that has these power peak agreements today, but this type of agreements will increase in the future. EG argue that EI projects that all property owners, including private homeowners, will have these types of agreements before 2027.

To sum up, the five financial benefits mentioned by the interviewees are self-consumption of electricity, spot price arbitrage, frequency contingency regulation, local-flex, and power peak cutting. DS argues that ancillary services are the most beneficial usage of a MG currently, followed by spot price arbitrage and power peak cutting. Self-consumption of electricity comes second to last in DS ranking and local-flex at last place. Local-flex is ranked last due to the uncertainty of this market due to that it is still under development. PZ explain that to reach optimal usage of ESS all these financial benefits can be utilised. To evaluate the investment a lifecycle cost analysis can be used (PL). This is a net present value calculation with a discount rate and several other assumptions. However, it is difficult to predict future revenues. For example, PL explain that in previous years it was easier because electricity prices were steadier while today, they are more volatile.

5 Development of managerial guidelines and financial evaluation model

The managerial guidelines and financial evaluation model are presented in this chapter. The guidelines are the result from the literature review and interview study and represents the necessary factors to consider, and in what order they should be considered. They therefore constitute a process for evaluating the financial feasibility of an MG. The financial evaluation model is used in the last step of the managerial guidelines and are mainly a result from the literature review where minor adjustments have been made to suit this thesis.

5.1 Development of managerial guidelines

The managerial guidelines presented in figure 7 are intended to be used by project or business developers in the real estate sector. The guidelines final output is a financial evaluation of an MG, and the process follows the causality between the factors. However, the development of managerial guidelines is a complex endeavour. It is complex since the definition of a MG is unclear and since the causality between all factors is difficult to determine. There is often a two-way relationship between factors and therefore the managerial guidelines have reiteration loops since information in a later stage could restart the evaluation. Stadler et al. (2016) argued that designing a MG is more complex than the traditional power grid but that it could be profitable since it creates new value streams which is an opinion shared by the interviewees. The guidelines intend to mitigate the complexity of evaluating the financial feasibility of MGs since project or business developers can follow a process of what to evaluate and in which order. Technology, design, and finance were the topics that were firstly investigated due to Sernekes' initial efforts of evaluating MGs. The topics are still present in the guidelines where the choice of technology to further investigate is the first decision gate (DG1). The second decision gate (DG2) is if restrictions or laws hinder the design of MGs, and if that is the case, then the project or business developer needs to reiterate to the technology step (DG1). The last decision gate (DG3) aims at evaluating if the choices made from previous decisions leads to profitable investment, otherwise the project or business developer needs to start over from the technology phase (DG1) or end the evaluation process. Notice that all information from previous steps should be included in the decision-making process per step.

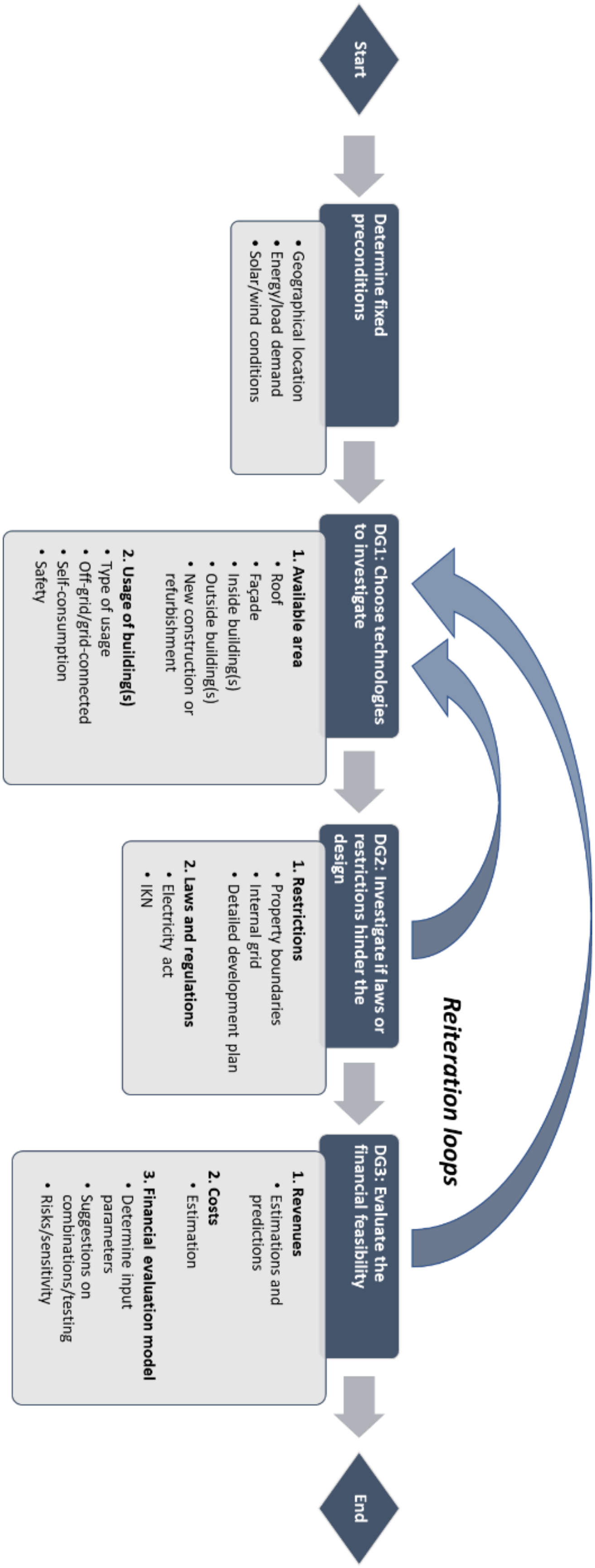


Figure 7. The managerial guidelines which represent important factors to consider when evaluating financial feasibility of a MG.

The guidelines are organised so that there, under each topic, exists a couple of bullet points which represents factors that needs to be investigated. The first step of the managerial guidelines is to determine fixed preconditions. The preconditions are geographical location, energy and load demand, and solar and wind conditions. These factors cannot be altered and therefore functions as constraints or boundaries for the remainder of the evaluation. The geographical location affects the choice of off-grid or grid-connected MG, determines the local solar and wind conditions, and determines which detailed development plan that is effective. The energy and load demand also affects the choice of constructing an off-grid or grid-connected MG, how high the self-consumption ratio should be and the size and number of production technologies. The solar and wind conditions are important to establish since an unfavourable condition of one energy source could lead to rejection of PV cells and wind turbines in DG1. However, unfavourable conditions do not automatically lead to rejection of connected production technologies. As in the case of wind turbines, VAWTs are more beneficial in turbulent and low-velocity areas than HAWTs, and therefore VAWTs could be chosen as technology to further evaluate if such conditions were prevalent. Similarly, PV cells can be mounted on the roof or façade of the building or besides the building depending on the location preconditions.

The second step, which is the first decision gate (DG1), is to determine and choose which technologies that should be further evaluated. The determinants for this choice are the fixed preconditions, the available area and usage of building(s) with connectivity to the MG. The available area factor constraints the choice of technologies since technologies cannot be adopted if they cannot be placed within the MG. There are also additional considerations needed regarding available area. For example, EG, NB and MOB argued that wind turbines are a good energy source but not in the urban context. MOB furthermore elaborated that wind turbines have a large economy of scale which implies that a large area is necessary to achieve best preconditions for profitability. Furthermore, wind turbines could be beneficial on tall buildings where the turbulence is lower and the velocities higher (Škvorc & Kozmar, 2021; Sunderland et al., 2016). But if wind turbines should be situated in the roof, then PV cells may need to be located elsewhere if the wind turbines for example cast shadows affecting the solar conditions. Furthermore, if there is not room for storage technologies, then they cannot be adopted. In the case of hydrogen, TM believed that it still is not safe to situate hydrogen tanks inside of buildings and therefore it becomes important to ascertain that area is available in a safe area outside. However, the project or business developer should not only consider the rejection or acceptation of technologies based on available area since it also is important to include the usage of buildings in the analysis.

Usage of building(s) aims at identifying the operations that will take place around the MG. The operations will determine the resilience and safety concerns. If the operations require a high level of resilience, then some sort of backup energy is needed, regardless of grid-connectivity (PZ, EG, MOB). The type of usage could also lead to rejection or acceptation of certain technologies that otherwise would not have been investigated. Imagine that there is a requirement that the MG should be self-sufficient for more than a couple of hours, then hydrogen is a necessity (MOB). This means that hydrogen is inevitable if the MG will not be grid-connected. Off-grid MGs are also generally over dimensioned in terms of energy storage since it requires larger energy storage (Ferrario et al., 2021). From an evaluation perspective, the energy storage aspect becomes important for a project or business developer if the MG will be an off-grid system. The choice of off-grid/grid-connectivity therefore has a large impact on choice of technologies and the decision of installed capacity for production or storage technologies. The self-consumption factor is included in the guidelines if there is any preference from the owner of the MG regarding how much of the demand that should be supplied by own production. Such a preference affects the choice of technologies and the emphasis on production or storage technologies.

Safety concerns becomes important when deciding on which storage technologies to include in the MG. PL explains that buildings need to be dimensioned for increased fire and structural load to be able to implement battery storage. Whereas hydrogen instead need large spaces due to it being explosive and flammable (PL). TM also argues that hydrogen storage cannot be located inside buildings yet, due to safety risks which leads to the requirement on finding available area outside. However, NB and TM argued that batteries and hydrogen have similar safety concerns associated with them, but batteries are favoured due to more widespread application and standardized safety precautions. Hydrogen can also become more costly since it is not as common. Such considerations could lead to rejection or acceptance of technologies, all dependent on the specific MGs preconditions and requirements.

The third step (DG2) is to investigate if restrictions hinder the design of the chosen technologies. Laws and regulations also guide the design of the MG to make it legal and profitable. The determinants are the chosen technologies (DG1), restrictions, i.e., property boundaries and internal net structure, and laws and regulations. Other law and regulations, such as the Swedish plan and building act, need to be followed per default when constructing or refurbishing buildings and should be included in the evaluation.

Design of a MG is important since it affects the revenue streams from electricity production or storage sources. Electricity sharing is restricted by EI (n.d.a.) as they grant certain grid operators the monopoly of distributing electricity in a geographical bound area. The issue with restrictions of transmitting electricity freely were also highlighted by the interviewees. It is therefore crucial to design a MG as a IKN to be able to distribute electricity freely by avoiding paying extra fees such as energy tax and electricity transmitting fee. The energy tax applies at consumed electricity, electricity distributed on a monopoly grid and for production facilities larger than 250 kW for wind and/or 500 kW for solar. Avoiding these fees can be interpreted as increased revenues thus increasing the revenue stemming from electricity production sources. According to PZ and MOB the energy tax issue is often the decisive factor for designing the MG setup. In 2023 the energy tax in Sweden is set to 0.36 SEK/kWh excluded VAT (EI, n.d.c.) and if it can be avoided, it yields a substantial increase in revenue. Like the energy tax, the electricity transmitting fee from the grid operator can also be avoided if the MG is properly designed. According to EI (n.d.d.), the electricity fee is dependent on the grid operator and is decreasing for larger customers.

The easiest way to achieve IKN is by having an internal grid (EI, n.d.b.). For large buildings with a mix between the usage of the building this could be more easily accomplished since it will be considered an internal grid. It is electricity distribution between buildings which complicates IKN granting. It is possible to distribute electricity between buildings by a low-voltage grid within the grid owner’s property boundaries if these buildings do not share the same connection to the external grid nor transmitted via airborne power lines (EI, n.d.b.). There are several more paragraphs in the regulations with exceptions to achieve IKN. But since the prejudices are outdated and cannot be used as reference projects it is hard for property or business developers to know for sure how to achieve IKN. It is also not certain that the produced electricity matches the demand for electricity at a given time, previously explained as the intermittency problem of RERs (Bahmani-Firouzi & Azizipanah-Abarghoose, 2014; Eriksson & Gray, 2017; Zhang et al., 2013; Mizani & Yazdani, 2009; Mengelkamp et al., 2018; NB, PL). This would affect the ability of distributing electricity freely without fees and taxes, and in the next step the overall profitability. In this case the project or business developers needs to consider designing a MG with storage technologies and reiterate back to DG1 if it is not already included.

Storage technologies can be used to utilise the overproduction of electricity instead of selling it to the external grid where it is not possible to avoid the fees. Therefore, the mix of production and storage sources is also important to consider in the MG design to be able to gain highest possible revenue. Several prior studies (Bahmani-Firouzi & Azizipanah-Abarghoose, 2014; Eriksson & Gray, 2017; Zhang et al., 2013; Mizani & Yazdani, 2009; Mengelkamp et al., 2018) emphasize the importance of mixing storage and production sources to reduce the intermittency problem with RERs. Storing electricity while the wholesale price is low and distributing it at high wholesale price can optimise the revenue streams and give better profitability. To succeed with this, the internal grid needs to be structured in a way so that the electricity can be transmitted between production and storage freely. Once again, if the electricity is transmitted between the sources on an IKN, that is not leaving the internal grid or building, the revenue streams is optimised. Therefore, the placement of decided technology is necessary to consider. The placement of all technologies must be designed to operate within the same IKN to gain the evaluated benefits. If this is not the case, the project or business developers must consider reiterating back to DG1 since it affects the overall profitability.

The fourth step (DG3) is to evaluate the financial feasibility of the MG investment. Determinants are the design of the MG (DG2), evaluated technologies (DG1), and estimated revenues and costs dependent on DG1 and DG2. The financial evaluation topic has a financial evaluation model as the last factor where the profitability is estimated. A risk and sensitivity analysis should be performed in connection to the financial evaluation model to establish the confidence of the estimation.

There are six possible revenue streams that can be achieved with MGs according to the interviewees. However, not all revenue streams are possible to achieve since there is a dependency on grid-connectivity and choice of technology. Therefore, which revenues that should be evaluated depends on the design and choice of technology from previous steps (DG1 and DG2). The six possible revenues are: self-consumption or sale of electricity, spot price arbitrage, ancillary services, local-flex, and load peak shaving (all interviewees). Spot price arbitrage, ancillary services, local-flex, and load peak shaving is dependent on the availability of energy storage (Kadri & Raahemifar, 2019; Dagget et al., 2017; EG; MOB; DS; NB; PZ; PL). Self-consumption or sale of electricity are the only revenue streams that is available if the MG does not have any available energy storage.

Spot price arbitrage and self-consumption of electricity are dependent on the spot price and therefore it needs to be predicted to estimate these revenues. However, consideration needs to be taken regarding taxes and transmission fees when estimating revenues originating from spot prices. If the electricity is assumed to be fully consumed within the MG, the taxes and transmission fees should be allocated to the end-consumer. This means that the retail price is the price at which electricity is sold and bought at. However, if the electricity is sold back to the external grid, then taxes and transmission fees should be included in the purchase price but not in the selling price. Therefore, there is a direct loss of revenue when dealing with the external grid. Renumeration for ancillary services (SvK, n.d.a) and local-flex markets depends on which service that is provided. Therefore, price predictions for every market that the MG intends to participate in needs to be performed. The load peak shaving leads to a reduction of the maximum load fee and should therefore be estimated by the percentage of reduction in maximum power and the corresponding maximum load fee. If the MG is not connected to the external grid, the only revenue stream that is possible to achieve is the direct sale of electricity to agents included in the MG. Direct sale of electricity is the same as self-consumption but where the consumed electricity is completely self-produced.

Costs should be calculated with a present value calculation where the LCOE is the ubiquitous one for electricity production projects (Hernàndez-Moro & Martínez-Duart, 2013). However, the profitability of the projects should be evaluated through NPV since the LCOE does not consider the size of revenues. Bazilian et al. (2013) argues that ROI also could be an appropriate measure of profitability and could be seen as a complementary measurement to NPV. The LCOE measurement is primarily intended for electricity production projects and not energy storage projects. However, some alterations of the calculations make it suitable for evaluation energy storage projects or combinations between production and storage (Lotfi & Khodaei, 2016; Pawel, 2014). The costs should be estimated through available cost data from academic research or through quote requests from suppliers.

The financial evaluation model aims at providing a complete overview of the financial performance for the chosen design and technologies included in the MG. The first action should be to determine all input parameters in the LCOE equation 4 and 5, and revenue figures. When these input parameters have been determined, LCOE, revenue and NPV figures should be calculated. Since revenues is hard to predict due to fluctuating electricity prices it is preferable to develop scenarios regarding price development (Hoppmann et al., 2014). The scenarios will widen the probable price range in the future and enable a more robust risk and profitability analysis. The combinations of technology with the largest NPV will be chosen by a rational investor (Berk & DeMarzo, 2014). Although the combinations with the highest NPV should be further evaluated, given that there is no limitation on financing, the combinations should be analysed through a risk perspective. Furthermore, a sensitivity analysis should be performed which guides the risk analysis since the sensitivity analysis gives the project or business developer a ranking regarding which factors that creates the biggest effects on the NPV value. The factors that which creates the biggest divergence in NPV should therefore be further and more thoroughly investigated. Previous studies shows that a common factor which have a big effect on the profitability is the discount rate (Hoppmann et al., 2014; Hèrnandez-Moro and Martínez-Duart, 2013; Bazilian et al., 2013; Abdelhady, 2021). There does also exist an interesting connecting between risk and the discount rate since an investor desire a higher premium the riskier an investment is (Berk & DeMarzo, 2014). The discount rate will therefore increase with the uncertainty of the project. This could lead to a negative NPV and uninitiated projects. Since the discount rate can be seen as risk factor (Berk & DeMarzo, 2014) it is the project or business developers' decision to choose discount rate, where common discount rates are ranging from five to 15 percent. This leads to the argument that financial evaluations should be performed thoroughly and accurately since profitable investments otherwise might be unrecognized. If the results are not financial favourable the project or business developers need to reiterate back to the first and second decision gate.

5.2 Development of financial evaluation model

The financial evaluation model is integrated in the managerial guidelines and constitutes the last part of the process. However, data regarding revenues and costs is needed to establish the financial feasibility of the MG. Therefore, this section aims at presenting the evaluation model that has been developed and will be tested based on the revenues and costs for the project Karlastaden previously introduced in section *1.2. Introduction to Karlastaden.*

The evaluation model consists of three parts: revenues, costs, and profitability. The most ubiquitous method for establishing costs in electricity production projects is the LCOE (Martínez-Duart, 2013). This method also provides the most detailed estimation since it evaluates parameters that varies depending on the geographical context (Bazilian et al., 2013). The LCOE method is also coherent with NPV which is stated to be an important feature (Marchioni & Magni, 2018). The LCOE method could be adjusted to involve financial parameters such as amortization, interest, and technical parameters such as combination of storage and production (Darling et al., 2011; Pawel, 2014). Pawel (2014), Lotfi and Khodaei (2016), and Darling et al. (2011) used different LCOE methods in their profitability investigations for electricity production projects. Darling et al. (2011) presented a calculation which involved financial parameters, Lotfi and Khodaei (2016) and Pawel (2014) included storage system in their evaluation of an MG, but with various approaches. Therefore, a combination of the applied methods will be used in this thesis and is presented in equation 9.

$$LCOE = \frac{I - \sum_{n=1}^{N} \frac{Dep}{(1+r)^n} * t_c + \sum_{n=1}^{N} \frac{OPEX}{(1+r)^n} * (1-t_c) + \sum_{n=1}^{N} \frac{CapEx}{(1+r)^n} - \frac{RV}{(1+r)^n}}{\sum_{n=1}^{N} \frac{kWh_{out/produced} * (1-SDR)^n}{(1+r)^n}} + \frac{St_{dummy} * CAGR * n * p_{r,0}}{\eta_{st}} \quad \text{(Eq.9)}$$

Equation 9 is the same as equation 5 presented in section *2.3.3. cost evaluation of electricity production projects* but with a dummy variable for the storage part of the equation. If the evaluated MG includes storage technology, the dummy variable is set to 1, otherwise it is set to 0.

Revenues are difficult to predict due to the long timespan for a financial evaluation and the difficulty of predicting prices for longer periods than three years with certainty (Ziel & Steinert, 2018). Since common evaluation periods are 30 years (Hunter et al., 2021; NREL, 2022), Darling et al. (2011) used CAGR estimates on spot prices to predict these for a longer period. This is seen as a suitable approach since more detailed approaches probably will have the same uncertainty. The approach could be suitable for other revenue categories as well, e.g., ancillary services. However, a plausibility analysis of price developments is needed, and other approaches may be more suiting in particular cases.

In a NPV calculation, the revenues and costs are combined in the same model (Berk & DeMarzo, 2014). However, LCOE is an NPV value with revenues set to 0 and divided with the produced electricity over the systems' lifetime (Darling et al.., 2011; Sunderland et al., 2016). This means that the NPV can be achieved by subtracting the LCOE from the revenues given that the revenues are stated as revenues per produced electricity over the systems' lifetime. The NPV in this financial evaluation is therefore calculated by equation 10 for this thesis.

$$NPV = Revenues * (1 - t_c) - LCOE \qquad \text{(Eq.10)}$$

6 Testing of managerial guidelines and financial evaluation model

The last step in the managerial guidelines and the financial evaluation model will be applied and tested at the urban district, Karlastaden, Gothenburg in this chapter. The evaluated technologies are PV cells, wind turbines, battery storage and hydrogen storage.

6.1 Introduction to Karlastaden

Karlastaden is an urban district being developed by Serneke and partly Balder. It is located in SE3 which is one of four electricity spot price areas in Sweden (SvK, n.d.b.). The potential for designing a financially feasible MG is considered high because of its high density seen in figure 8 and different consumers. It is mainly residential buildings at approximately 192,500 square meters and commercial buildings at 92,500 square meters. There is also a two-storage underground garage at approximately 50,000 square meters with charging infrastructure. The ambition of the developer is that electricity can be freely shared within Karlastaden. And they want that whoever owns the electricity production and storage technology can sell electricity with maximum profitable which implies avoiding the energy tax and grid fee. See location of Karlastaden in figure 8.

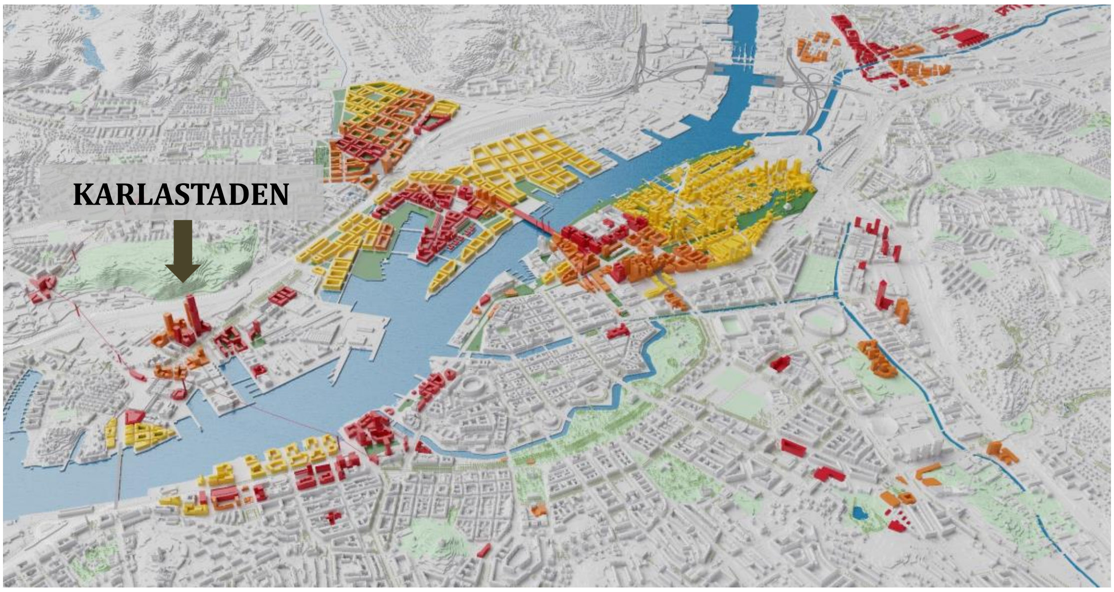


Figure 8. Location of Karlastaden in Gothenburg (City of Gothenburg, n.d.)

6.2 Revenue estimations and predictions

The financial evaluation period has been assumed to 30 years, coherent with Hunter et al. (2021) and NREL (2022). Prices per revenue category have therefore been calculated for the coming 30 years (2023-2053) for all categories except peak load fees. The peak load fee, transmission fee and tax development are difficult to determine since the prices is not determined on an open market, i.e., no available data to analyse. The development of these fee has therefore been assumed to increase according to the Swedish target inflation rate of 2 percent (Swedish Riksbank, n.d.). Electricity prices and demand have spiked due to the recent global energy crises. Therefore, the financial evaluation uses price data from 2021 or earlier if available since 2022 data could be seen as outliers. However, if there are little historic price data, then 2022 have been included in the analysis. In the case of seasonal variety, e.g., load demand and electricity prices, August and February have been assumed to represent summer and winter months respectively.

CAGR have been applied as the primary price prediction tool in this thesis. However, the logarithmic rate has been applied to ancillary services due to unplausible results when using CAGR. Cost savings that erupt due to load (peak) shaving or increased amount of self-sufficiency is not a revenue stream per se but is seen as a revenue in this thesis. However, the mere difference is that taxes are excluded for cost savings. Local-flex have been disregarded in this thesis due to that this market currently is immature and its development uncertain.

6.2.1 Compound annual growth rate for electricity prices

In section *2.3.4. Revenue estimations of electricity projects* Hoppmann et al. (2014) argued for CAGR to be a suitable method for predicting electricity spot prices. Since this thesis is applying the guidelines at Karlastaden located in Gothenburg the spot prices for SE3 were collected from Nord Pool (n.d.) on monthly basis. Spot prices in SE3 were analysed for the period ranging from November 2011 to October 2022. The average monthly spot prices in electricity area SE3 are presented in figure 9. By a visual analysis of figure 9, it could be argued that the spot prices have been heavily volatile during 2022 compared to other time periods and that the spot prices have increased in recent years. CAGR was calculated by using the average spot price in 2021 and 2012 to mitigate the effects of the current energy crisis in the estimation, i.e., excluding values from 2022. CAGR seems to be overpredicting the electricity spot prices for the period of 2013 to 2021 which is probably due to the large increase for the third and fourth quarter of 2021. An outlier was also found which severely affected CAGR with 236 base points. However, the spot prices tend to rise more dramatically in the later years.

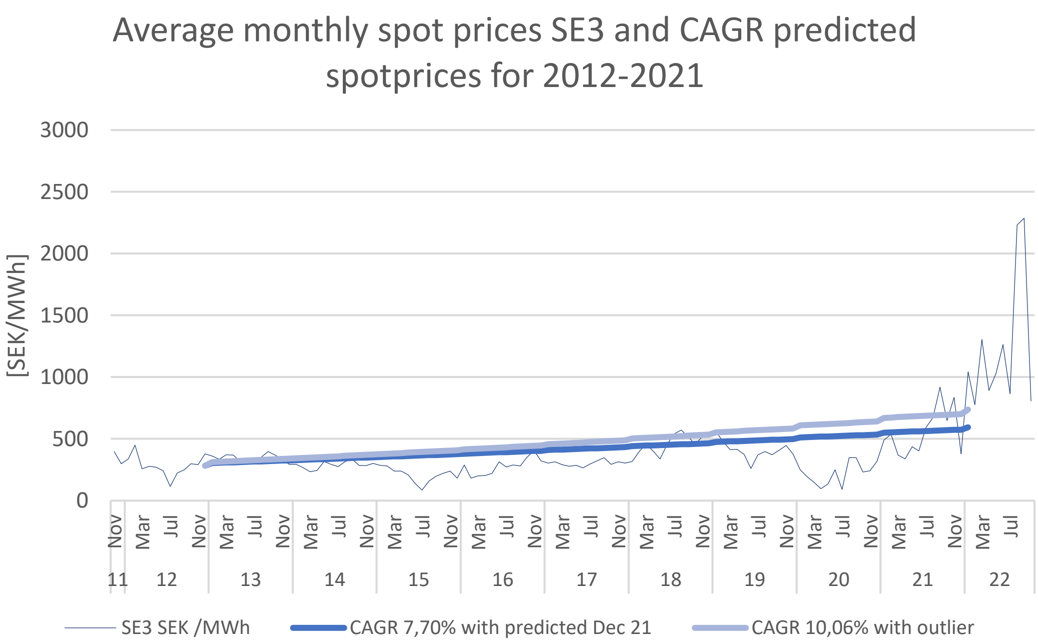


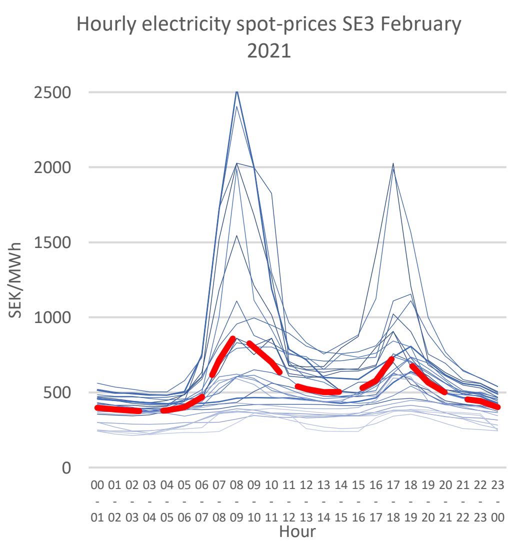
Figure 9. Average monthly spot prices in the market SE3 with predicted CAGR for 2012-2021. An outlier was found December 2021 at 1807 SEK/MWh, by including this outlier the prediction of CAGR increase with 236bps. The

predicted spot price for December 2021 by CAGR 2012-2021 is estimated to 379 SEK/MWh. More on this topic can be viewed in appendix B, C and D.

The increasing electricity spot price is good for investments in MGs because it will increase savings potential by self-consumption and revenue if sold to the external market. But according to short-term market analysis by SvK (2021), the average electricity spot price is predicted to peak in 2022 due to high fuel prices at the reference point and decline steady to a yearly average of 39 [EUR/MWh] in 2026 for SE3. This is not favourable for investments electricity production, and the CAGR method will fail to predict that scenario due its estimated yearly increase of 10.06 percent. These types of situations need to be handled when adopting the guidelines at a MG project and being updated with estimates are important. However, SvK (2021) estimate that the spot price volatility, in line with previous result in interviews and literature, will increase due to larger amount of RERs in the energy mix which is interesting for spot price arbitrage, peak shaving and ancillary services related to EES.

6.2.2 Spot price arbitrage

The spot price arbitrage is determined on the differences between high prices and low prices. Therefore, by utilizing energy storages, energy could be purchased and stored when prices are low and sold when prices are higher. This analysis has evaluated the spot price arbitrage potential in 2021 to mitigate effects from the current energy crisis in the financial evaluation. All months in 2011-2021 was analysed to identify reference months that aligns with winter and summer prices. However, the largest and smallest spot price arbitrage differed between the years and no month could clearly be identified. Therefore, August and February were assumed to represent summer and winter spot prices, respectively. In figure 10 and 11, hourly prices for each day of these months are shown whereas the red dashed line shows the average price for a day per analysed month. It is possible to conclude that the spot prices peak two times each day, which are called cycles. The spot price arbitrage potential in February is larger compared to August.



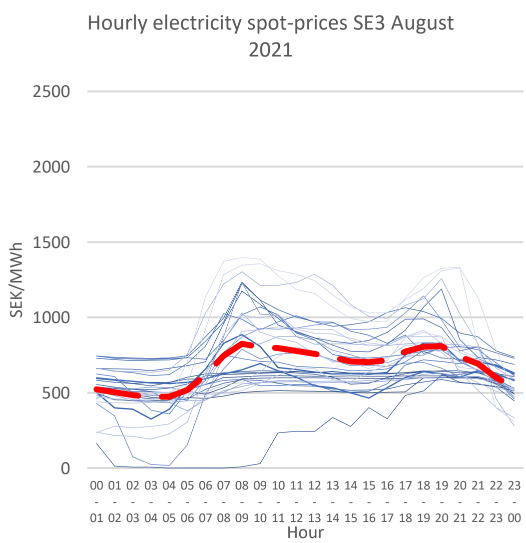


Figure 10. to the left. Hourly electricity spot prices in SE3 February 2021. The red stretched line is average spot price per hour (Nordpool, n.d.). Figure 11. to the right. Hourly electricity spot prices in SE3 August 2021. The red stretched line is average spot price per hour (Nordpool, n.d.).

The lowest and highest price per cycle are necessary data to determine the arbitrage potential and are presented in table 3. For nights in February, recharging from the grid during the lowest average prices of 373 [SEK/MWh] and dispensing to the grid during the highest average prices of 900 [SEK/MWh] it is possible to achieve an arbitrage of 527 [SEK/MWh] per cycle, see table 3. Similar approach to analysing cycles during the days in February would have achieved 234 [SEK/MWh] per cycle. The cycles during the day are between hours 21-11 and the night during hours 11-21. The cycles in August does not have the same volatility which makes it more difficult to determine the optimal recharge and dispense periods. This also makes it more difficult to determine the arbitrage potential. Nevertheless, the estimated arbitrage for nights in August are 354 [SEK/MWh] and days in August are 105 [SEK/MWh]. The cycles also appear to be shifted one hour into the day compared with February. Since two reference months are representing half a year, 182 or 183 days, and it exists two cycles per day, the total amount of cycles are 730. The average yearly revenue per cycle is 55,632 [SEK/MWh] which equals approximately 222,530 [SEK/MWh] in yearly revenue if accounting for all cycles, see table 4.

Table 3. Electricity spot price arbitrage in the market SE3, for reference months February and August while not accounting for any grid fee or electricity taxation. All figures in [SEK/MWh].

Electricity spot price arbitrage		*Recharge from the grid*		*Dispense to the grid*		
Month and cycle used for prediction	**Cycle hours**	**Avg. Lowest price [SEK]**	**Min. hour**	**Cycle hours**	**Avg. highest price [SEK]**	**Max. hour**
2021 February Night	21-06	373	03-04	06-11	900	08-09
2021 February Day	11-16	502	13-14	16-21	736	17-18
2021 August Night	22-07	471	03-04	07-12	825	08-09
2021 August Day	12-17	704	15-16	17-22	809	19-20

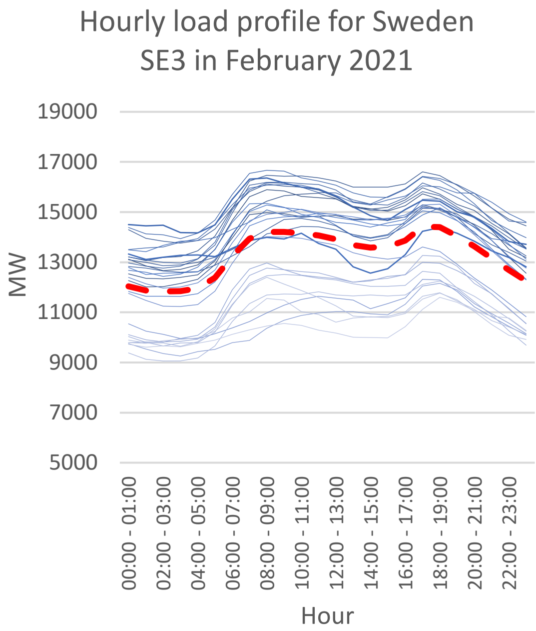
Table 4. Electricity spot price potential per reference month and revenue potential per month and cycle.

Month and cycle used for prediction	**Arbitrage per cycle [SEK/MWh]**	**Days during the year [No. of days]**	**Total revenue [SEK/MWh]**
2021 Feburary Night	527	182	95,924
2021 Feburary Day	234	182	42,611
2021 August Night	354	183	64,692
2021 August Day	105	183	19,303
Average	**305**	**183**	**55,632**

6.2.3 Peak shaving

In the previous section, two reference months were introduced for spot price arbitrage. The same months are used in this section for estimating the potential of peak shaving. The data was collected from ENTSO-E Transparency Platform (n.d.) and is representing the load profile for the entire market of SE3. The load profiles for these months are used to determine the duration of island mode and the potential cost saving for peak shaving. Since the data represents the entire electricity area SE3, the monetary potential is determined based on a percentual reduction to shave off the maximum peak.

The load tariff was determined based on data from EI for the grid operator Göteborg energi nät AB (n.d.). Reduction in maximum load leads to a cost reduction since the load fee is based on three parameters, fixed fee, electricity transfer fee [SEK/kWh], and load fee [SEK/KW]. By visually analysing figure 12 and 13, it appears to be two cycles occurring in February at approximately hours 07-11 and 16-20. However, it appears to be no clear cycles expect one during the entire day in August.



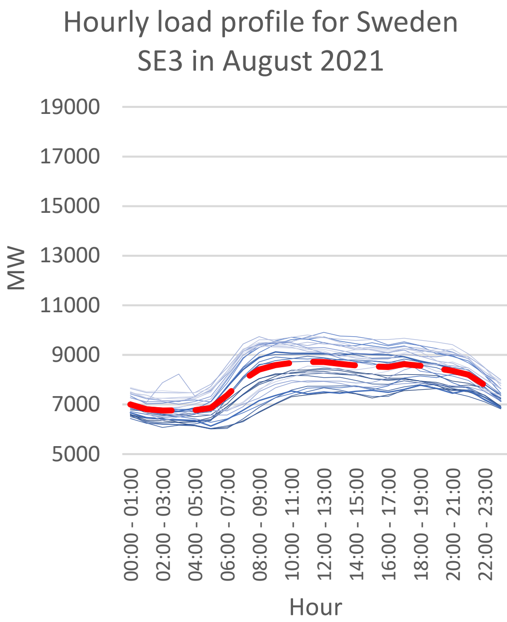


Figure 12. to the left. Hourly load profile for the entire SE3 market in February 2021. Two cycles at 07-11 and 16-20. All figures in MW. Figure 13. to the right. Hourly load profile for the entire SE3 market in August 2021. No apparent cycles during the day. All figures in MW.

In table 5, the estimations are showed for peak shaving potential and durations at each reference months. The peak shaving potential is the highest for 2021 February Day at 5 percent and significantly lower in August with three times longer duration to achieve the load peak shaving.

Table 5. Electricity load and estimated peak shaving potential in the entire SE3 market.

Peak shaving				
Month used for prediction	**Peak** cycle	**Avg**. Lowest load **[MW]**	**Avg**. Highest load **[MW]**	**Duration**
2021 February Morning	07-11	13 941	14 210	4 hours
2021 February Day	16-20	13 634	14 419	4 hours
2021 August	08-20	8 411	8714	12 hours

Month used for prediction	**Peak shaving potential [MW]**	**Peak shaving potential, %**
2021 February Night	268	2%
2021 February Day	785	5%
2021 August	303	3%

Due to that the potential is measured in percentual terms, the actual saving potential is dependent on the consumption, maximum load, and storage capacity. Saving potentials and storage capacity per load is presented in table 6. Since there is no benefit in trying to reduce the load in the summer season, the load peak shaving potential is assumed to only be realized in three months, i.e., winter months. The total savings per year, if the battery is only used for load peak shaving, can be estimated by the reduction in max effect and thus reduced load fee. Renumeration from electricity sold within the MG during peak hours is assumed to be equal to the purchase price. No additional revenue from price arbitrage is therefore considered. According to EI (n.d.d.) the load fee for Gothenburg is 46.6 [SEK/maxkW], hence, the total saving potential is 35.7 [SEK/ kWh] for these assumptions. This means that the costs of the storage system must be less than 35.7 [SEK/kWh] if the investment should be profitable if the storage is not used in other applications that generate revenue as well.

Table 6. Peak shaving potential for February.

Peak shaving February Morning 07-11					
Max load in system kW	**Peak shaving potential**	**Peak shaving kW/month**	**Load fee SEK/kW,month**	**Total saving SEK/month**	**Peak shaving months**
100	5.4%	5.4	47.6	259.1	3
500	5.4%	27.2	47.6	1,295.7	3
1,000	5.4%	54.4	47.6	2,591.5	3
1,500	5.4%	81.7	47.6	3,887.2	3
2,000	5.4%	108.9	47.6	5,183.0	3
3,000	5.4%	163.3	47.6	7,774.4	3
5,000	5.4%	272.2	47.6	12,957.4	3
7,500	5.4%	408.3	47.6	19,436.1	3
10,000	5.4%	544.4	47.6	25,914.8	3
15,000	5.4%	816.6	47.6	38,872.1	3
Max load in system kW	**Total saving SEK/year**	**Total saving SEK/year,kW**	**Duration hour**	**Battery capacity kWh**	**Total saving SEK/year,kWh**
100	777.4	142.8	4.0	21.8	35.7
500	3,887.2	142.8	4.0	108.9	35.7
1,000	7,774.4	142.8	4.0	217.8	35.7
1,500	11,661.6	142.8	4.0	326.7	35.7
2,000	15,548.9	142.8	4.0	435.5	35.7
3,000	23,323.3	142.8	4.0	653.3	35.7
5,000	38,872.1	142.8	4.0	1,088.9	35.7
7,500	58,308.2	142.8	4.0	1,633.3	35.7
10,000	77,744.3	142.8	4.0	2,177.7	35.7
15,000	116,616.4	142.8	4.0	3,266.6	35.7

6.2.4 Predictions of ancillary services

Ziel and Steinert (2018) argued that there exists few, or any, statistical methods for predicting energy prices for periods longer than three years. Therefore, Hoppmann et al. (2014) used CAGR to consider the price increases of energy prices over time. The same approach was considered regarding predicting prices for ancillary services. However, this method led to unreasonable price increases, especially when forecasting over a long period. This is both due to large price increases recently and few data points for FCR-D Down and FFR since these ancillary services are relatively new. Therefore, a linear equation model is assumed to better predict the growth rate of revenues from ancillary services. There is also a large volatility regarding ancillary services, and especially during 2021 and 2022. The volatility makes it more difficult to predict future prices with confidence. As example, and that is presented in figure 14, the increase in prices for aFFR Up was 700 percent from April 2022 to May 2022. The figure also shows that the prices for ancillary services was rather low in 2020 and that the prices have steadily increased since then.

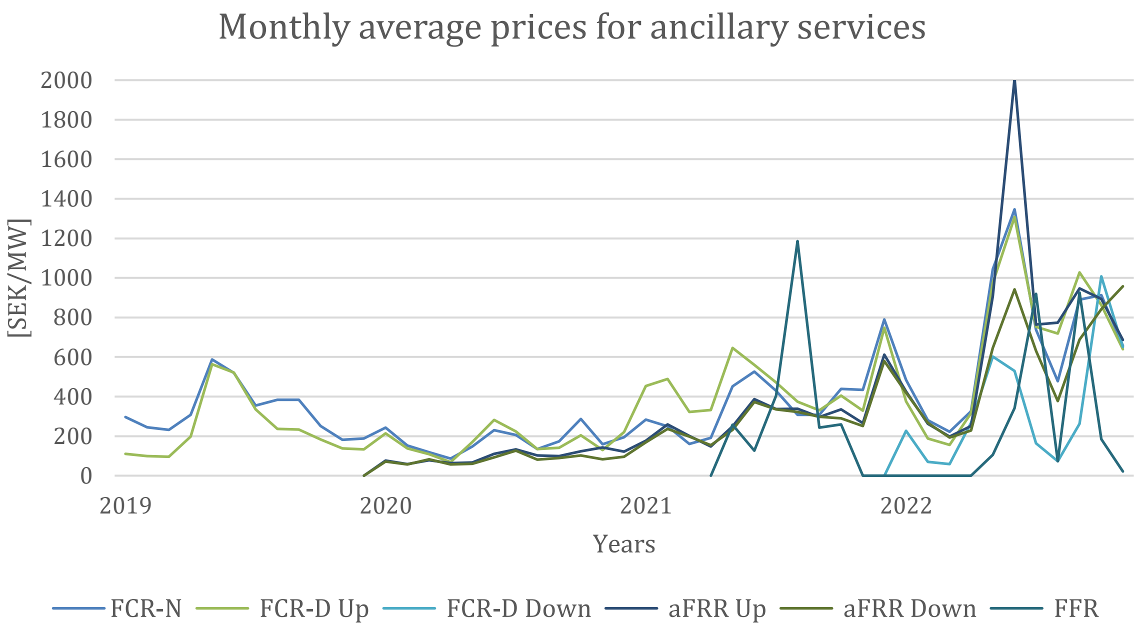


Figure 14. Illustration of monthly price trend for ancillary services between 2019 – Nov 2022.

The estimation of price increases is in line with SvK (2021) which argues that prices for ancillary services will increase due to increased proportion of RERs in the energy mix. The prediction of prices for ancillary services is somewhat disputed by the interviewees where some argue that the markets will have a lot higher turnover in the future compared to today's volumes (MOB, EG). However, since the prices are rather high today, there is an expectancy that more agents will enter the market and reduce the prices due to increased competition (NB, EG). Therefore, a logarithmic rate was the approach taken to consider the interviewees and SvKs approximations of future prices by assuming that the prices will increase but with decreasing rate. See figure 15 and table 7 for an illustration of the predictions. Sabo and Boone (2013) argue that the logarithmic rate is a common approach for similar prediction situations.

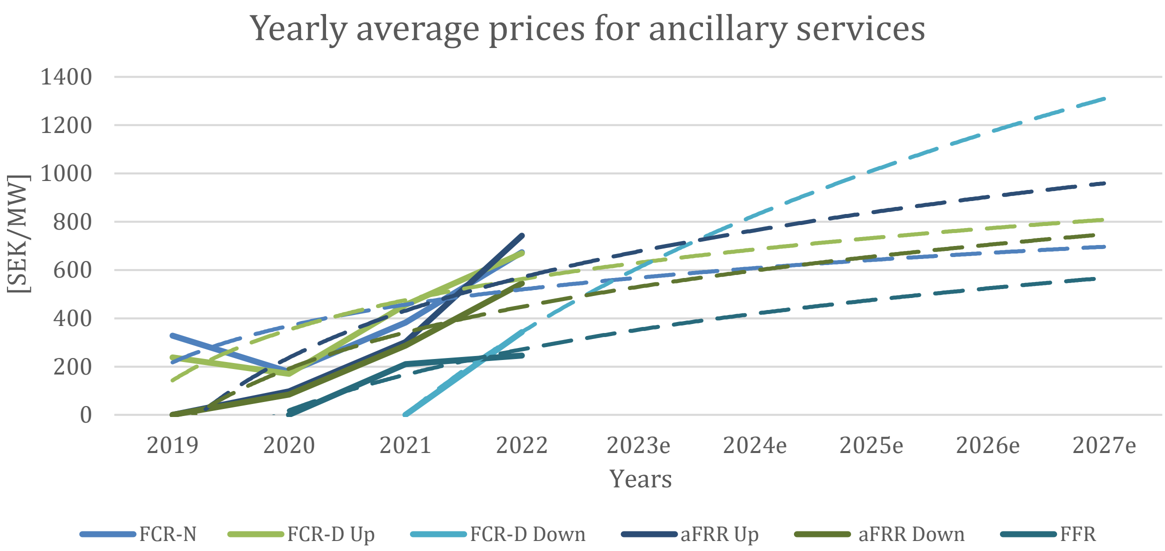


Figure 15. Logarithmic price prediction for ancillary services between 2019-2027.
Table 7. Logarithmic price predictions for ancillary services until 2027.

Logarithmic linear equation	*y = 217.93*ln(x) + 217.25*	*y = 302.89 * ln(x) + 142.45*	*y=1191.5*ln(x) - 1309*	*y = 480.28*ln(x) - 96.347*	*y = 369.91*ln(x) - 65.124*	*y = 364.89 * ln(x) - 234.89*
Period [Year]	**FCR-N [SEK/MW]**	**FCR-D Up [SEK/MW]**	**FCR-D Down [SEK/MW]**	**aFRR Up [SEK/MW]**	**aFRR Down [SEK/MW]**	**FFR [SEK/MW]**
2022	519.4	562.3	342.8	569.5	447.7	271.0
2023e	568.0	629.9	608.6	676.6	530.2	352.4
2024e	607.7	685.2	825.9	764.2	597.7	418.9
2025e	641.3	731.8	1009.6	838.2	654.7	475.2
2026e	670.4	772.3	1168.7	902.4	704.1	523.9
2027e	696.1	808.0	1309.0	958.9	747.7	566.9

6.3 Cost estimations

Cost and performance data for the chosen technologies have been collected from multiple sources and are summarized in table 8 and 9. DThe collected data shows that wind turbines are two to four times as expensive as PV cells and with shorter lifetime. Hydrogen storage is also two to four times as expensive as battery storage but with an increased lifetime compared to batteries. All technologies have rather low Opex.

Table 8. Cost data for the evaluated technologies.

Technology	***Investment cost [SEK/kW]***	***CapEx [SEK/kW and after X Years]***	***Opex [SEK/kW and year]***
PV cells	13,500[3] - 15,584[1]	0	178[1]
Wind turbines	30,000[3] - 56,037[1]	56,037 after 20 years[1]	364[1]
Battery	5,167[1]- 5,932[2] - 10,000[3]	5,167 after 15 years[1] - 5,932 after 10 years[1,2] - 10,000 after 10 years[3]	367[1]

Hydrogen (electrolytes, tank/pipes, fuel cell)	21,963[2] (pipes)	0	259[2]

Note. Data from NREL (2022)[1], Hunter et al. (2021)[2], Serneke[3].

PV cells and wind turbines are the only technologies that produces electricity whereas wind turbines are assumed to produce 3.5 times to 2.5 times as much kWh per kW and year. This entails that the efficiency for wind turbines is better than for PV cells. However, since the cost of the wind turbines are larger, the cost per kWh is similar. PV cells and hydrogen storage are the only technologies which does not require an additional CapEx during the evaluation period (30 years) due to sufficiently long lifetime. PV cells and wind turbines have a small degradation rate per year (Adaramola, 2015; EERE, n.d.b.; Staffel & Green, 2014). The battery storage system is assumed to have no degradation given that it is maintained and serviced according to plan (NREL, 2022). The cost for this is included in the Opex estimation. Hydrogen suffers from a low efficiency mainly stemming from the low efficiency in the fuel cell process (Hunter et al., 2021).

Table 9. Performance data for the evaluated technologies.

Technology	*Specific production [kWh/kW and year]*	*Lifetime [Years]*	*Degradation rate [%/Year]*	*Roundtrip efficiency [%]*
PV cells	1,000[3] -1,083[1]	>20[4] – > 25[5,6]	0.67[5] – 0.8[6]	N/A
Wind turbines	2,456[1] - 3,491[3]	20[3]	1.6[7]	N/A
Battery	N/A	10[1,2,3] – 15[1]	N/A	86[2]
Hydrogen (electrolytes, tank/pipes, fuel cell)	N/A	30[2]	N/A	36[2]

Note. Data from NREL (2022)[1], Hunter et al. (2021)[2], Serneke[3], Walker (2013)[4], Adaramola (2015)[5], EERE (n.d.b.)[6], and Staffel and Green (2014)[7].

6.4 Profitability assessment

The profitability assessment is based on the financial evaluation model in *5.2 Development of financial evaluation model*. General assumptions for the profitability assessment are a lifetime of 30 years, Swedish corporate tax rate of 20.6 percent (The Swedish Tax Agency, n.d.), and discount rates spanning from five to 15 percent with an interval of 100 basis points. In section *6.2 Revenue estimations and predictions* and *6.3 Costs* the detailed assumptions to the profitability assessment are evaluated. However, many are presented as an interval between different sources. To perform a profitability assessment with the developed financial evaluation model several assumptions were therefore made based on these sections. The final assumptions for evaluation the profitability of a MG in Karlastaden are categorized based on technology, revenue and costs which are presented in table 10, 11 and 12. The tables represent one unit of installed power or energy which can be multiplied to the fit the project or business developers design of the MG. CAGR is an important parameter in the model and will be further investigated based on three cases. The normal case represents the CAGR found in *6.2 Revenue estimations and predictions*. However, in the pessimistic case the estimated CAGR is reduced by 50 percent while in the optimistic case CAGR is increased by 150 percent.

Table 10. Revenue estimates used as inputs in the financial evaluation model.

Technology	*Specific production [kWh/kW and year]*	*Distributed electricity [kWh]*	*CAGR electricity spot price [%]*	*Electricity spot price 2022 [SEK/kWh]*	*2022 Energy tax and transmission fee [SEK/kWh]*	*2022 Average electricity spot price arbitrage [SEK/kWh]*	*2022 Average ancillary services availability renumeration [SEK/kWh]*
PV cells	1,042	N/A	Defined in section 6.4.1.	0.67	0.66	N/A	N/A
Wind turbines	3,491	N/A	Defined in section 6.4.1.	0.67	0.66	N/A	N/A
Battery Spot price arbitrage	N/A	730	Defined in section 6.4.1.	N/A	N/A	0.37	N/A
Battery Peak Shaving	N/A	180	N/A	N/A	N/A	N/A	N/A
Battery Ancillary services	N/A	6,132	Defined in section 6.4.1.	N/A	N/A	N/A	Depending on market, see appendix E.
Hydrogen Spot price arbitrage	N/A	730	Defined in section 6.4.1.	N/A	N/A	0.37	N/A
Hydrogen Peak Shaving	N/A	180	N/A	N/A	N/A	N/A	N/A
Hydrogen Ancillary Services	N/A	6,132	Defined in section 6.4.1.	N/A	N/A	N/A	Depending on market, see appendix E.

For electricity production technologies, PV cells and wind turbines, an annual specific production is assumed. Since both estimations from the gathered data are roughly equal an average value has been assumed. Predicted increase in electricity spot price is predicted by CAGR and it is assumed to start at the price level of 2022. It is assumed that the MG can achieve IKN, hence, the 2022 energy tax and transmission fee are added to the wholesale price in the profitability assessment on produced electricity. For electricity storage technologies, batteries and hydrogen, the revenue streams are divided into electricity spot price arbitrage, peak shaving, or ancillary services. The distributed electricity is based on the cycles found for each estimated revenue, with one-to-one power energy ratio, therefore no other assumption is needed. Each estimated revenue stream is assumed to be implemented by itself, that is, no combination is evaluated. Similarly, to electricity production, the average arbitrage for 2022 is used and predicted with CAGR. Average ancillary services are assumed to be renumerated only for availability and with a successful bid factor of 70 percent (DS).

Final determination of cost data was also needed before used as inputs in the financial evaluation model. The predominant approach was to use the average value if values was presented as intervals. However, an extreme value for the specific production of wind turbines was chosen due to that Serneke had conducted an extensive wind analysis specific for Karlastaden. Therefore, the production figures for this technology are more reasonable. Additionally, the lifetime for batteries was chosen rather pessimistic due to that both Hunter et al. (2021) and Serneke mentioned lifetimes of 10 years. NREL (2022) mentioned lifetimes for batteries in the interval of 10 to 15 years and therefore 10 years seemed to be the most reliable estimation. See table 11 and 12 for final cost and technology estimations.

Table 11. Cost estimates used as inputs in the financial evaluation model.

Technology	*Investment cost [SEK/kW]*	*CapEx [SEK/kW and after X Years]*	*Opex [SEK/kW and year]*
PV cells	14,524	0	178
Wind turbines	43,000	43,000 after 20 years	364
Battery	8,000	8,000 after 10 years	367
Hydrogen (electrolytes, tank/pipes, fuel cell)	21,963	0	259

Table 12. Performance estimates used as inputs in the financial evaluation model.

Technology	*Specific production [kWh/kW and year]*	*Lifetime [Years]*	*Degradation rate [%/Year]*	*Roundtrip efficiency [%]*
PV cells	1,042	30	0.75	N/A
Wind turbines	3,491	20	1.6	N/A
Battery	Dependent on scenario	10	0	86
Hydrogen (electrolytes, tank/pipes, fuel cell)	Dependent on scenario	30	0	36

6.4.1 Three cases for Karlastaden’s microgrid

The profitability assessment provided the necessary input parameters to apply and test the financial evaluation model on Karlastaden’s MG. As noted in the profitability assessment CAGR is an important factor which affects several input parameters in the model. Therefore, three cases are studied based on different CAGR predictions. In table 13, the cases are presented as optimistic, normal and pessimistic case. For each case the corresponding revenue variants are categorised by the estimated LCOE, Revenue and NPV from the financial evaluation model. CAGR is then multiplied by a factor depending on the case. In the optimistic case CAGR the factor is 1.5, in the normal case the factor is 1.0 and the pessimistic case the factor is 0.5. The normal case represents the starting point of CAGR 10.06 percent. Similarly, the predicted logarithmic functions of revenue for ancillary services are multiplied with the case factor. Peak-shaving is not evaluated in the different cases since this revenue variant is assumed to vary with the electricity spot price. The discount rate is chosen at five percent for an initial evaluation since it is depending on the company that performs the investment calculation (Virlics, 2013). If the discount rate is higher the profitability will decrease and if the discount rate is lower the profitability will increase. The complete table with discount rates from five to 20 percent can be viewed in appendix E. With these cases and assumptions, the results suggest that some revenue variants are favourable to implement in Karlastaden's MG.

Table 13. LCOE, Revenue and NPV comparison between the cases. Discount rate chosen at five percent. Values presented as optimistic, normal or pessimistic case.

Revenue variants	***LCOE [SEK/kWh]***			***Revenue [SEK/kWh]***			***NPV [SEK/kWh]***		
	Optimistic case	***Normal case***	***Pessimistic case***	***Optimistic case***	***Normal case***	***Pessimistic case***	***Optimistic case***	***Normal case***	***Pessimistic case***
Battery spot price arbitrage	12.73	6.59	4.43	8.80	3.67	1.85	(3.93)	(2.93)	(2.57)
Battery peak shaving	6.46	6.46	6.46	0.01	0.01	0.01	(6.45)	(6.45)	(6.45)
Battery FCR-N	0.19	0.19	0.19	0.92	0.61	0.31	0.73	0.42	0.12
Battery FCR-D Up	0.19	0.19	0.19	1.08	0.72	0.36	0.90	0.53	0.17
Battery FCR-D Down	0.19	0.19	0.19	2.04	1.36	0.68	1.85	1.17	0.49
Battery FRR Up	0.19	0.19	0.19	1.34	0.89	0.45	1.15	0.70	0.26
Battery FRR Down	0.19	0.19	0.19	1.04	0.69	0.35	0.85	0.50	0.16
Battery FFR	0.19	0.19	0.19	0.82	0.55	0.27	0.63	0.36	0.08
Hydrogen Spot price arbitrage	31.63	16.97	11.80	8.95	3.82	2.00	(22.68)	(13.16)	(9.79)
Hydrogen peak shaving	8.24	8.24	8.24	0.01	0.01	0.01	(8.23)	(8.23)	(8.23)
Hydrogen FCR-N	0.24	0.24	0.24	0.92	0.61	0.31	0.68	0.37	0.06
Hydrogen FCR-D Up	0.24	0.24	0.24	1.08	0.72	0.36	0.84	0.48	0.12
Hydrogen FCR-D Down	0.24	0.24	0.24	2.04	1.36	0.68	1.80	1.12	0.44
Hydrogen FRR Up	0.24	0.24	0.24	1.34	0.89	0.45	1.09	0.65	0.20
Hydrogen FRR Down	0.24	0.24	0.24	1.04	0.69	0.35	0.80	0.45	0.10
Hydrogen FFR	0.24	0.24	0.24	0.82	0.55	0.27	0.58	0.31	0.03
PV cells	1.00	1.00	1.00	8.11	3.54	1.92	7.11	2.54	0.92
Wind turbines	1.10	1.10	1.10	8.93	3.89	2.12	7.83	2.80	1.02

The revenue variants with positive NPV are a profitable investment and should be undertaken (Berk & DeMarzo, 2014). For Karlastaden's MG this implies that the revenue variants based on spot price arbitrage and peak shaving are not profitable, whereas all other revenue variants are profitable for the three cases. The electricity production technologies, PV cells and wind turbines, are the most profitable and is therefore preferred. The revenue variants with ancillary services from storage technologies are also profitable investments. There are different forms of revenue variants for ancillary services where NPV for FCR-D Down is the highest and therefore more favourable. Considering the ancillary services, batteries have slightly higher NPV than hydrogen and is therefore favourable. To complete the financial evaluation model testing, the MG in Karlastaden should include both wind turbines and PV cells for electricity production technologies, and ancillary services for electricity storage technologies. In figure 16, the selected revenue variants are presented by varying discount rates.

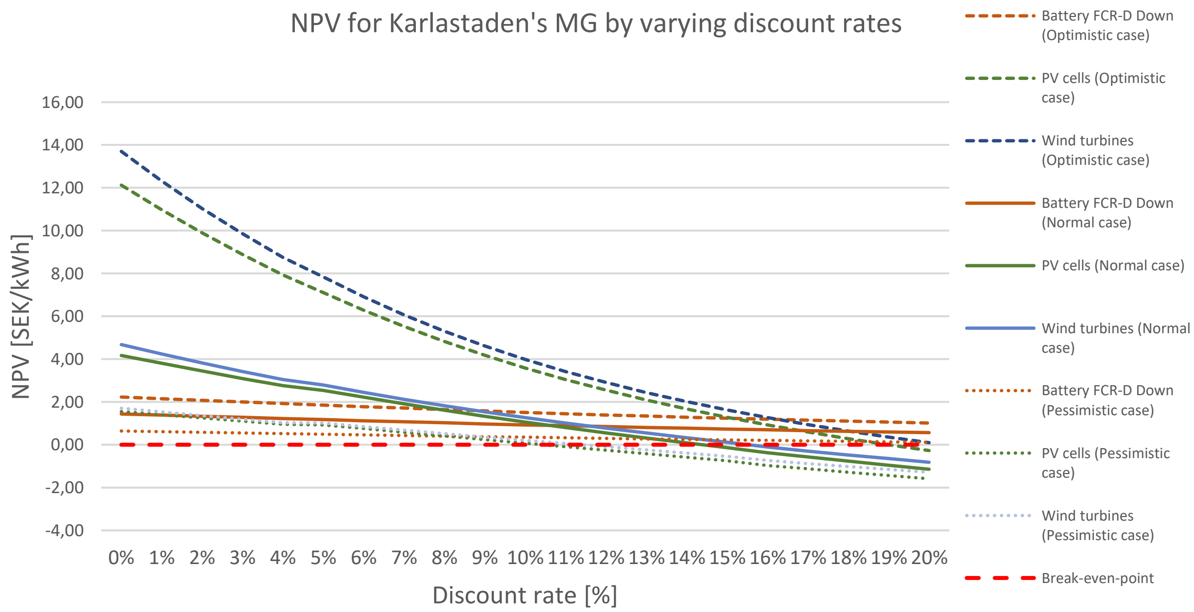


Figure 16. Illustration of NPVs in all cases for the technologies with top three NPVs at 5 percent discount rate.

In figure 16, the break-even-point at which discount rates the NPV is zero provides more information about the risk. By visual analysis the result implies that the electricity production technologies reach break-even-point at approximately ten percent discount for the pessimistic case. The ancillary services do not reach the break-even-point at any given discount rate up to 20 percent. This result suggest that ancillary services are less risky investment. However, at lower discount rates the electricity production yields higher NPV. The discount rate is the most common factor to vary when analysing investments in MG (Hoppmann et al., 2014; Hèrnandez-Moro & Martínez-Duart, 2013; Bazilian et al., 2013; Abdelhady, 2021). But to fully understand the risk and potential of Karlastaden's MG a sensitivity analysis should be performed by varying other input parameters independently.

6.4.2 Sensitivity analysis by varying investment cost and electricity production

In section *2.3.4. Sensitivity analysis*, investment cost (Hoppmann et al., 2014; Bazilian et al., 2013) and electricity production (Hèrnandez-Moro & Martínez-Duart, 2013) where considered to be important parameters to perform a sensitivity analysis with. The sensitivity analysis is performed as ceteris paribus, that is all other parameters hold constant.

To simplify the sensitivity analysis only the normal case is evaluated with the discount rate 5 percent. Similarly, to previous case factor for CAGR and ancillary services revenues the investment cost and electricity production are multiplied with a sensitivity factor ranging from 0.5 to 1.5 with the interval ten basis points. The result is presented in table 14 and show that the suggested MG in Karlastaden is still profitable with 50 percent decrease in production and 50 percent increase in investment cost. The decrease in production is more sensitive than increasing the production or varying the investment cost.

Table 14. Sensitivity analysis by varying investment cost and production with differences from original NPV.

Revenue variants	*NPV difference [%] - varying investment cost with sensitivity factor*										
Sensitivity factor	0.50	0.60	0.70	0.80	0.90	1.00	1.10	1.20	1.30	1.40	1.50
Battery FCR-D Down	6	5	4	2	1	0	(1)	(2)	(4)	(5)	(6)
PV cells	17	13	10	7	3	0	(3)	(7)	(10)	(13)	(17)
Wind turbines	18	14	11	7	4	0	(4)	(7)	(11)	(14)	(18)
	NPV difference [%] - varying production with sensitivity factor										
Sensitivity factor	0.50	0.60	0.70	0.80	0.90	1.00	1.10	1.20	1.30	1.40	1.50
Battery FCR-D Down	(16)	(11)	(7)	(4)	(2)	0	2	3	3	5	5
PV cells	(39)	(26)	(17)	(10)	(4)	0	4	6	9	11	13
Wind turbines	(39)	(26)	(17)	(10)	(5)	0	4	6	9	11	13

7 Discussion

The discussion aims at evaluating the guidelines and financial evaluation model. Starting with the guidelines, there are a couple of factors which have not been investigated in this thesis, but which are reasonable to perform in an applied case. Energy/load demand from the fixed preconditions have not been considered due to that this precondition only stays relevant to identify if there are desires to be off-grid or to have a high self-sufficiency rate. Such desires have not been declared and therefore this factor becomes irrelevant for this thesis. Furthermore, available area has not been investigated and therefore all values have been presented as divided by the load [kW] or production [kWh]. However, available area becomes important for a project or business developer to investigate since this determines the actual business potential and financial need. The estimated units for LCOE, revenue and NPV can be utilised by project or business developers if their project has the same structure as Karlastaden. Safety issues, self-consumption and off or on-grid preferences have been disregarded since this is subjective and case-specific preferences. Most of the laws and hinderances (DG2) have been investigated from a general perspective but it is implied that a thorough investigation regarding regulatory aspects is needed when applied to a real case. In final, the guidelines represent a logic process which should be used as guiding principle when applied. Although the factors may not be exhaustive, they cover the main topics and important factors to consider. The decision gates included in the managerial guidelines evaluates these factors with a multi-disciplinary approach with the purpose of evaluating the most profitable design of a MG.

Moving on with the financial evaluation model, all revenue variants resulted in positive NPVs except for spot price arbitrage and peak shaving, see table 13. The LCOE calculation was based on formula constructs from Hoppmann et al. (2014), Pawel (2014) and Lotfi and Khodaei (2016). Furthermore, the cost data was gathered from multiple sources in which many had in turn gathered data from many other sources. Therefore, the LCOE estimation could be seen as the more reliable one out of the revenue and LCOE estimation. A project or business developer should prefer cost data from suppliers since this is estimations that reasonably could be realized if a project is undertaken and becomes more accurate for that specific case. However, the estimation of revenues is difficult and associated with uncertainty since predictions can be inaccurate. This thesis has attempted to estimate the development of prices by statistical methods and by methods applied by scholars investigating the same subject. But as mentioned before, the CAGR overpredicts the development in some cases. Therefore, a project or business developer should review the revenue estimations carefully and subjectively adjust these accordingly. The estimations and testing of the financial evaluation model at Karlastaden can be viewed as a demonstrative approach of how project or business developer can evaluate the financial feasibility of their MG. Additionally, the risk could be seen to increase due to the uncertain revenue estimates and an increase in the discount rate could partly mitigate the risk.

Additional considerations to include in a final evaluation are the combination of revenue streams and potential synergies them in between. Starting with the combinations, there could be reasonable to assume that the load and spot prices are correlated since peak shaving implies to discharge energy when the demand is high and recharge when the demand is low. Therefore, spot price arbitrage and peak shaving could be achieved simultaneously. This is however only true if the energy could be sold to end-consumers internally and not used for own operations. Although the estimated revenue for peak shaving is low, case-specific conditions could make this combination promising. Potential synergies of revenue streams are the combination of ancillary services and peak shaving or spot price arbitrage. This would most likely be the real usage of a storage solution since the choice of revenue depends on which generates the largest daily revenue. Therefore, a MG should reasonably include multiple revenue streams and be optimised based on which one that gives the highest revenue for each time-period. Other synergies could be identified by different technologies such as, battery/hydrogen to mitigate large seasonal differences in price if there are some, and the combination of production and storage technologies in general to be able to match the production profile with the consumption profile and to ensure that maximum revenue is achieved. A storage technology enables storage of energy until it is most efficient to sell it or use it. Without storage technologies in the MG, the produced electricity needs to be sold directly to end-consumer when generated.

This thesis evaluated the profitability through LCOE, revenue and NPV. This splitting of the financial parameters is important from an evaluation perspective since the revenue estimations are uncertain. Therefore, LCOE allows the project or business developer to evaluate the lowest cost that the electricity must be sold at to break-even. However, this is only a good measurement for technologies of the same type, i.e., storage or production and therefore analysis of inbound technologies could be made by LCOE. LCOE are therefore constrained in MG evaluation unless the comparison of LCOE is made up by combined MG systems through usage of Eq.6 and Eq.7. However, making decisions only by LCOE could be harmful since this does not consider all aspects. For example, LCOE for wind turbines are larger than for PV cells and therefore PV cells should be the chosen investment if only deciding based on LCOE. However, the potential revenue stream for wind turbines is larger than for PV cells in all cases, i.e., optimistic, normal, and pessimistic, and therefore leads to a larger NPV. If the revenue would not have been estimated, then the less profitable investment would have been chosen. Therefore, this thesis shows the criticality of reviewing multiple profitability measurements to ensure that the most profitable investment is undertaken.

8 Conclusion

This thesis aims to develop managerial guidelines for evaluating the financial feasibility of MGs. The developed managerial guidelines intend to help project or business developers evaluate important factors to include in an urban MG with a financial evaluation model. Initially, it is necessary to establish the preconditions for the project before making any decision on included technologies, design of the MG and profitability assessment. The guidelines are conceptually designed with three decision gates as an iterative process for evaluating the most profitable MG in a specific location. To find the optimal MG design and profitability, both production and storage technologies should be considered since the storage technologies complement the intermittency problem with RERs. Furthermore, the revenue variants stemming from storage can be utilised and mixed in synergies to possibly increase the profitability. However, the revenue variants from MGs are difficult to predict since it is affected by laws, regulations, and the design.

The testing at Karlastaden led to the conclusion that many of the revenue variants are profitable investments and that construction of an MG should be carried out. Furthermore, PV cells and wind turbines was the most profitable technologies but also more sensitive to the discount rate. But for a reasonable discount rate that have been adopted by other scholars, i.e., 5 percent, all revenue variants were profitable except spot price arbitrage and peak shaving. Peak shaving has rather low revenue but could be an attractive revenue stream if used in combinations so that peak shaving only is utilised the days with the biggest impact. On other days, the MG utilises other revenue streams that are more profitable. Since LCOE does not consider all aspects and the revenues are difficult to predict the investment decision should be accompanied by a scenario analysis.

To conclude the managerial guidelines gives the project or business developer tools for evaluating the important factors to consider when designing a profitable MG. Whereas, the test at Karlastaden can be viewed as a demonstration of how to use the guidelines. Based on this test, MGs are a profitable investment for most of the revenue variants.

9 Future research

This thesis has provided insights into investment and construction of an MG. However, these insights could be widened and extended through three topics that have been identified. Two of the three topics are related to the financial evaluation and are described firstly. The last one regards construction and management of the MG.

One common approach taken by scholars to evaluating the financial feasibility of MG or RERs are by using Monte Carlo simulations. The Monte Carlo simulation does both support a risk analysis, since the results are computed together with probability assessments, but also more reliable profitability estimations. Therefore, uncertainty is considered in a logical way and the profitability estimations gets more certain. This approach would have elevated the results and facilitated a more confident discussion and evaluation.

Furthermore, evaluation of mixes/combinations of technologies were not performed in this thesis. The results would have benefited by such an evaluation since comparison between mixes are more accurate. The mixes of technologies could also be evaluated by LCOE given that all mixes include the same technology types, e.g., production and storage technology. Although calculation of LCOE for MGs are defined in the literature, revenue estimates are more complex since there are multiple which are exclusive at a given period in time. Therefore, revenues need to be estimated based on the expected trade on each specific market and revenues should be chosen where they have the highest pay-off.

Another important topic that should be further researched is energy management systems. These systems control all energy flows within the MG. Since decisions regarding electricity supply needs to be performed quickly, the energy management system needs to be smart which increases the complexity. The energy management system should also be able to decide on which revenue variant that should be pursued each day and to be an active party on the markets. This topic is important to cover since this enables the operation of an MG.

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Appendix A

Interview guide – MG

Performed by Anton Persson & Jacob Tauson, Autumn 2022.

General

1. Background about yourself
2. Employer and role?
3. Are you familiar with the term 'Microgrid'?

A short description of the project is provided before any of finance, design and technology questions are conducted.

Finance

In your opinion...

1. How should you evaluate if an investment in microgrid is profitable?
2. What is the problem with today's investment evaluation?
3. What kind of financial hindrances and risk with an microgrid can you identify?
4. What is the overall public opinion of microgrid investments?

Design

In your opinion...

1. How do you determine if the project is feasible from a design perspective?
    a. I.e., what are necessary preconditions?
2. How does demand from the city council/detailed development plan affect design?
3. What are the main drawbacks with designing these projects today?
4. What is the overall knowledge/experience of designing these projects today?

Technology

In your opinion...

1. What energy production technologies have the highest potential regarding buildings?
2. What energy storage technologies have the highest potential regarding buildings?
3. What is your take in current technology advancements?
    a. Is it getting better?
    b. Is it getting cheaper?
    c. Is it getting more accessible?
4. What are the main drawbacks with today's technology?
5. What is the overall knowledge/experience of such technologies today?

Interview guide - Specific case

1. Can you describe the project?
2. Why did you undertake the project?
    a. Financial gains?
    b. Innovation
    c. Etc
3. What kind of preconditions did you face?
4. Can you describe the system/microgrid configuration?
5. How did you determine sizes of energy storage, sizes of electricity production plant etc?
6. What were the revenues (payment system, agreements etc)?
    a. Payment system

    b. Agreements (Feed-in-tariffs)?
    c. Subsidies
7. What were the costs?
    a. Investment costs?
    b. Operation and maintenance costs?
8. What kind of challenges did you encounter?
    a. How did you solve them?
9. What kind of tool would you like to use in a future similar project?

<u>Concluding remarks</u>

In your opinion...

1. How is the future of MGs?
    a. Is it bright or not, why?
    b. Have there been a significant change in general opinion?
2. Is there anything you would like to add?
3. Is there anyone you think we should have a conversation/interview with regarding this topic?

Thank you for your time!

Appendix B

MATLAB Script for functions

```
function LCOE = functionLCOE(Dep1, OPEX1, CapEx1, RV1, I1, production1,
SDR, inflation, CAGR1, price_IKN, price, eta, T, r, n, N, z)
%This function calculates LCOE based on following input parameters;
%Dep, OPEX, CapEx, RV, I, production, SDR, inflation, CAGR, price_IKN, price,
eta, T, r, n, N, z

for n = 1:N
    Dep(1,n) = Dep1/((1+r)^n)*T;
    OPEX(1,n) = OPEX1/((1+r)^n)*(1-T);
    CapEx(1,n) = CapEx1(1,n)/((1+r)^n);
    production(1,n) = production1*((1-SDR).^z(1,n))/((1+r)^n);
    CAGR(1,n) = (price_IKN*(1+inflation)^n +
(1+CAGR1)^n.*price(1,n))*production1*(1/eta)/((1+r)^n);
end
RV(1,N) = RV1/((1+r)^N);
LCOE = (I1 - sum(Dep(1:N)) + sum(OPEX(1:N)) + sum(CapEx(1:N)) - RV(1,N) +
sum(CAGR(1:N)))/sum(production(1:N));

function loadfee = functionLoadfee(inflation, loadfee1, peak_shaving, production,
SDR, r, n, N)
%This function calculates discounted revenue based on following input parameters;
%inflation, loadfee1, peak_shaving, production, SDR, r, n, N

for n = 1:N
Revenue(1,n) = ((1+inflation)^n.*loadfee1*peak_shaving)/((1+r)^n);
production1(1,n) = production*((1-SDR)^n)/((1+r)^n);
end

loadfee = sum(Revenue(1:N))/(sum(production1(1:N)));

function Revenue = functionRevenue(inflation, CAGR, price_IKN, price, production,
SDR, T, r, n, N)
%This function calculates discounted revenue based on following input parameters;
%inflation, CAGR, price_IKN, price, production, SDR, T, r, n, N

for n = 1:N
Revenue(1,n) = (price_IKN*(1+inflation)^n +
(1+CAGR)^n.*price(1,n))*production*(1-T)/((1+r)^n);
production1(1,n) = production*((1-SDR)^n)/((1+r)^n);
end

Revenue = sum(Revenue(1:N))/(sum(production1(1:N)));

function NPV = functionNPV(I, T_value, EBIT, T_c, Dep, CapEx, dNWC, n, N, r,
CAGR)
%This function calculates NPV for an investment
% I, T_value, EBIT, T_c, Dep, CapEx, NWC, n, N, r -> input parameters
```

```
NPV = zeros(1,N);
FCF = zeros(1,N);

for n = 1:N
FCF(1,n) = EBIT*(1-T_c) + (T_c*Dep) - CapEx - dNWC;
NPV(1,n) = FCF(1,n);
end

NPV(1,1) = -I + FCF(1,1); %intial cost
NPV(1,N) = T_value + FCF(1,N); %terminal value
NPV = sum(NPV(1:N));
```

Appendix C

MATLAB Script with varying discount rate for all revenue variants

```
clear all
%% Input parameters
% Import data
filename1 = 'RAS.prn';
delimiterIn = ';';
headerlinesIn = 1;
RAS = importdata(filename1,delimiterIn,headerlinesIn);
%%

% General
n = 1;
N = 30; %cashflow lifetime
I = 21; %scenario runs
case_factor = 1.0;
CAGR = 0.106*case_factor;
infl = 0.02;
price = zeros(1,N);
price(1,:) = 0.67;
price_IKN =0.36+0.30;% spot price, energy tax and electricity transmission fee ****
z = [1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29
30];
T = 0.206;

% Input parameters Wind
SDR_w = 0.016;
z_w = [1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 1 2 3 4 5 6 7 8 9 10];
pInitialcost_w = 43018; % per kW
life_time_w = 20;
pRV_w = pInitialcost_w/2;
production_w = 3491; % kWh/kW
pDep_w = pInitialcost_w/life_time_w;
pCapEx_w = zeros(1,N);
pCapEx_w(1,life_time_w) = pInitialcost_w;
pOPEX_w = 364; % per kW

% Input parameters PV
SDR_pv = 0.0075;
z_pv = [1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15];
pInitialcost_pv = 14542; % per kW
life_time_pv = 30;
pRV_pv = 0;
production_pv = 1042; %kWh/kW år
pDep_pv = pInitialcost_pv/life_time_pv;
pCapEx_pv = 0;
pCapEx_pv = zeros(1,N);
pOPEX_pv = 178; % per kW
```

```
% Input parameters Battery
SDR_b = 0; % see NREL
eta_b = 0.86;
price_spot_in = zeros(1,N);
price_spot_in(1,:) = 0.454;
price_spot_out = zeros(1,N);
price_spot_out(1,:) = 0.821;
sInitialcost_b = 8000; % per kW
life_time_b = 10;
sRV_b = 0;
kWh_in_b = 730; % 2 cycles each day at 1kW per cycle during 1h.
production_b = kWh_in_b*eta_b;
AS_sucessfull_bid = 0.7;
production_AS = 8760*AS_sucessfull_bid; % number of hours in a day and year
load_b = 1;
sDep_b = sInitialcost_b/life_time_b;
sCapEx_b = zeros(1,N);
sCapEx_b(1,10) = sInitialcost_b;
sCapEx_b(1,20) = sInitialcost_b;
sOPEX_b = 367; % per kW

% Input parameters Hydrogen
SDR_h = 0;
eta_h = 0.36;
sInitialcost_h = 21963; % per kW
life_time_h = 30;
sRV_h = 0;
kWh_in_h = 730; % LCOE arb with 2 cycles each day 1kW.
production_h = kWh_in_h*eta_h;
sDep_h = sInitialcost_h/life_time_h;
sCapEx_h = zeros(1,N);
sOPEX_h = 259; % per kW

% Discount rate variation
r1 = zeros(1, I);
y=0;
for i = 1:I
    r1(1,i) = y;
    y=y+0.20/(I-1);
end

% LCOE & Revenue Calculations
for i = 1:I
% Wind
LCOE_w(1,i) = functionLCOE(pDep_w, pOPEX_w, pCapEx_w, pRV_w,
pInitialcost_w, production_w, SDR_w, 0, CAGR, 0, zeros(1,N), 1, T, r1(1,i), n, N,
z_w);
Revenue_w(1,i) = functionRevenue(infl, CAGR, price_IKN, price, production_w,
SDR_w, T, r1(1,i), n, N);
NPV_w(1,i) = Revenue_w(1,i) - LCOE_w(1,i);
```

```
% PV
LCOE_pv(1,i) = functionLCOE(pDep_pv, pOPEX_pv, pCapEx_pv, pRV_pv,
pInitialcost_pv, production_pv, SDR_pv, 0, CAGR, 0, zeros(1,N), 1, T, r1(1,i), n, N,
z_pv);
Revenue_pv(1,i) = functionRevenue(infl, CAGR, price_IKN, price, production_pv,
SDR_pv, T, r1(1,i), n, N);

NPV_pv(1,i) = Revenue_pv(1,i) - LCOE_pv(1,i);
% Battery LCOE
LCOE_b_spot(1,i) = functionLCOE(sDep_b, sOPEX_b, sCapEx_b, sRV_b,
sInitialcost_b, production_b, SDR_b, infl, CAGR, price_IKN, price, eta_b, T, r1(1,i),
n, N, z);
LCOE_b_AS(1,i) = functionLCOE(sDep_b, sOPEX_b, sCapEx_b, sRV_b,
sInitialcost_b, production_AS, SDR_b, 0, CAGR, 0, zeros(1,N), eta_b, T, r1(1,i), n,
N, z);

% Battery spot price
Revenue_b_spot(1,i) = functionRevenue(0, CAGR, price_IKN, price_spot_out,
production_b, SDR_b, T, r1(1,i), n, N);
NPV_b_spot(1,i) = Revenue_b_spot(1,i) - LCOE_b_spot(1,i);

% Battery peak shaving
loadfee = 46.6; % loadfee Gothenburg energy per max kW
peak_shaving = 0.035; % approx between 5 and 2.
production = 3*30*2; % 3 months during the winter two times each day
Revenue_b_peak(1,i) = functionLoadfee(infl, loadfee, peak_shaving, production,
SDR_b, r1(1,i), n, N);
LCOE_b_peak(1,i) = functionLCOE(sDep_b, sOPEX_b, sCapEx_b, sRV_b,
sInitialcost_b, production, SDR_b, 0, CAGR, 0, zeros(1,N), eta_b, T, r1(1,i), n, N, z);
NPV_b_peak(1,i) = Revenue_b_peak(1,i) - LCOE_b_peak(1,i);

% Battery ancillarly services
%FCR-N
Revenue_b_FCR_N(1,i) = functionRevenue(0, 0, 0, RAS.data(:,1)'*case_factor,
production_AS, SDR_b, T, r1(1,i), n, N);
NPV_b_FCR_N(1,i) = Revenue_b_FCR_N(1,i) - LCOE_b_AS(1,i);

%FCR-D Up
Revenue_b_FCR_D_Up(1,i) = functionRevenue(0, 0, 0, RAS.data(:,2)'*case_factor,
production_AS, SDR_b, T, r1(1,i), n, N);
NPV_b_FCR_D_Up(1,i) = Revenue_b_FCR_D_Up(1,i) - LCOE_b_AS(1,i);

%FCR-D Down
Revenue_b_FCR_D_Down(1,i) = functionRevenue(0, 0, 0,
RAS.data(:,3)'*case_factor, production_AS, SDR_b, T, r1(1,i), n, N);
NPV_b_FCR_D_Down(1,i) = Revenue_b_FCR_D_Down(1,i) - LCOE_b_AS(1,i);

%aFRR Up
```

```
Revenue_b_FRR_Up(1,i) = functionRevenue(0, 0, 0, RAS.data(:,4)'*case_factor,
production_AS, SDR_b, T, r1(1,i), n, N);
NPV_b_FRR_Up(1,i) = Revenue_b_FRR_Up(1,i) - LCOE_b_AS(1,i);

%aFRR Down
Revenue_b_FRR_Down(1,i) = functionRevenue(0, 0, 0, RAS.data(:,5)'*case_factor,
production_AS, SDR_b, T, r1(1,i), n, N);
NPV_b_FRR_Down(1,i) = Revenue_b_FRR_Down(1,i) - LCOE_b_AS(1,i);
%FFR
Revenue_b_FFR(1,i) = functionRevenue(0, 0, 0, RAS.data(:,6)'*case_factor,
production_AS, SDR_b, T, r1(1,i), n, N);
NPV_b_FFR(1,i) = Revenue_b_FFR(1,i) - LCOE_b_AS(1,i);

% LCOE Hydrogen
LCOE_h_spot(1,i) = functionLCOE(sDep_h, sOPEX_h, sCapEx_h, sRV_h,
sInitialcost_h, production_h, SDR_h, infl, CAGR, price_IKN, price, eta_h, T, r1(1,i),
n, N, z);
LCOE_h_AS(1,i) = functionLCOE(sDep_h, sOPEX_h, sCapEx_h, sRV_h,
sInitialcost_h, production_AS, SDR_h, 0, 0, 0, zeros(1,N), eta_h, T, r1(1,i), n, N, z);

% Hydrogen spot price
Revenue_h_spot(1,i) = functionRevenue(infl, CAGR, price_IKN, price_spot_out,
production_h, SDR_h, T, r1(1,i), n, N);
NPV_h_spot(1,i) = Revenue_h_spot(1,i) - LCOE_h_spot(1,i);

% Hydrogen peak shaving
loadfee = 46.6; % loadfee Gothenburg energy per max kW
peak_shaving = 0.035; % approx between 5 and 2.
production = 3*30*2; % 3 months during the winter two times each day
Revenue_h_peak(1,i) = functionLoadfee(infl, loadfee, peak_shaving, production,
SDR_h, r1(1,i), n, N);
LCOE_h_peak(1,i) = functionLCOE(sDep_h, sOPEX_h, sCapEx_h, sRV_h,
sInitialcost_h, production, SDR_h, 0, CAGR, 0, zeros(1,N), eta_h, T, r1(1,i), n, N, z);
NPV_h_peak(1,i) = Revenue_h_peak(1,i) - LCOE_h_peak(1,i);
% Hydrogen ancillary services

%FCR-N
Revenue_h_FCR_N(1,i) = functionRevenue(0, 0, 0, RAS.data(:,1)'*case_factor,
production_AS, SDR_h, T, r1(1,i), n, N);
NPV_h_FCR_N(1,i) = Revenue_h_FCR_N(1,i) - LCOE_h_AS(1,i);

%FCR-D Up
Revenue_h_FCR_D_Up(1,i) = functionRevenue(0, 0, 0, RAS.data(:,2)'*case_factor,
production_AS, SDR_h, T, r1(1,i), n, N);
NPV_h_FCR_D_Up(1,i) = Revenue_h_FCR_D_Up(1,i) - LCOE_h_AS(1,i);

%FCR-D Down
Revenue_h_FCR_D_Down(1,i) = functionRevenue(0, 0, 0,
RAS.data(:,3)'*case_factor, production_AS, SDR_h, T, r1(1,i), n, N);
NPV_h_FCR_D_Down(1,i) = Revenue_h_FCR_D_Down(1,i) - LCOE_h_AS(1,i);
```

```
%aFRR Up
Revenue_h_FRR_Up(1,i) = functionRevenue(0, 0, 0, RAS.data(:,4)'*case_factor,
production_AS, SDR_h, T, r1(1,i), n, N);
NPV_h_FRR_Up(1,i) = Revenue_h_FRR_Up(1,i) - LCOE_h_AS(1,i);

%aFRR Down
Revenue_h_FRR_Down(1,i) = functionRevenue(0, 0, 0, RAS.data(:,5)'*case_factor,
production_AS, SDR_h, T, r1(1,i), n, N);
NPV_h_FRR_Down(1,i) = Revenue_h_FRR_Down(1,i) - LCOE_h_AS(1,i);

%FFR
Revenue_h_FFR(1,i) = functionRevenue(0, 0, 0, RAS.data(:,6)'*case_factor,
production_AS, SDR_h, T, r1(1,i), n, N);
NPV_h_FFR(1,i) = Revenue_h_FFR(1,i) - LCOE_h_AS(1,i);
End

plot(r1, NPV_b_spot)
hold on
plot(r1, NPV_b_peak);
plot(r1, NPV_b_FCR_N);
plot(r1, NPV_b_FCR_D_Up);
plot(r1, NPV_b_FCR_D_Down);
plot(r1, NPV_b_FRR_Up);
plot(r1, NPV_b_FRR_Down);
plot(r1, NPV_b_FFR);
plot(r1, NPV_h_spot);
plot(r1, NPV_h_peak);
plot(r1, NPV_h_FCR_N);
plot(r1, NPV_h_FCR_D_Up);
plot(r1, NPV_h_FCR_D_Down);
plot(r1, NPV_h_FRR_Up);
plot(r1, NPV_h_FRR_Down);
plot(r1, NPV_h_FFR);
plot(r1, NPV_pv);
plot(r1, NPV_w);


r_Table_LCOE = [r1; LCOE_b_spot; LCOE_b_peak; LCOE_b_AS; LCOE_h_spot;
LCOE_h_peak; LCOE_h_AS; LCOE_pv; LCOE_w];
r_Table_Revenue = [r1; Revenue_b_spot; Revenue_b_peak; Revenue_b_FCR_N;
Revenue_b_FCR_D_Up; Revenue_b_FCR_D_Down; Revenue_b_FRR_Up;
Revenue_b_FRR_Down; Revenue_b_FFR; Revenue_h_spot; Revenue_h_peak;
Revenue_h_FCR_N; Revenue_h_FCR_D_Up; Revenue_h_FCR_D_Down;
Revenue_h_FRR_Up; Revenue_h_FRR_Down; Revenue_h_FFR; Revenue_pv;
Revenue_w];
r_Table_NPV = [r1; NPV_b_spot; NPV_b_peak; NPV_b_FCR_N;
NPV_b_FCR_D_Up; NPV_b_FCR_D_Down; NPV_b_FRR_Up;
NPV_b_FRR_Down; NPV_b_FFR; NPV_h_spot; NPV_h_peak; NPV_h_FCR_N;
```

```
NPV_h_FCR_D_Up; NPV_h_FCR_D_Down; NPV_h_FRR_Up;
NPV_h_FRR_Down; NPV_h_FFR; NPV_pv; NPV_w];
```

Appendix D

<u>MATLAB Script for sensitivity analysis with varying investment cost</u>

```
clear all
%% Input parameters
% Import data
filename1 = 'RAS.prn';
delimiterIn = ';';
headerlinesIn = 1;
RAS = importdata(filename1,delimiterIn,headerlinesIn);
%%

% General
n = 1;
N = 30; %cashflow lifetime
I = 11; %scenario runs

% LCOE & Revenue Calculations
case_factor = 1.0;
r1 = 0.05;
CAGR = 0.106*case_factor;
infl = 0.02;
price = zeros(1,N);
price(1,:) = 0.67;
price_IKN =0.36+0.30;% spot price, energy tax and electricity transmission fee ****
z = [1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29
30];
T = 0.206;

%% Sensitivty analysis variation factor
sens_factor = zeros(1, I);
y=0.5;
for i = 1:I
    sens_factor(1,i) = y;
    y=y+1.0/(I-1);
end
%%
for i = 1:I

% Input parameters Wind
SDR_w = 0.016;
z_w = [1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 1 2 3 4 5 6 7 8 9 10];
pInitialcost_w = 43018*sens_factor(1,i); % per kW
life_time_w = 20;
pRV_w = pInitialcost_w/2;
production_w = 3491; % kWh/kW
pDep_w = pInitialcost_w/life_time_w;
pCapEx_w = zeros(1,N);
pCapEx_w(1,life_time_w) = pInitialcost_w;
pOPEX_w = 364; % per kW
```

```
% Input parameters PV
SDR_pv = 0.0075;
z_pv = [1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15];
pInitialcost_pv = 14542*sens_factor(1,i); % per kW
life_time_pv = 30;
pRV_pv = 0;
production_pv = 1042; %kWh/kW år
pDep_pv = pInitialcost_pv/life_time_pv;
pCapEx_pv = 0;
pCapEx_pv = zeros(1,N);
pOPEX_pv = 178; % per kW

% Input parameters Battery
SDR_b = 0; % see NREL
eta_b = 0.86;
price_spot_in = zeros(1,N);
price_spot_in(1,:) = 0.454;
price_spot_out = zeros(1,N);
price_spot_out(1,:) = 0.821;
sInitialcost_b = 8000*sens_factor(1,i); % per kW
life_time_b = 10;
sRV_b = 0;
kWh_in_b = 730; % 2 cycles each day at 1kW per cycle during 1h.
production_b = kWh_in_b*eta_b;
AS_sucessfull_bid = 0.7;
production_AS = 8760*AS_sucessfull_bid; % number of hours in a day and year
load_b = 1;
sDep_b = sInitialcost_b/life_time_b;
sCapEx_b = zeros(1,N);
sCapEx_b(1,10) = sInitialcost_b;
sCapEx_b(1,20) = sInitialcost_b;
sOPEX_b = 367; % per kW

% Wind
LCOE_w(1,i) = functionLCOE(pDep_w, pOPEX_w, pCapEx_w, pRV_w,
pInitialcost_w, production_w, SDR_w, 0, CAGR, 0, zeros(1,N), 1, T, r1, n, N, z_w);
Revenue_w(1,i) = functionRevenue(infl, CAGR, price_IKN, price, production_w,
SDR_w, T, r1, n, N);
NPV_w(1,i) = Revenue_w(1,i) - LCOE_w(1,i);

% PV
LCOE_pv(1,i) = functionLCOE(pDep_pv, pOPEX_pv, pCapEx_pv, pRV_pv,
pInitialcost_pv, production_pv, SDR_pv, 0, CAGR, 0, zeros(1,N), 1, T, r1, n, N,
z_pv);
Revenue_pv(1,i) = functionRevenue(infl, CAGR, price_IKN, price, production_pv,
SDR_pv, T, r1, n, N);
NPV_pv(1,i) = Revenue_pv(1,i) - LCOE_pv(1,i);

% Battery LCOE
```

```
LCOE_b_AS(1,i) = functionLCOE(sDep_b, sOPEX_b, sCapEx_b, sRV_b,
sInitialcost_b, production_AS, SDR_b, 0, CAGR, 0, zeros(1,N), eta_b, T, r1, n, N, z);


% Battery ancillarly services
%FCR-D Down
Revenue_b_FCR_D_Down(1,i) = functionRevenue(0, 0, 0,
RAS.data(:,3)'*case_factor, production_AS, SDR_b, T, r1, n, N);
NPV_b_FCR_D_Down(1,i) = Revenue_b_FCR_D_Down(1,i) - LCOE_b_AS(1,i);

end
plot(sens_factor, NPV_b_FCR_D_Down);
hold on
plot(sens_factor, NPV_pv);
plot(sens_factor, NPV_w);

r_Table_LCOE = [sens_factor; LCOE_b_AS; LCOE_pv; LCOE_w];
r_Table_Revenue = [sens_factor; Revenue_b_FCR_D_Down; Revenue_pv;
Revenue_w];
r_Table_NPV = [sens_factor; NPV_b_FCR_D_Down; NPV_pv; NPV_w];
```

MATLAB Script for sensitivity analysis with varying production

```
clear all
%% Input parameters
% Import data
filename1 = 'RAS.prn';
delimiterIn = ';';
headerlinesIn = 1;
RAS = importdata(filename1,delimiterIn,headerlinesIn);
%%

% General
n = 1;
N = 30; %cashflow lifetime
I = 11; %scenario runs

% LCOE & Revenue Calculations
case_factor = 1.0;
r1 = 0.05;
CAGR = 0.106*case_factor;
infl = 0.02;
price = zeros(1,N);
price(1,:) = 0.67;
price_IKN =0.36+0.30;% spot price, energy tax and electricity transmission fee ****
z = [1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29
30];
T = 0.206;

%% Sensitivty analysis variation factor
sens_factor = zeros(1, I);
```

```
y=0.5;
for i = 1:I
    sens_factor(1,i) = y;
    y=y+1.0/(I-1);
end

for i = 1:I

% Input parameters Wind
SDR_w = 0.016;
z_w = [1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 1 2 3 4 5 6 7 8 9 10];
pInitialcost_w = 43018; % per kW
life_time_w = 20;
pRV_w = pInitialcost_w/2;
production_w = 3491*sens_factor(1,i); % kWh/kW
pDep_w = pInitialcost_w/life_time_w;
pCapEx_w = zeros(1,N);
pCapEx_w(1,life_time_w) = pInitialcost_w;
pOPEX_w = 364; % per kW

% Input parameters PV
SDR_pv = 0.0075;
z_pv = [1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15];
pInitialcost_pv = 14542; % per kW
life_time_pv = 30;
pRV_pv = 0;
production_pv = 1042*sens_factor(1,i); %kWh/kW år
pDep_pv = pInitialcost_pv/life_time_pv;
pCapEx_pv = 0;
pCapEx_pv = zeros(1,N);
pOPEX_pv = 178; % per kW

% Input parameters Battery
SDR_b = 0; % see NREL
eta_b = 0.86;
price_spot_in = zeros(1,N);
price_spot_in(1,:) = 0.454;
price_spot_out = zeros(1,N);
price_spot_out(1,:) = 0.821;
sInitialcost_b = 8000; % per kW
life_time_b = 10;
sRV_b = 0;
kWh_in_b = 730% 2 cycles each day at 1kW per cycle during 1h.
production_b = kWh_in_b*eta_b;
AS_sucessfull_bid = 0.7;
production_AS = 8760*AS_sucessfull_bid*sens_factor(1,i); % number of hours in a
day and year
load_b = 1;
sDep_b = sInitialcost_b/life_time_b;
sCapEx_b = zeros(1,N);
```

```
sCapEx_b(1,10) = sInitialcost_b;
sCapEx_b(1,20) = sInitialcost_b;
sOPEX_b = 367; % per kW

% Wind
LCOE_w(1,i) = functionLCOE(pDep_w, pOPEX_w, pCapEx_w, pRV_w,
pInitialcost_w, production_w, SDR_w, 0, CAGR, 0, zeros(1,N), 1, T, r1, n, N, z_w);
Revenue_w(1,i) = functionRevenue(infl, CAGR, price_IKN, price, production_w,
SDR_w, T, r1, n, N);
NPV_w(1,i) = Revenue_w(1,i) - LCOE_w(1,i);

% PV
LCOE_pv(1,i) = functionLCOE(pDep_pv, pOPEX_pv, pCapEx_pv, pRV_pv,
pInitialcost_pv, production_pv, SDR_pv, 0, CAGR, 0, zeros(1,N), 1, T, r1, n, N,
z_pv);
Revenue_pv(1,i) = functionRevenue(infl, CAGR, price_IKN, price, production_pv,
SDR_pv, T, r1, n, N);
NPV_pv(1,i) = Revenue_pv(1,i) - LCOE_pv(1,i);

% Battery LCOE
LCOE_b_AS(1,i) = functionLCOE(sDep_b, sOPEX_b, sCapEx_b, sRV_b,
sInitialcost_b, production_AS, SDR_b, 0, CAGR, 0, zeros(1,N), eta_b, T, r1, n, N, z);

% Battery ancillarly services
% FCR-D Down
Revenue_b_FCR_D_Down(1,i) = functionRevenue(0, 0, 0,
RAS.data(:,3)'*case_factor, production_AS, SDR_b, T, r1, n, N);
NPV_b_FCR_D_Down(1,i) = Revenue_b_FCR_D_Down(1,i) - LCOE_b_AS(1,i);
end
plot(sens_factor, NPV_b_FCR_D_Down);
hold on
plot(sens_factor, NPV_pv);
plot(sens_factor, NPV_w);

r_Table_LCOE = [sens_factor; LCOE_b_AS; LCOE_pv; LCOE_w];
r_Table_Revenue = [sens_factor; Revenue_b_FCR_D_Down; Revenue_pv;
Revenue_w];
r_Table_NPV = [sens_factor; NPV_b_FCR_D_Down; NPV_pv; NPV_w];
```

Appendix E

Discount rate tables - LCOE, revenue and NPV in SEK/kWh

Worst case

LCOE											
Discount rate (r)	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.12	0.13	0.14	0.15
Battery spot price	4.43	4.44	4.46	4.49	4.52	4.56	4.60	4.65	4.71	4.77	4.83
Battery peak shaving	6.46	6.74	7.03	7.33	7.63	7.94	8.25	8.57	8.89	9.22	9.56
Battery AS	0.19	0.20	0.21	0.22	0.22	0.23	0.24	0.25	0.26	0.27	0.28
Hydrogen spot price	11.80	12.27	12.78	13.33	13.91	14.53	15.16	15.83	16.51	17.21	17.93
Hydrogen peak shaving	8.24	9.17	10.14	11.14	12.18	13.25	14.34	15.45	16.58	17.73	18.89
Hydrogen AS	0.24	0.27	0.30	0.33	0.36	0.39	0.42	0.45	0.49	0.52	0.55
PV cells	1.00	1.11	1.22	1.34	1.47	1.59	1.72	1.85	1.99	2.12	2.26
Wind turbines	1.10	1.19	1.29	1.39	1.49	1.59	1.70	1.80	1.91	2.02	2.13
Revenue											
Discount rate (r)	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.12	0.13	0.14	0.15
Battery Spot price arbitrage	1.85	1.81	1.77	1.73	1.69	1.66	1.62	1.60	1.57	1.55	1.53
Battery Peak shaving	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Battery FCR-N	0.31	0.30	0.30	0.29	0.29	0.29	0.28	0.28	0.28	0.28	0.27
Battery FCR-D Up	0.36	0.36	0.35	0.35	0.34	0.34	0.33	0.33	0.32	0.32	0.32
Battery FCR-D Down	0.68	0.66	0.64	0.62	0.60	0.58	0.56	0.55	0.53	0.52	0.51
Battery FRR Up	0.45	0.44	0.43	0.42	0.41	0.41	0.40	0.39	0.39	0.38	0.37
Battery FRR Down	0.35	0.34	0.33	0.33	0.32	0.32	0.31	0.31	0.30	0.30	0.29
Battery FFR	0.27	0.27	0.26	0.26	0.25	0.24	0.24	0.23	0.23	0.22	0.22
Hydrogen Spot price arbitrage	2.00	1.95	1.90	1.85	1.81	1.77	1.73	1.70	1.66	1.64	1.61
Hydrogen Peak shaving	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Hydrogen FCR-N	0.31	0.30	0.30	0.29	0.29	0.29	0.28	0.28	0.28	0.28	0.27
Hydrogen FCR-D Up	0.36	0.36	0.35	0.35	0.34	0.34	0.33	0.33	0.32	0.32	0.32
Hydrogen FCR-D Down	0.68	0.66	0.64	0.62	0.60	0.58	0.56	0.55	0.53	0.52	0.51
Hydrogen FRR Up	0.45	0.44	0.43	0.42	0.41	0.41	0.40	0.39	0.39	0.38	0.37
Hydrogen FRR Down	0.35	0.34	0.33	0.33	0.32	0.32	0.31	0.31	0.30	0.30	0.29
Hydrogen FFR	0.27	0.27	0.26	0.26	0.25	0.24	0.24	0.23	0.23	0.22	0.22
PV cells	1.92	1.86	1.81	1.76	1.71	1.67	1.63	1.59	1.56	1.53	1.50
Wind turbines	2.12	2.04	1.97	1.91	1.85	1.80	1.75	1.70	1.66	1.63	1.59
NPV											
Discount rate (r)	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.12	0.13	0.14	0.15
Battery Spot price arbitrage	-2.57	-2.63	-2.70	-2.76	-2.83	-2.90	-2.98	-3.06	-3.14	-3.22	-3.30
Battery Peak shaving	-6.45	-6.73	-7.02	-7.32	-7.62	-7.93	-8.24	-8.56	-8.88	-9.21	-9.55
Battery FCR-N	0.12	0.10	0.09	0.08	0.07	0.05	0.04	0.03	0.02	0.01	-0.01
Battery FCR-D Up	0.17	0.16	0.14	0.13	0.12	0.10	0.09	0.08	0.06	0.05	0.04
Battery FCR-D Down	0.49	0.46	0.43	0.40	0.38	0.35	0.32	0.30	0.27	0.25	0.22
Battery FRR Up	0.26	0.24	0.22	0.21	0.19	0.17	0.16	0.14	0.13	0.11	0.09
Battery FRR Down	0.16	0.14	0.13	0.11	0.10	0.08	0.07	0.05	0.04	0.03	0.01

Battery FFR	0.08	0.07	0.06	0.04	0.03	0.01	0.00	-0.02	-0.03	-0.05	-0.06
Hydrogen Spot price arbitrage	-9.79	-10.32	-10.89	-11.48	-12.11	-12.76	-13.43	-14.13	-14.84	-15.57	-16.32
Hydrogen Peak shaving	-8.23	-9.16	-10.13	-11.13	-12.17	-13.24	-14.33	-15.44	-16.57	-17.72	-18.88
Hydrogen FCR-N	0.06	0.03	0.00	-0.03	-0.07	-0.10	-0.14	-0.17	-0.21	-0.24	-0.28
Hydrogen FCR-D Up	0.12	0.09	0.05	0.02	-0.02	-0.05	-0.09	-0.13	-0.16	-0.20	-0.24
Hydrogen FCR-D Down	0.44	0.39	0.34	0.29	0.24	0.19	0.14	0.09	0.05	0.00	-0.05
Hydrogen FRR Up	0.20	0.17	0.13	0.09	0.06	0.02	-0.02	-0.06	-0.10	-0.14	-0.18
Hydrogen FRR Down	0.10	0.07	0.04	0.00	-0.04	-0.07	-0.11	-0.15	-0.19	-0.22	-0.26
Hydrogen FFR	0.03	0.00	-0.04	-0.07	-0.11	-0.14	-0.18	-0.22	-0.26	-0.30	-0.33
PV cells	0.92	0.75	0.58	0.41	0.24	0.07	-0.09	-0.26	-0.43	-0.59	-0.75
Wind turbines	1.02	0.85	0.68	0.52	0.36	0.20	0.05	-0.10	-0.25	-0.39	-0.54

Normal case

LCOE											
Discount rate (r)	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.12	0.13	0.14	0.15
Battery spot price	6.59	6.41	6.25	6.12	6.00	5.91	5.83	5.77	5.73	5.70	5.69
Battery peak shaving	6.46	6.74	7.03	7.33	7.63	7.94	8.25	8.57	8.89	9.22	9.56
Battery AS	0.19	0.20	0.21	0.22	0.22	0.23	0.24	0.25	0.26	0.27	0.28
Hydrogen spot price	16.97	16.98	17.07	17.23	17.45	17.75	18.10	18.50	18.95	19.45	19.98
Hydrogen peak shaving	8.24	9.17	10.14	11.14	12.18	13.25	14.34	15.45	16.58	17.73	18.89
Hydrogen AS	0.24	0.27	0.30	0.33	0.36	0.39	0.42	0.45	0.49	0.52	0.55
PV cells	1.00	1.11	1.22	1.34	1.47	1.59	1.72	1.85	1.99	2.12	2.26
Wind turbines	1.10	1.19	1.29	1.39	1.49	1.59	1.70	1.80	1.91	2.02	2.13
Revenue											
Discount rate (r)	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.12	0.13	0.14	0.15
Battery Spot price arbitrage	3.67	3.46	3.27	3.09	2.93	2.78	2.65	2.53	2.43	2.33	2.25
Battery Peak shaving	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Battery FCR-N	0.61	0.60	0.60	0.59	0.58	0.58	0.57	0.56	0.56	0.55	0.55
Battery FCR-D Up	0.72	0.71	0.70	0.69	0.68	0.67	0.66	0.66	0.65	0.64	0.63
Battery FCR-D Down	1.36	1.32	1.28	1.24	1.20	1.16	1.13	1.10	1.07	1.04	1.01
Battery FRR Up	0.89	0.87	0.86	0.84	0.83	0.81	0.80	0.78	0.77	0.76	0.75
Battery FRR Down	0.69	0.68	0.67	0.66	0.64	0.63	0.62	0.61	0.60	0.59	0.58
Battery FFR	0.55	0.54	0.52	0.51	0.50	0.49	0.48	0.47	0.46	0.45	0.44
Hydrogen Spot price arbitrage	3.82	3.60	3.40	3.21	3.05	2.89	2.76	2.63	2.52	2.42	2.33
Hydrogen Peak shaving	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Hydrogen FCR-N	0.61	0.60	0.60	0.59	0.58	0.58	0.57	0.56	0.56	0.55	0.55
Hydrogen FCR-D Up	0.72	0.71	0.70	0.69	0.68	0.67	0.66	0.66	0.65	0.64	0.63
Hydrogen FCR-D Down	1.36	1.32	1.28	1.24	1.20	1.16	1.13	1.10	1.07	1.04	1.01
Hydrogen FRR Up	0.89	0.87	0.86	0.84	0.83	0.81	0.80	0.78	0.77	0.76	0.75
Hydrogen FRR Down	0.69	0.68	0.67	0.66	0.64	0.63	0.62	0.61	0.60	0.59	0.58
Hydrogen FFR	0.55	0.54	0.52	0.51	0.50	0.49	0.48	0.47	0.46	0.45	0.44
PV cells	3.54	3.33	3.13	2.96	2.80	2.65	2.52	2.41	2.30	2.21	2.12
Wind turbines	3.89	3.64	3.41	3.21	3.02	2.86	2.71	2.57	2.45	2.35	2.25

NPV											
Discount rate (r)	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.12	0.13	0.14	0.15
Battery Spot price arbitrage	-2.93	-2.95	-2.99	-3.03	-3.07	-3.12	-3.18	-3.24	-3.30	-3.37	-3.44
Battery Peak shaving	-6.45	-6.73	-7.02	-7.32	-7.62	-7.93	-8.24	-8.56	-8.88	-9.21	-9.55
Battery FCR-N	0.42	0.41	0.39	0.37	0.36	0.34	0.33	0.31	0.30	0.28	0.27
Battery FCR-D Up	0.53	0.51	0.50	0.48	0.46	0.44	0.42	0.40	0.39	0.37	0.35
Battery FCR-D Down	1.17	1.12	1.07	1.02	0.98	0.93	0.89	0.85	0.81	0.77	0.73
Battery FRR Up	0.70	0.68	0.65	0.63	0.60	0.58	0.56	0.53	0.51	0.49	0.47
Battery FRR Down	0.50	0.48	0.46	0.44	0.42	0.40	0.38	0.36	0.34	0.32	0.30
Battery FFR	0.36	0.34	0.32	0.30	0.28	0.26	0.24	0.22	0.20	0.18	0.16
Hydrogen Spot price arbitrage	-13.16	-13.38	-13.67	-14.01	-14.41	-14.85	-15.34	-15.87	-16.43	-17.03	-17.65
Hydrogen Peak shaving	-8.23	-9.16	-10.13	-11.13	-12.17	-13.24	-14.33	-15.44	-16.57	-17.72	-18.88
Hydrogen FCR-N	0.37	0.33	0.30	0.26	0.22	0.19	0.15	0.11	0.07	0.03	-0.01
Hydrogen FCR-D Up	0.48	0.44	0.40	0.36	0.32	0.28	0.24	0.20	0.16	0.12	0.08
Hydrogen FCR-D Down	1.12	1.05	0.98	0.91	0.84	0.77	0.71	0.64	0.58	0.52	0.46
Hydrogen FRR Up	0.65	0.60	0.56	0.51	0.47	0.42	0.38	0.33	0.29	0.24	0.20
Hydrogen FRR Down	0.45	0.41	0.37	0.33	0.29	0.24	0.20	0.16	0.12	0.07	0.03
Hydrogen FFR	0.31	0.27	0.23	0.18	0.14	0.10	0.06	0.01	-0.03	-0.07	-0.11
PV cells	2.54	2.22	1.91	1.61	1.33	1.06	0.80	0.55	0.32	0.09	-0.13
Wind turbines	2.80	2.45	2.13	1.82	1.54	1.27	1.01	0.77	0.54	0.33	0.12

Best case

LCOE											
Discount rate (r)	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.12	0.13	0.14	0.15
Battery spot price	12.73	11.89	11.14	10.48	9.88	9.37	8.91	8.52	8.19	7.90	7.66
Battery peak shaving	6.46	6.74	7.03	7.33	7.63	7.94	8.25	8.57	8.89	9.22	9.56
Battery AS	0.19	0.20	0.21	0.22	0.22	0.23	0.24	0.25	0.26	0.27	0.28
Hydrogen spot price	31.63	30.08	28.75	27.64	26.73	26.01	25.46	25.07	24.82	24.70	24.69
Hydrogen peak shaving	8.24	9.17	10.14	11.14	12.18	13.25	14.34	15.45	16.58	17.73	18.89
Hydrogen AS	0.24	0.27	0.30	0.33	0.36	0.39	0.42	0.45	0.49	0.52	0.55
PV cells	1.00	1.11	1.22	1.34	1.47	1.59	1.72	1.85	1.99	2.12	2.26
Wind turbines	1.10	1.19	1.29	1.39	1.49	1.59	1.70	1.80	1.91	2.02	2.13
Revenue											
Discount rate (r)	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.12	0.13	0.14	0.15
Battery Spot price arbitrage	8.80	8.05	7.36	6.74	6.18	5.68	5.23	4.83	4.48	4.17	3.89
Battery Peak shaving	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Battery FCR-N	0.92	0.91	0.89	0.88	0.87	0.86	0.85	0.84	0.84	0.83	0.82
Battery FCR-D Up	1.08	1.07	1.05	1.04	1.02	1.01	1.00	0.98	0.97	0.96	0.95
Battery FCR-D Down	2.04	1.98	1.92	1.86	1.80	1.75	1.69	1.65	1.60	1.56	1.52
Battery FRR Up	1.34	1.31	1.29	1.26	1.24	1.22	1.20	1.18	1.16	1.14	1.12
Battery FRR Down	1.04	1.02	1.00	0.98	0.97	0.95	0.93	0.92	0.90	0.89	0.88
Battery FFR	0.82	0.80	0.78	0.77	0.75	0.73	0.72	0.70	0.69	0.67	0.66
Hydrogen Spot price arbitrage	8.95	8.19	7.49	6.86	6.30	5.79	5.34	4.93	4.58	4.26	3.98
Hydrogen Peak shaving	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

Hydrogen FCR-N	0.92	0.91	0.89	0.88	0.87	0.86	0.85	0.84	0.84	0.83	0.82
Hydrogen FCR-D Up	1.08	1.07	1.05	1.04	1.02	1.01	1.00	0.98	0.97	0.96	0.95
Hydrogen FCR-D Down	2.04	1.98	1.92	1.86	1.80	1.75	1.69	1.65	1.60	1.56	1.52
Hydrogen FRR Up	1.34	1.31	1.29	1.26	1.24	1.22	1.20	1.18	1.16	1.14	1.12
Hydrogen FRR Down	1.04	1.02	1.00	0.98	0.97	0.95	0.93	0.92	0.90	0.89	0.88
Hydrogen FFR	0.82	0.80	0.78	0.77	0.75	0.73	0.72	0.70	0.69	0.67	0.66
PV cells	8.11	7.40	6.75	6.17	5.64	5.18	4.77	4.40	4.08	3.79	3.54
Wind turbines	8.93	8.10	7.36	6.69	6.10	5.58	5.11	4.71	4.35	4.03	3.75
NPV											
Discount rate (r)	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.12	0.13	0.14	0.15
Battery Spot price arbitrage	-3.93	-3.85	-3.79	-3.74	-3.71	-3.69	-3.68	-3.69	-3.70	-3.73	-3.77
Battery Peak shaving	-6.45	-6.73	-7.02	-7.32	-7.62	-7.93	-8.24	-8.56	-8.88	-9.21	-9.55
Battery FCR-N	0.73	0.71	0.69	0.67	0.65	0.63	0.61	0.59	0.58	0.56	0.54
Battery FCR-D Up	0.90	0.87	0.85	0.82	0.80	0.78	0.75	0.73	0.71	0.69	0.67
Battery FCR-D Down	1.85	1.78	1.71	1.64	1.58	1.51	1.45	1.39	1.34	1.29	1.24
Battery FRR Up	1.15	1.11	1.08	1.05	1.02	0.98	0.95	0.93	0.90	0.87	0.84
Battery FRR Down	0.85	0.82	0.79	0.77	0.74	0.72	0.69	0.67	0.64	0.62	0.60
Battery FFR	0.63	0.61	0.58	0.55	0.52	0.50	0.47	0.45	0.43	0.40	0.38
Hydrogen Spot price arbitrage	-22.68	-21.89	-21.26	-20.78	-20.44	-20.22	-20.13	-20.14	-20.24	-20.44	-20.71
Hydrogen Peak shaving	-8.23	-9.16	-10.13	-11.13	-12.17	-13.24	-14.33	-15.44	-16.57	-17.72	-18.88
Hydrogen FCR-N	0.68	0.64	0.60	0.56	0.52	0.47	0.43	0.39	0.35	0.31	0.27
Hydrogen FCR-D Up	0.84	0.80	0.76	0.71	0.67	0.62	0.58	0.53	0.49	0.44	0.40
Hydrogen FCR-D Down	1.80	1.71	1.62	1.53	1.44	1.36	1.27	1.19	1.11	1.04	0.96
Hydrogen FRR Up	1.09	1.04	0.99	0.93	0.88	0.83	0.78	0.72	0.67	0.62	0.57
Hydrogen FRR Down	0.80	0.75	0.70	0.66	0.61	0.56	0.51	0.46	0.42	0.37	0.32
Hydrogen FFR	0.58	0.53	0.49	0.44	0.39	0.34	0.30	0.25	0.20	0.15	0.11
PV cells	7.11	6.29	5.52	4.82	4.18	3.59	3.05	2.55	2.09	1.67	1.28
Wind turbines	7.83	6.91	6.07	5.30	4.61	3.99	3.42	2.91	2.44	2.01	1.62