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Assessing the areas of concern regarding decarbonisation of industrial microgrids based on a novel classification framework

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ABSTRACT:
This thesis is made for a technology company in Vaasa, Finland which has the focus on decarbonisation of microgrids through optimisation with different aspects in mind, such as, reducing emissions, decreasing fuel consumption, increasing grid reliability and asset availability, and lowering operation costs. The aim of the thesis is to investigate the fundamental areas of concern, when making an early assessment of the potential for decarbonisation through optimisation in industrial microgrids. This is done through a qualitative study based on semi-structured interviews with experts with different areas of expertise in the company. The interviews are then analysed and compared to relevant literature in the field. The outcome is a proposed classification framework grouped into three different sections: generation, network & control, and load. These sections are further divided into different sub-sections with own themes, where categories are listed. Additionally, some suggestions on further utilisation are also proposed in the work, for example, in customer conversations or as an aid for experts.

KEYWORDS: Industrial microgrids, Decarbonisation, Classification, Optimisation, Generation, Network, Load

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ABSTRAKT:

Detta diplomarbete är gjort åt ett teknologiföretag beläget i Vasa, Finland, vilket fokuserar på utfasning av fossila bränslen (eng. decarbonisation) i mikronätverk genom optimering inom olika fokusområden. Exempel på dessa är minskning av utsläpp och bränsleförbrukning, ökning av nätverksstabilitet och tillgänglighet av elproduktionsanläggningar samt optimering av driftskostnader. Målet med diplomarbetet är att utreda inom vilka områden det kan uppstå utmaningar när man i ett tidigt skede kartlägger möjligheterna för utfasning av fossila bränslen genom optimering i industriella mikronätverk. Det här är gjort genom en kvalitativ studie baserad på semistrukturerade intervjuer med sakkunniga med olika expertisområden inom företaget i fråga. Intervjuerna är sedan analyserade och jämförda med relevant litteratur inom ämnet. Resultatet av studien är ett klassificeringssystem indelat i tre olika huvudområden: generering, nätverk & kontroll och last. Dessa är vidare uppdelade i underområden med egna teman i vilka olika kategorier är listade. Därtill i arbetet ges även förslag på användningsområden för detta klassificeringssystem, exempelvis i kundsamtal eller som hjälpmedel för experter.

NYCKELORD: Industrial microgrids, Decarbonisation, Classification, Optimisation, Generation, Network, Load

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1 Introduction

The results of what impact climate change has on the earth is further realised year after year with record temperature beaten for every year (WMO, 2023). The importance of reducing CO_2 emissions is at top level and the timespan for doing it decreases year after year. The industrial sector is slowly realising this, and more industries are trying to lower their CO_2 emissions, thus the opportunity for selling hardware and software for decarbonising industries is at its highest.

This thesis is made for a technology company in Vaasa, Finland with focus on decarbonisation through optimisation of microgrids with different aspects in mind, such as reducing emissions, decreasing fuel consumption, increasing grid reliability and asset availability and thus lower operation costs. For doing an optimisation of a microgrid, rigorous techno-economic analyses and dynamic power system modelling is required to make a good model that a business case can be based upon. The importance of these analyses is to have reliable data and good knowledge of the grid and the customer in order to catch the “low hanging fruit”. This can take time and especially the data collection can be extended before getting right data in the right format. “Knowing the customer” means that the basic functions and what factors characterises the microgrid are understood. This process can take time when data of the grid must be analysed and many experts from different areas of expertise must be consulted.

For speeding up this process and to make an early assessment of a project, the idea arises of a classification framework that would take into consideration the fundamental areas of concerns in microgrid optimisation when trying to develop a business case. This thesis tries to retrieve these fundamental parameters and compose a classification framework that can be used for pinpointing the main challenge areas (see Figure 1). This way, focus could be set on the relevant areas of concern by asking relevant questions in an early stage.

Another aspect of this method is also to present the quite complex knowledge in a briefer way and try to see how different topics ties into together and what impact a certain topic can have on other topics, thus also get the persons that are in close contact with the customer, necessarily not experts in power systems, to understand the broadness and multifaceted topics that a microgrid will introduce.

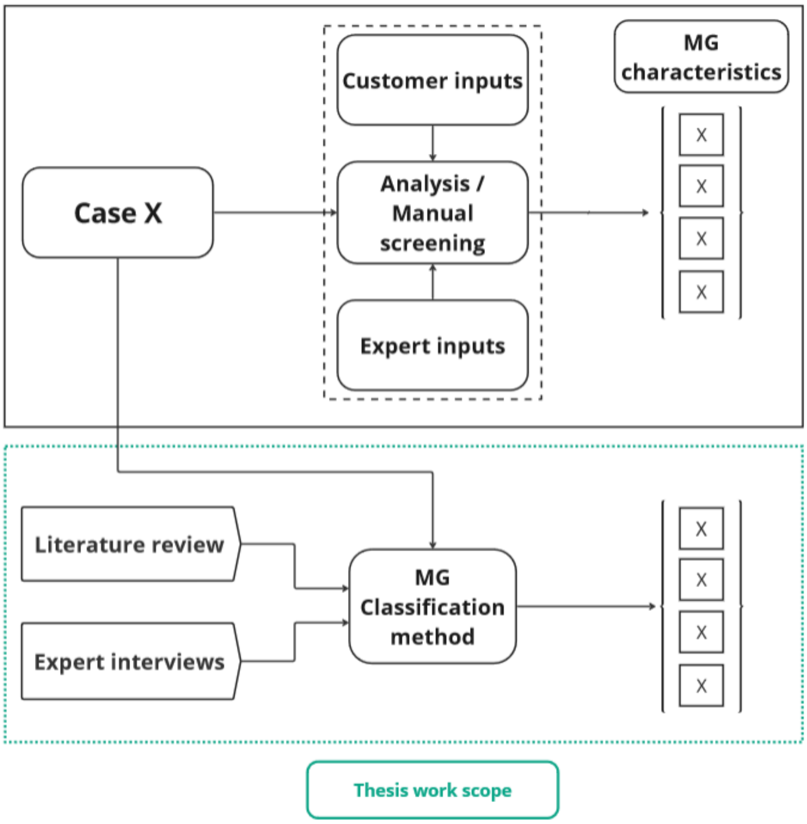

Figure 1. How the thesis fits into the existing process.

2 Background

To understand what a microgrid is and to know what is meant by the decarbonisation of it, I will in the following section go through the definition of a microgrid, what characterises a microgrid, what differentiates an industrial microgrid from other types of microgrids, and what is meant by the decarbonisation of a microgrid.

2.1 Defining a microgrid

The concept of microgrids has gained a lot of interests in the recent years due to the evolution of smart grids. To combat the climate change that emissions of CO2 has led to, replacing generation based on fossil fuels with renewable energy sources is a must. However, the traditional power system is limited to incorporate large amounts of renewable energy sources (RES) due to these systems are not built to cope with the intermittent nature of these sources. The evolution from a traditional grid to a smart grid is therefore seen as the following step in the development of our power system, to be able incorporate as much RES as possible. A smart grid would be a grid that follows the available power in the system by optimising the use of existing generation assets, keeping losses at minimum, controlling the demand with the possibility of load control, and with incentives for users to conserve load when needed (Farhangi 2017, p. 2). To achieve this kind of reactive system, the implementation of intelligence is needed in steps and one step towards this would be the implementation of small entities called microgrids (Farhangi 2017, p. 20).

There are different definitions of what a microgrid is. A well cited definition is the one that the US Department of Energy has at an early stage proposed:

> A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. It can connect and disconnect from the grid to enable it to operate in grid-connected or island-mode. (Ton & Smith, 2012, p. 1)

As Hirsch et al. (2018, p. 2) summarises it, this definition sets three demands on the system that could be called a microgrid: the system should have clear boundaries so it can be told apart from the rest of the system it is connected to (if connected to a larger grid); the assets connected in the system is controlled in symbiosis with each other; and the grid should be able to operate with or without a connection to a larger grid. An almost similar definition is also used by the IEC:

> A group of interconnected loads and distributed energy resources with defined electrical boundaries forming a local electric power system at distribution voltage levels, that acts as a single controllable entity and is able to operate in either grid-connected or island mode (IEC 60050: 'Microgrid', 2017).

The IEC definition adds to the definition mentioned above that a microgrid is implemented on distribution level. This means that a grid entity implemented on sub distribution levels would not be defined as a microgrid. These could be defined instead as a nano-, or picogrid (Mbungu et al., 2019, p. 11). According to Hirsch et al. (2018, p. 5), the capacity size of microgrids can vary from below a MW and to tenths of MWs. However, the grid sizes that the company I do my thesis for, faces often microgrids in the customer segment of islands and industries ranging from tenths of MW to a couple of hundred MWs. For grids in this size range, the word minigrid could be a more suitable name. According to (IEC, n.d.), the term minigrid can be used for individual grids that would be in a larger configuration for example, in factories or islands. However, when searching for articles in databases like IEEE, ScienceDirect, and MDPI, the term minigrid is giving few results even when combined with the search word industrial or island. The term microgrid combined with the terms industrial and island gives more results across all the databases mentioned earlier. Because of this I will refer to the term microgrid and industrial microgrids even if the grid size considered in this work would be more suitable to be called a minigrid.

To these definitions above, different attributes are often also added depending on what stakeholder group defines the microgrid is coming from. As Farhangi (2017, p. 20) describes it, if the focus is on environmental priorities, then the microgrid should contain

RES. If the reliability of the system is of highest importance, then the microgrid should have focus on the existence of firm power and if combined with RES then there should be included ESS in some configuration. If the cyber security part of the microgrid is of highest priority, then different layers of security that will be able to cope with various cyber threats should be in place. If the cost of the whole system is of highest importance, then optimisation and efficiency should be prioritised. Safe to say is that a microgrid would contain a combination of these traits.

As gone through above, the microgrid concept is a grid with the ability to be in an islanded state with its own loads and generation assets, and can help to achieve the goal of decarbonising electrical power systems by grouping parts of the traditional grid into several microgrids. This way, the management of a higher RES penetration could be easier. However, the concept of isolated or islanded grid is not a new thing, before the term microgrid has gained interest there have been, for example, small islands operating as a microgrid matching the definitions discussed above (Yuksel, 2021). However, as Farhangi (2017, p. 21) states, these microgrids has not been intelligent in that sense, rather miniature versions of traditional power systems. Now when these islanded grids define goals to become less CO_2 intensive or become completely decarbonised, there is need for them to add a layer of intelligence to become smart microgrids, in order to install additional RES and optimise the system in terms of load management, efficiency, cost, and reliability.

2.2 Microgrid characteristics

As earlier mentioned, a microgrid is a small grid with its own generation and loads, thus having different characteristics than a traditional electrical power system. According to Farrokhabadi et al. (2020, p. 3), these differences are often related to the microgrid size. In a microgrid, small change in the generation or load can have relatively large implications to the global voltage and frequency, for example starting or stopping a generation asset, or the disconnection or connection of a large load. Also, regarding this small relative size, the implementation of RES would have larger effect on microgrids, due to the lower inertia level in the system, leading to higher frequency fluctuations in the grid. Due to the smaller size, a microgrid will also have shorter power lines and lower voltage compared to traditional systems, leading to more difficult control of reactive and active power.

When controlling a microgrid, the reliability and economic operation is often of top priorities. According to Hirsch et al. (2018, p. 2–3), to fulfil these requirements, the following functionalities should the microgrid be able to do: operate as one entity towards the main grid (if grid connected), keeping line power flows on an acceptable level, regulate the voltage and frequency when islanded, be able to dispatch assets for keeping the power balance, keep a smooth transition between grid and off-grid connection. For achieving all these requirements, a control system based on a hierarchical control is often suggested, these control functions consist of three control levels: primary, secondary, and tertiary control; each level acting in different time spans.

According to Zahraoui et al. (2021, p. 9), primary control, also called field control, is the fastest control level, and it is located in each generation asset. The objective of the primary control is to react to any changes in the frequency and voltage and with all means try to stabilise any deviations in these. In microgrids, this is done autonomously mainly by different predefined droop functions, thus not requiring any communication because its actions are based on local measurements. These functions could have different strategies, but the most common ones change the active power produced based on measured frequency and alternatively changes the reactive power produced based on the measured voltage.

Zahraoui et al. (2021, p. 11–12) continues, the main function for the secondary control is to restore the frequency and voltage to the nominal values after the primary control has, by its droop functions, stabilised them. It is also responsible for the resynchronisation to the main grid (if the microgrid is grid connected), coordinates the operation of

DERs in the system for minimising operations cost, and manages the stability in the microgrid by taking into consideration available capacity, ESS constraints, etc. The tertiary control is the highest level of the hierarchical control, this level ensures that most optimal operation is done on a long-term basis (Zahraoui et al., 2021, p. 21). It is doing this by taking into consideration the cost of own operation and main grid (if grid connected), it also produces forecasts based on weather and economic data. Based on these forecasts it can set the active and reactive controls for the primary control. In Figure 2 it can be seen how the hierarchical controls work together and in what timespan.

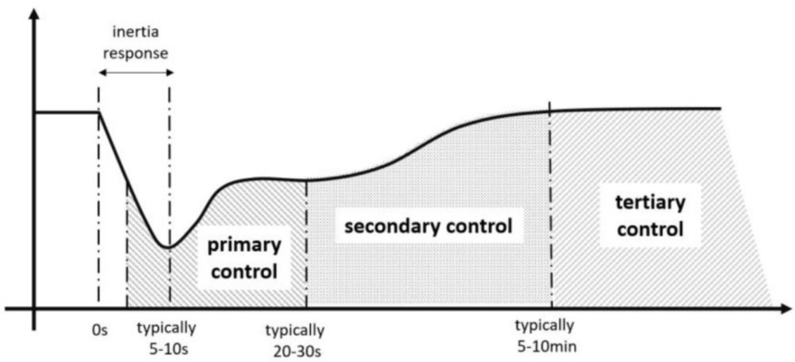

Figure 2. Typical power system frequency response to a sudden loss of generation (Ntomalis et al., 2020, p. 4).

Related to the control hierarchy is the different grid codes standards used in microgrids. According to Tamrakar et al. (2017, p. 4), there are different standards if the microgrid is grid connected or not. When grid connected the standard are tighter than during islanded operation. For grid connected operation there are several standards that can be followed, for example, the IEEE recommends frequency limits at ±0,036 Hz. There are standards in the same way for islanded operation, however, ISO 8528-5 standard suggests that the normal frequency range should be between ±1,5 Hz and for the critical frequency range ±9 Hz. Furthermore, recovery time should be 10 s and maximum rate of change of frequency (ROCOF) is 0,6 Hz/s.

2.3 Industrial microgrids

The microgrid concept can be used in many different segments, for this work I am going to focus on the industrial segment. According to Polleux et al. (2022), the continuity of supply is of highest priority in an industrial microgrid, and the operational costs are strongly linked to the produced product and the cost of it. A stop in electricity supply would have direct financial impact due to broken down equipment or product batches that would become ruined, also a stop without notice could have safety implications (Shoreh et al., 2016). In manufacturing, the production requires often detailed schedule of processes which means that precise control of the plant is prioritised (Shafie-khah et al., 2019). In addition, Polleux et al. (2022) points out that the generation and transmission assets can be owned, financed, or operated by different entities, but the load, all production assets, of the grid would be regarded as one entity with one goal. This is different compared to a residential microgrid where the load would be split into several different entities.

There would also be some technical differences between industrial microgrids and regular microgrids. An industrial microgrid could have more inductive characteristics due to large number of electric motors used for pumping, torque production, and compression (Polleux et al., 2022). Furthermore, loads would not typically be as flexible as loads in residential or commercial microgrids, related to the factors mentioned of above, this is also why mostly in industries there has been more focus on management of generation than on loads (Gomez et al., 2020).

2.4 Decarbonisation through optimisation

Decarbonisation refers to reduction of carbon emitted from, for example, production of goods, electricity, or transport. For this work, the reduction of carbon related to the generated electricity in an industrial setting is considered, this off course will also have an impact on the carbon footprint for the produced good that the electricity was used for.

In a power system, decarbonisation could be done by running the existing assets in the most efficient way by operating them where they have the best heat rate, replacing fossil fuels used for electricity production with carbon free or carbon-neutral alternatives, for example, or replacing thermal assets with RES like wind and solar (Kyriacou & Burke, 2020). In other words, the way of decarbonisation is to optimise a microgrid in regards of reliability, emissions, and cost. When adding RES and furthermore operating assets in the most efficient manner, the control of all these things becomes quite complex and the need of an energy management system (EMS) becomes relevant and will be the key to a decarbonised and optimised power system (Zia et al., 2018, p. 3).

An EMS could also be called microgrid supervisory controller or microgrid central controller and would hierarchically be in the secondary control and tertiary control level (Meng et al., 2016, p. 3). The objective of the EMS is thus the same as the functions of the secondary and tertiary control level mentioned in the previous section. What kind of system that would ultimately do the optimisation is a bit overlapping in the literature. The main systems mentioned in the literature are power management system (PMS) and EMS. According to Jamal et al. (2021), the PMS would be related to technical parameters like power, current, and voltage, whereas the EMS would be focused more on energy economic objectives like operational costs, emission intensity, etc. However, according to Meng et al. (2016, p. 2–3), both the technical and energy economic objective would be done by the EMS. Whereas in the work by Ravikumar et al. (2016), the PMS would be the only system that manages the microgrid. For the management system to get the real-time data, it bases its decisions usually upon a supervisor control and data acquisition (SCADA) system (Litvinov et al., 2019).

Regardless of what the management system is called, the function would be the same; to control and manage generation and load for the microgrid to operate at the most optimal way as possible (Zia et al., 2018, p. 3). To do this, data is gathered and analysed in real time in order to calculate the most optimal operation parameters, this is done by implementing optimisation algorithms with more or less intelligence. This is described by Zia et al. (2018, p. 5–6) and Khan et al. (2016, p. 3–4), the optimisation algorithms range from classical methods, like rule-based methods, to artificial intelligent systems implementing machine learning. Furthermore, to optimise a system, a clear goal of what should be optimised is needed. For the EMS to do its job, there must be objective functions and constraints implemented in the system. An objective function is a goal that the EMS is trying to achieve, this could be minimising operational costs, minimising maintenance costs, maximising revenue from electricity sales, minimising CO2 emissions, etc. Additionally, every asset connected to the system has their own limitations that must not be exceeded. These limitations are put into the EMS as constraints, for instance, output limits on generation assets, charging/discharging limitations on ESS, reliability in form of frequency and voltage boundaries, limitations on certain network connections, etc.

In other words, the EMS would optimise the microgrid according to implemented objective functions (as emissions, and costs) with additional constraints for keeping a sufficient reliability in the system. However, in this work I will not look at the financial impact different categories can have on the system. Because financial impact is a very customer specific parameter that is hard to generalise. Furthermore, by considering cost, the approach starts to look at the optimal solution for a project, whereas in this thesis I am only looking at possible concerns and challenges that experts and salespeople must take into consideration for finding the optimal solution.

3 Literature review

In this topic's state of art there are not many articles with detailed ways of classifying or distinguishing different microgrids from each other, the classification methods are often general and few. However, there are a set of recurrent classifying methods used throughout the literature. According to Mittal et al. (2022, p. 3), the two most common ways to classify microgrids are by distinguishing between the type of current in the system (AC, DC, or AC/DC hybrid) and dividing microgrids into what type of market segments (or utility areas) they are used in. Other authors are then evolving from these methods with different variations and additions.

In the work done by Cagnano et al. (2020, p. 3), the authors are adding to the idea of distinguishing between the electrical type by also dividing into what kind of structure the network itself is built in, for example radial, ring, meshed, or mixed architecture. Despite these alternatives, according to the authors, radial structure with an AC network is used the most throughout the world. Another method is also to separate between microgrids with on or off-grid connection. According to Cabana-Jiménez et al. (2022, p. 3), this is a fundamental way to classify microgrids, because according to different IEEE standards (Cabana-Jiménez et al., 2022, p. 1) the pure definition of a microgrid is that it must consist of local energy resources and loads that can operate as one unit and be able to operate in island or grid connected mode.

In a white paper made by Borghese et al. (2017), they are combining the connection type with the market segment by introducing if the microgrid is used for a facility or community, where facility is a private entity. Thus, the combinations are off-grid facility and off-grid community or on-grid facility and on-grid community microgrid. For example, an off-grid facility could be a remote industrial site and an off-grid community could be a for example a campus, whereas an on-grid community could be an island and an on-grid facility a smart community. This way of categorising is touching the second method that Mittal et al. (2022) stated; to classify microgrids according to their market segments.

Categorising microgrids into different market segments helps in mapping the purposes and core functions required to be fulfilled for the operation of the microgrid. According to Mittal et al. (2022, p. 3), the applicable market segments are: utility, institutional, commercial, transportation, and remote area microgrids. This is also supported to some extent by a comprehensive article made by Chartier et al. (2022, p. 5–7), they are referring to an earlier work where it was identified that the microgrid market segments are: remote locations, commercial/industrial, community, utility distribution, institutional/campus, and military. These different segments would have in their turn different needs and ways to optimally operate the microgrid in question.

One good example of a classification methodology that is combining all the above classification methods is introduced in Choudhury (2022, p. 4). The author is also adding a subsection to the classification, which takes into consideration where the microgrid control system is located, in this case, the microgrid control system can either be centralised, distributed, or decentralised. See Figure 3.

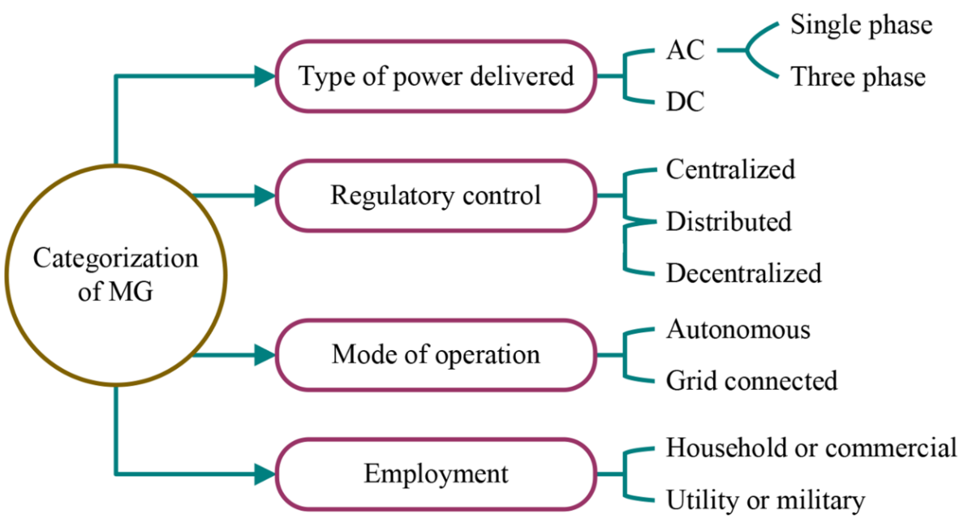

Figure 3. Classification of microgrid (Choudhury, 2022, p. 4).

Chartier et al. (2022, p. 5–7) are further introducing that microgrids should also be classified according to their size in terms of the number of customers or maximum capacity. This way it will be easier to pinpoint the purpose of the microgrid and to understand how it fits in a wider system (see Figure 4). Supporting this sizing method is also Mbungu et al. (2019, p. 11). In their article, they are classifying microgrids based on the size of the power system, in terms of the voltage level and maximum power. Based on these parameters, they classify if the power system is a pico-, nano-, or microgrid and in what application it would be used in, for example, individual customer or commercial.

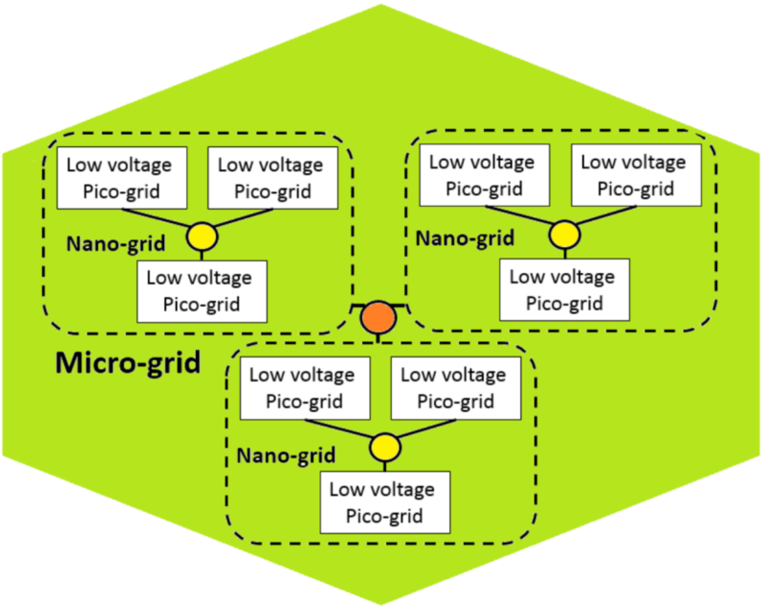

Figure 4. Breakdown of functions of smaller grids (Chartier et al., 2022, p. 5).

The classifications discussed so far considered the microgrid as one unit with different characteristics; however, it is also possible to take into consideration individual components in the grid that the grid itself is built upon. In an conference article made by Gagnaire et al. (2016), the authors are modelling a household system where the loads and sources are classified into three categories, whether they are time flexible - can the asset be switched on or off at any time, power flexibility – do the asset have a possibility to change its power demand/production at any time, and service time compactness – if the load or source cannot be stopped for a certain time period after it has started.

In an article made by Naeem and Hassan (2020), the authors go through different ways of classifying microgrids, and the mitigation techniques used for RES intermittency. In this work they combine the earlier proposed classifications but adding the communication method and a management level as well. The communication part it is considering whether the microgrid has wired or wireless communication in place. The management levels are split into planning, operational, and hybrid level. Planning level considers only if there is long term planning in the microgrid mostly related to investment decisions, whereas the operational level covers the scheduling and operational aspects of the microgrid. The hybrid level would be a mix of these two and is considered the most optimal but with increased complexity.

In an article made by Moran (2016), the author does a classification of the loads in the microgrid. This load would be grouped into tier-1, must run loads; tier-2, discretionary loads; tier-3, emergency load shed. Must run loads are loads that cannot at any time be shed and discretionary loads are loads that can be shed for short time for peak shaving or load shifting. Emergency-load-shed loads are loads that can, as the name suggests, only be shed in emergency. These would only be shed, for example, for preventing a blackout.

In the articles made by Chartier et al. (2022), Sirviö et al. (2020), and Martin-Martínez et al. (2016) they also introduce the principle to split the microgrid into different functional layers where different aspects of the microgrid are concerned. The functional layering principle, that is introduced in the articles mentioned above, is essentially based on the Smart Grid architecture model made by the European Commission but each of them with their different variations. The model that is proposed in Martin-Martínez et al. (2016, p. 2) ties in good with the sizing methodology mentioned in Chartier et al. (2022, p. 5).

There are the functional layers combined with the size of the grids: pico-, nano-, or microgrid. In this article, the picogrid represents different loads in households and the nanogrid represents buildings with their own energy resources and loads, whereas the microgrid represents a whole neighbourhood up to a distribution level.

According to Chartier et al. (2022, p. 9), the functional layer principle is varying between references, but the core layers are a physical layer, a communication layer, an intelligence layer, and an overarching SCADA layer. In the physical layer all the physical components that are part of the microgrid are considered for example, generating units, ESS, and power electronic systems. The communication layer consists of the types of communication protocols used in the system and must provide the intelligence layer with status of the physical layer. In the intelligence layer exists the control and decision making that operates individual devices in the physical layer and in the final SCADA layer exists EMS systems and HMIs that controls the general operation in the microgrid. However, this way of thinking is not considered in this work. By going into the functional layer concept, we start to touch the implementation of microgrids instead of high-level categories, therefore I will not consider this in my work.

When combining these different classifications, we get the preliminary classification method. I have decided to split all the categories into three different segments: generation, network, and load (see Figure 5). This is done to get a better grasp of the different categories and makes it clearer to what part of the power system it is linked to. This is also a logical way of splitting the power system. The load part is always the final user of electricity, and it is why we have a power system in place in the first place; to supply the user with the needed amount of energy. For creating the electricity, some kind of generation is needed. The generation is seldom at the same place as the user; thus, we need a network for transmitting the generated electricity to the user.

Generation

RES type	Generation characteristics	Management level	Microgrid size
Dispatchable	Time flexible	Planning level	Maximum capacity
Non-dispathable	Power flexible	Operational level	
	Service time compactness	Hybrid level	

Network

Type of Power	Connection type	Microgrid Control location	Microgrid size	Communication type	Network topology
AC	Off-grid	Centralised	Voltage level	Wired	Radial
DC	On-grid	Distributed	Micro-, Nano-, Picogrid	Wireless	Ring
AC/DC Hybrid		Decentralised			Meshed
					Mixed

Load

Microgrid size	Load characteristics	Classification of loads
Number of customers	Time flexible	Must run (tier-1)
	Power flexible	Discretionary loads (tier-2)
	Service time compactness	Emergency load shed (tier-3)

Figure 5. Preliminary classifiaction framework based on the literature review.

4 Methodology

I will base this thesis on a qualitative study in form of interviews with different experts with different areas of expertise, these experts are working for the same company I am doing my thesis for. I will conduct the interviews in a semi-structured way with open ended focus questions and with the freedom to go around the question if seen relevant. Due to the possibility of confidential information discussed in the interviews, the transcription of each interview is not provided, however, each interviewees viewpoint is described as detailed as possible. In the following sections, the research process is gone through in detail, then the proceedings of each interview and the findings with the largest impact on the classification framework is described.

4.1 Process description

For mapping the ways of distinguishing microgrids between each other and be able to retrieve the key challenges in a specific type of microgrid, a literature review and interviews with experts throughout the company are made. Both the literature review and the interviews are done in a two-fold process. The first part of the process is the literature review that was described in the chapter above. From the literature review I gathered different ways of classifying microgrids and put them into a framework where topics related to generation, network, and load was grouped together. I call this framework the preliminary method. The second step is to conduct the interviews with the preliminary method as a basis. The interviews are split into two parts with different focus points, and they are done on two different occasions for each individual. Thus, steps two and three are done two times. See Figure 6.

When the interviews are done, step four takes part, where the analysis is done. Here, each category is analysed and compared with different answers and compared with relevant literature if there are any similarities or differences. After the analysis the final proposed method will be presented.

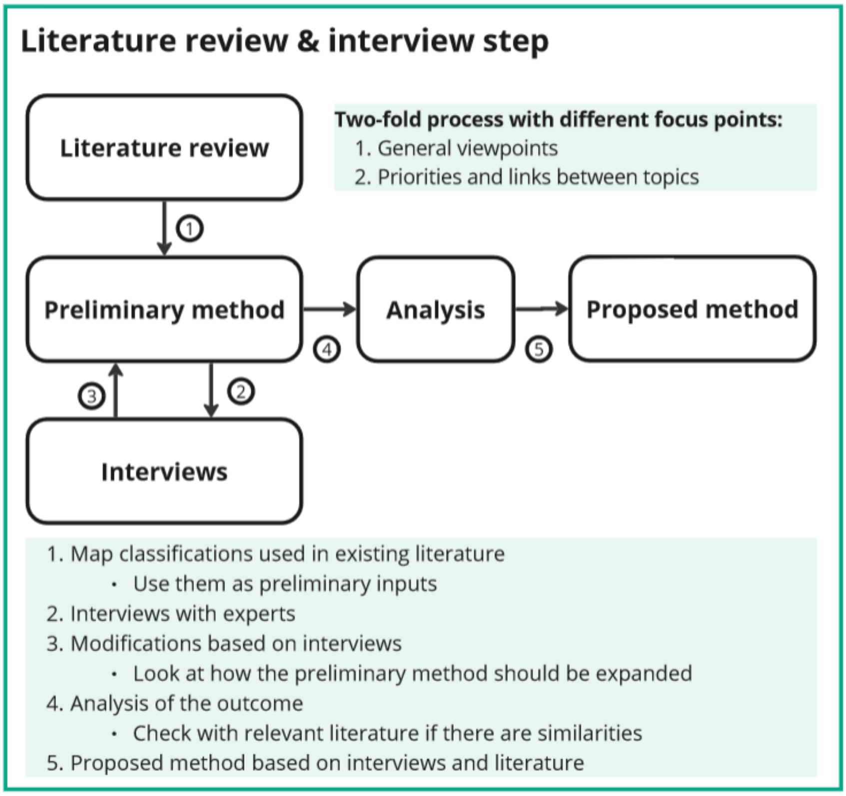

Figure 6. Description of the work process.

4.2 First set of interviews

In the following section the process of the first interview is gone through. Firstly, the plan is described, then the interviewees and the questions are presented. Secondly, the main findings from the interviews are discussed.

4.2.1 Plan for the first interviews

In the first interview the preliminary method is gone through with the experts. The aim with this interview is to look at the general topics that they think is relevant when doing a classification of different microgrids. First the question is for them to think of classification in general and from their area of expertise come up with important categories that will have an impact on how a project would be approached. Then they will be questioned to look at the preliminary method and think of how their suggestions would fit into that method and to see if the preliminary categories are good, if something must be removed or if something must be added. By doing it this way, the idea is to retrieve as many different views and ideas as possible for getting as an extensive viewpoint as possible. In other words, the purpose is to create a method based on new ideas and different ways of thinking.

The expert selection is based on the different topics that was retrieved in the literature review and presented in the preliminary method. The different experts consulted can be seen in Table 1 and the focus questions are gathered below.

Table 1. Classification of experts participating in interview one.

Expert A	Techno-economic analysis
Expert B	Power system architecture & control
Expert C	Power system stability
Expert D	Business models & financial modelling
Expert E	Communication & connectivity
Expert F	Generation optimisation
Expert G	Device integration & control

The interview questions used in the first interview are listed below. The first two questions focus on a more general discussion on what, according to the experts' area of expertise, is important. The following two questions tries to place these viewpoints into the preliminary method.

1. When looking at decarbonisation from your area of expertise, what are the key categories that would bring challenges to the system when starting decarbonisation activities?
2. What would the different classes be of these categories?

3. Looking at the preliminary method, do you find excessive categories or lack of essential ones for assessing the decarbonisation challenges for a microgrid?
4. If modifications are required what would these be?

4.2.2 Main outcomes of the first interviews

The idea of splitting the categories into different segments depending on if they are related to generation, network, or load was agreed upon. Furthermore, there were several suggestions on changes that included additions and removal of categories. These will be briefly gone through next, starting with the generation segment. A more detailed analysis of each category is done in the analysis part of this work.

There were many suggestions related to the generation part of the framework. In the interview with expert D, the topic of dependability was suggested. With this way of thinking the idea is to map what is the reliable source of energy in the power system in question. For example, solar PV in Sahara, where cloud coverage would be concentrated to few days during a year, could be dependable source of energy, though it is a non-dispatchable source with little flexibility. Compared to a thermal asset located on a remote location with an unreliable fuel supply, the solar PV plant could be an asset with higher dependability. This would be good to get insight of in an early stage to better understand the customer.

The following additions is generation capacity and adequacy. In the preliminary framework, generation capacity was only regarded as the total installed capacity in the system. According to expert A, B and C, this is though too narrow for getting a good insight into the system. It should also be added what the capacity of each generating asset is and what the total load demand is during low, base, and peak load.

All these variables are strongly linked to each other and will not reveal the characteristics of the system if only looked at as individual values. Suggested by expert A was also to consider what the tightness of the system is in terms of capacity meeting the demand. This could be covered by the term capacity adequacy.

A suggestion by expert C was to add a category that considers the amount of synchronous or inverter-based interface. With this addition, the idea is to understand what the level of inverter-based generation is in the system and if there would be any challenges to add more inverter-based generation to it. This becomes relevant, with regards to the level of inertia in the system, if a decarbonisation option would be to install more RES. Touching this is the operation philosophy in the system. According to expert A, a crucial addition to the framework is what kind of operation philosophy the customer has for the system. This is closely related to what reliability is required, are there any rules in place during contingencies, and how do the customer look at spinning reserve requirements. The level of reliability required will set the level of the other mentioned topics, if reliability requirement is high then the customer would probably not be so prone to take risks with not having enough spinning reserve in the system. These kinds of precautions will off course have a financial impact on the production costs.

The management level with the classes planning level, operation level, and hybrid level was suggested by expert F to be split into two different categories: long-term plans and level of operation. The long-term plans will take into account if there are some long-term plans in place and what they are in that case. This could be anything from generation capacity additions needed or what the decarbonisation goals would be. With the level of operation, the aim is to understand how they are operating their plant at the moment and what the degree of automation is. Another subject touched upon was co-optimised dependencies. According to expert F, this could be regarded as a separate category and refers to essential commodities produced other than electricity, for example heat and cooling. This could easily be overlooked and would have large impact on the business case if not considered.

Regarding decarbonisation, several categories was discussed. These would be RES penetration, land availability, and contractual constraints. Both expert B and F suggested that the level of renewables in the system should be added. RES penetration would be considering the energy penetration and the power penetration separately when discussing the installed capacity in the system. When talking about possibilities of RES additions, both land availability and contractual constraints. Land availability covers the available spatial area for installing RES, whereas contractual constraints would cover any agreements that could prohibit this expansion, for example, fuel savings or additional usage of a grid connection.

Moving on to the network section and the type of power. According to expert F the type of power would at this stage not be considered, there has not yet been any customer with a dedicated DC bus in an existing or potential future project. According to expert C, the implementation of a DC bus could become relevant in the future as the customer base expands but at this point of time there are no customers that would have a separated DC bus. Because of this, the type of power is removed from this framework, this will also limit the scope a bit due to separate characteristics that a DC bus would provide.

Regarding the microgrid size in the network section, both the distinction between micro-, nano-, and picogrid; and the voltage level is removed. According to experts B, C, and F; any relevant case would not be smaller than a microgrid, so therefore different categories for that would be unnecessary. Expert C points out that the voltage level would not be such of an interest in an early assessment of different cases. Instead, the distinction if there is a HV line, in addition to the LV and MV network, is more of interest because that would bring additional concerns that must be considered. Expert C is further adding that this could instead be included into a hardware category, that would also cover if there is a lot of cables or long runs of overhead lines in the system. These things would have an effect on the reactive power in the system. What also could be considered in this category, is if there are any reactive power compensating units like FACT devices or capacitor banks that must be controlled. Another network related suggestion from expert B, was also to expand the grid connection category to import or export only, or both import and export. Expert C would also add to this category if there is a zero exchange agreement in the grid connection.

In the preliminary framework, the distinction of communication was by if it was wired or wireless communication. This is quite narrow. In the interview with expert E, it was proposed that in addition to the type of connection, wired or wireless, there could also be a type of communication category that would include the types of protocols used. Different protocols would have different advantages and disadvantages and these protocols could also have problems to communicate with each other, requiring converters to be able to have data transfer between them. However, connecting to an existing system is not risk free either, for example, there is a risk that you could poll a system to much and that could lead to a tripping of the communication system. If separate systems have different earthing points, a galvanic isolation would be needed for not getting potential differences between earth points, which in turn could lead to break down of hardware.

Expert E continues, that the fundamental thing needed when going into an existing control system, old or new, is knowledge of which all places is data needed from and how is that accessed. When accessing the data, the next question is if both read and write rights are needed or is only read rights needed. When having only read rights to a system, one problem could be that how is it ensured that you are not able to write as well. This is closely related to the level of cyber security in the system. How is it ensured that the system is protected from unauthorised access and if there would be a breach how is it ensured that they will not be able to control the system, this becomes relevant when talking about operation of power plants. The problem with having control of operation is that, when connecting different devices with each other you want, on a network level, the systems as far from each other as possible for keeping out from unauthorized access.

However, at the same time you must have a very close access to these systems for being able to control different assets and devices in real time with minimal delay.

Expert G states that, it all boils down to what the visibility is between generation and load in the system and how much work is required to get a sufficient visibility to control and optimise the different assets and loads. Obstacles prohibiting this visibility in the system could be communications protocols that is not supported, no digital signals in place and would require hardwiring of devices, fibre cables needed for having a galvanic isolation or keeping a certain speed, the customer could be using some proprietary communication system that is not accessible. All of this could bring challenges when starting to implement a new system into an existing one. What becomes clear when discussing this topic, is that it is very multifaceted and case specific and is not really under the same subject that my thesis work is covering. Because of this I will not analyse this in more detail in this work, it can though be added to my framework as a heads up for what to keep in mind when discussing the type of communication existing in the grid in question.

Related to visibility and level of operation is what kind of system control type does the existing system have. In the preliminary framework the classification was called microgrid control location and with the classification centralised, distributed, or decentralised. Expert B, suggested to call it system control type and split it into centralised or distributed classification, because decentralised and distributed could be an overlapping definition, this was also suggested by expert G.

Last part discussed is the load section. The largest addition is the type of industry category proposed by expert B. It was stated that the type of industry could have impact on several categories, and as an example was to consider cement, chemical, and mining industries. These industries are mainly part of the company customer base as of now in the industrial microgrid segment. Expert C suggested to take into consideration what kind of load types are in the grid, for example, large DOL (Direct Online) motors could cause implication on the power system especially in reactive power requirements and voltage control. Expert A, C, and F mentioned the importance of knowing the predictability of the load profile, can certain loads be predicted or do they come and go whenever. Expert D emphasizes that a possible load growth should be considered and included in a category to be able to assess the project correctly. Expert A and D both suggests assessing the seasonal flexibility in the load profile, for example, if there would be more available RES in one part of the season can this additional energy be utilised. Another larger addition, suggested by expert A, is the load demand of the system, and more precisely the demand during low, base, and peak load. How often does the peak occur, once a year or once a day. From this framework the number of customers is removed and is replaced with the earlier mentioned categories.

4.3 Second set of interviews

In this section the details of the second interviews are gone through. As similarly done for the first interview in chapter 4.2, the process plan is described first and then the main outcomes are presented.

4.3.1 Plan for the second interviews

The second interview focus on the links between the different categories and how they affect each other. Prioritisation of different categories is also looked at, if some categories have a greater impact on the overall framework compared to others. The focus questions for the second interview are listed below. The first question takes into account if the interviewee has something to add that was not mentioned during the first interview. In this second interview the interviewee will for the first time see the other participants suggestions as well and have the possibility in this first question to comment on that. The rest of the questions touches the aim for the second interview that was described above.

1. When looking at the new method, are there anything you would like to add or comment on that wasn't brought up in the first interview?
2. Which categories would be prioritised before another? (Categories with a larger impact on the system as a whole)
3. What would the change in impact be depending on which alternative is chosen for the different categories?

The experts participating in the second interview are listed in table 2. Due to the second interview is focusing on how different aspects of the grid are linked together, the interviewees in table 2 was chosen for their good insight of the grid as a whole. Whereas the interviewees not participating had more focused insight in their specific field.

Table 2. Experts participating in the second interview.

Expert A	Techno-economic analysis
Expert B	Power system architecture & control
Expert C	Power system stability
Expert F	Generation optimisation

4.3.2 Main outcomes of the second interviews

Starting with the dependability aspect, expert B agreed that the dependability of the source is important to get insight of. It was proposed that it could be drawn back to what the primary energy source is and what is the reliability of it. To catch this, it was suggested to add a source type category and implement an energy security index that would cover the reliability aspect of that source. Expert A suggested that included in the dependability could also be a maintenance aspect, if there are available spare parts and are there people who are able to maintain the specific assets. Expert F stated that, the capacity adequacy is strongly linked to the operation philosophy, because the tightness of the system will have an impact on the way the plant is operated. Are there spare generating assets that could be used for spinning reserve and so on. This in turn, would have a great impact on the long-term plans of the power system and especially for the capacity planning.

The topic of addition of RES was discussed with experts C and F. According to expert F, some customers fear the impacts RES will have on their system. According to expert A and C, the impact of RES implementation is strongly linked to the kind of existing assets in the system, are these assets, for example, capable of balancing or only operate during peaking and base load conditions. When adding RES, the role of flexible assets, capable of balancing, becomes more important. Furthermore, automatic operation becomes more important so the system can react fast enough to the balancing needs additional RES requires. Related to this, expert B suggested to change the name of service time compactness to cycling limitations, to cover the aspect of generation assets' capability to do balancing.

Regarding decarbonisation potential, expert A thought that a category for assessing the emission intensity should be added. This index would be expressed as g/kWh and with this, it could be easier to compare the system to other reference systems with similar setups, for example, the RES penetration does not tell how decarbonised the system is. There could be a momentary high penetration of RES, but large parts are curtailed rest of the time. Thus, not resulting in a lower emission intensity. Related to this category addition, expert B suggested that also the aspect of what the tapped/untapped amount of energy from RES should be included. With this aspect the amount of curtailed energy from RES could be covered. The curtailment would be linked mostly to technical constraints in the system, for example, if there are any transmission bottlenecks or if there is a lack of consumption at the point when RES are producing the most.

Furthermore, other aspects of untapped energy could also be included, for example, if there are available land available for RES additions, or if there is a grid connection with a possibility to transmit unused capacity to the main grid, if not already done.

According to experts B and F, for enabling a full optimisation there is a need to have the EMS at a centralised control point of view. Expert B points out though that a distributed control does not directly mean that the system is not controlled in a good way, however, they are probably not operating the grid in an optimal way. Regarding centralised and distributed control point, expert B brought up that different parts of the control could be centralised or distributed. According to expert B, the central control system could be split into three parts that would control each section of the power system, the automated generation control (AGC) for the generation, network control for the network, and a demand side control for the load side. With this viewpoint, the customer could have different parts of their control system centrally or distributed. This would tell us that some part of the system would maybe have the required communication in place already and that there is a level of visibility in the system or that they are to some extent already utilising some optimisation. Depending on what signals are gathered and what the objective functions are, the existing system could provide us with what the necessary inputs for implementing an EMS. Expert C discusses the potential of having a centralised control of the network. This would help in obtaining optimisation objectives related to the network management. Another aspect of this is if the breakers can also provide data of, for example, power flows. These data inputs could help to provide a better load forecast for the system.

For the load section, expert C suggests that a control philosophy of loads should be added to the framework. This aspect would look at how additions of loads are communicated to the operator. The question is if loads are connected on demand or if the load addition is requested beforehand, to ensure that there is enough capacity to cope with the increase in demand that the additional load would imply. This would maybe mainly be relevant for certain demanding loads, for example, large DOL motors. This aspect could probably be linked to the type of industry, due to certain industries having more demanding loads than others. The type of industry would also be linked to the load profiles and the predictability of them, for example, in the chemical industry the load profile would be quite even and be tied to different processes, while in the mining industry the load profile would be more uneven and unpredictable, depending on the type of rock that goes through the system. Expert F adds to this that the type of industry will also have an impact on the load characteristics of the system.

When discussing the load flexibility, expert C points out that the flexibility aspect could be looked at a long-term or short-term timespan, where the long-term would maybe be a couple of days while the short term would be in the closest hour. Any longer timespan would not maybe be part of the flexibility of the asset, instead it would be more related to the planning aspect of loads. Related to this, expert A discusses the possibility to steer loads to times where there would be abundant RES in the system. First suggestion was that it would be related to the load flexibility, however, considering the comments of expert C, this would be more related to planning of loads, because these times with abundant RES would be mainly coupled to periods on a seasonal basis.

Expert F emphasizes the impact the load growth could have on a power system, for example, in the mining industry where the fleet electrification is increasing, the load growth could on a single power system double the existing load demand, thus having great implications on the current system. Both expert A and F points out that the load growth would be closely linked to the long-term planning of the power system and specifically on the capacity planning, this would especially be the case in the example above. Another aspect of load growth, that expert A emphasises, is what type of loads is growing in the system. In a utility case, an acceptable method would be to multiply the existing load demand with the load growth variable, however, in an industry case there could be the possibility that just expanding the existing load curve is too simple. If a certain type of load is growing, then that could also introduce different type of load characteristics than just the need for more capacity. The expansion of the EV fleet would be a good example of that.

5 Analysis of the interview results

In this section, the proposed categories that has been mentioned in the interviews are now analysed. This is done by going through each category and look at the possible challenges that may arise in that topic and answers by experts and looking at relevant literature to find similarities and differences.

5.1 Generation

The generation part focuses on, as the name suggests, categories coupled to the generation side of the microgrid. This part will go through what the primary energy sources are, the characteristics of the prime movers, what kind of planning and energy management is used, and what the decarbonisation potential is for the system.

Dependability. Expert D suggested that the dependability aspect of the different energy sources should be considered. Depending on the location, the dependability of resources can vary quite much. One example of this would be an island at the equator where the number of cloudy days is few during a year. For this case, a solar PV plant, that would usually be seen as a non-dispatchable source with very little flexibility, could be the most dependable resource of energy due to a very limited fuel supply to the island. To catch this viewpoint, it was proposed by expert B to split this aspect into the type of primary energy source and what the security is of it. In the book chapter made by Chicco et al. (2021, p. 3), this type of thinking is to a certain extent touched upon. The primary energy source could be grouped into a system-based energy and environment-based energy category. The system-based energy could be in the form of electricity, fuel, or storage, whereas the electricity would be supplied from an outside network. In an environment-based system the primary energy source would be the solar irradiance or the speed and direction of the wind. The energy security index that was mentioned by expert B could be covered by the availability of the energy source. The availability of system-based energy sources could be described as a limitation in the connection to the main grid or instability of the main grid and regarding the fuel supply, this could be related to problems in the delivery chain of the fuel. For the environment-based sources, the availability aspect would be how often the right conditions are met. Chicco et al. (2021) also considered storage to be part of the system-based energy source, however, I consider that a storage would not be a primary source of energy, rather a storage of energy that a generation asset has produced, thus I will consider the storage to be part of assets in the grid. In this category I will not consider the maintenance aspect that expert A suggested because that would be related to the specific generation asset instead of the primary energy source.

Asset type. After knowing the source of energy there must be a generation asset the transforms this energy into electricity. Then the asset type must be known. Depending on the generating asset characteristics it will bring different challenges or possibilities to the power system. As stated by expert B, every generating asset has some limitations both in the aspect of power and energy, these limitations are brought up in this section. By mapping the types of assets, you can further look at the characteristics of them. Example of this could be a non-dispatchable source like a wind or solar PV plant or a dispatchable source, such as, a dammed hydro plant or a reciprocating engine plant. One question that was raised in the interviews was if the ESS could also be considered as an asset and according to Chicco et al. (2021, p. 3) and expert F, it could be more than well be incorporated into this kind of thinking. The constraint of the ESS must be considered and then it could be classed as any other generation source.

Prime mover interface. When the asset is known then the type of interface between the prime mover and the grid must be known. As proposed by expert C, this could be split into synchronous and inverter-based interfaces. As Klimstra (2014, p. 30–49) explains it, synchronous-based generators are spinning generators that can supply a natural inertia to the system. When the implementation of RES is increasing, with the exclusion of hydro, the level of inertia in the system decreases due to RES are usually connected to the system via power electronic converters. These cannot provide natural inertia to the system, thus making the system more vulnerable to fluctuations. Fluctuations would lead to higher rate-of-change-of-frequency (ROCOF) and lower frequency nadir (Tamrakar et al., 2017, p. 3). As can be seen in Figure 7, the different sections represent the different control levels of a microgrid. First the inertial response, after that the primary level that the governor responds to, the secondary acts as the automatic generation control and restores the frequency to nominal levels, and tertiary would be able to plan additional backup as it sees fit. If the inertia level decreases too much, without any countermeasures, the ROCOF or frequency nadir could be so severe that the whole power system will likely collapse.

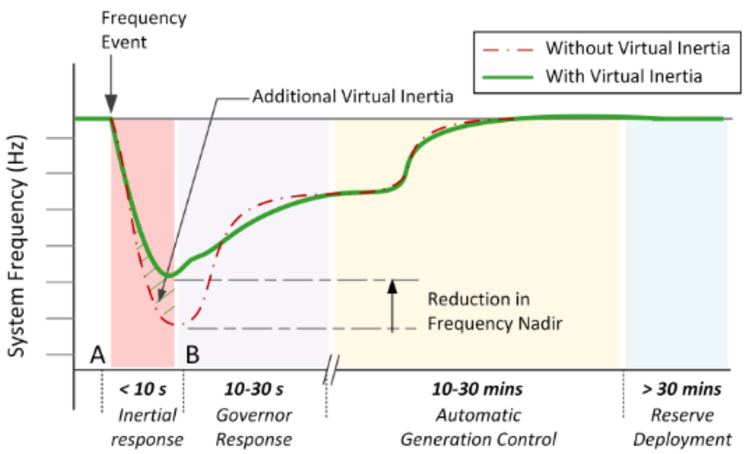

Figure 7. Multiple time-frame frequency response in a power system following a frequency event (Tamrakar et al., 2017, p. 3).

According to Tielens and Van Hertem (2016, p. 3), the level of inertia for a synchronous generator can be estimated with the inertia constant H_{SG}. This constant can be retrieved from equation (1), where E_{SG} equals the stored energy in form of rotating inertia, dependent to the mass and size of the spinning object and the system frequency, expressed in joules (J). S_{SG} equals the apparent power of the generation asset expressed in voltampere (VA) or joules/seconds (J/s). Thus, obtaining the inertia constant expressed in seconds (s).

$$H_{SG} = \frac{E_{SG}}{S_{SG}}. \tag{1}$$

This inertia constant can also be expressed as H_{sys} for the total system in equation (2):

$$H_{sys} = \frac{\sum E_{SG}}{S_{sys}}, \tag{2}$$

where the total stored energy for the system (only synchronous generation) is divided by the total capacity connected to the system, S_{sys}.

The inertia constants tell us for how long the assets can sustain the nominal load without any energy input from the prime mover, for traditional generating asset this constant lies between 2 and 9 s (Tielens & Van Hertem 2016, p. 3). Klimstra (2014, p. 30–49) continues, these extra seconds allows the system to react to any imbalances in the power system. As synchronous generation decreases, the inertia constant of the system will also decrease and thus becoming more vulnerable to fluctuations. To cope with this deficit of inertia, you could add additional reserve capacity by having, for example, more spinning reserve in the system. This, however, would lead to having more units in operation with lower load per unit and this in turn will lead to lower efficiency of the units with higher costs, higher fuel consumption, and more emissions. Another alternative would be to have fast reacting reserve capacity that could respond more quickly to imbalances in the system than traditional power plants. This introduces the possibility of virtual or synthetic inertia provided by very fast acting inverters coupled to an energy source, for example an ESS.

According to Tamrakar et al. (2017), there are different methodologies for supplying virtual inertia to the system, some tries to mimic a synchronous generator with exact mathematical models, some tries only to approximate how the synchronous generator (SG) would behave, while others use a droop-based function that just will respond linearly to the frequency deviations. What should be considered is what type of inverter is going to supply the virtual inertia, especially if it is an islanded microgrid in question. As Hossain et al. (2017, p. 3) describes it, inverters can be grouped into two different types: grid-following inverters, also called current source inverters (CSI), and grid-forming inverters, also called voltage source inverters (VSI).

A grid-following inverter need to have a reference voltage and frequency provided by a robust source to be able to supply the grid with the correct power, usually a main grid or a strong islanded grid, whereas a grid-forming inverter can provide this correct power by itself. Tamrakar et al. (2017) emphasizes that because of the differences between CSIs and VSIs, it is important to keep in mind that some virtual inertia methods require a reference frequency, thus not suitable for use in islanded grids where grid forming capabilities are required. Another thing to notice is that if an ESS, for example a li-ion storage, would additionally to regular cycling also be used for frequency regulation, then it will have a negative impact on the aging of the BESS compared to regular cycling. However, different ESSs could be combined to cope with additional fast discharging that virtual inertia would require, for example, could a BESS be combined with an ultra-capacitor or flywheel. Furthermore, when the virtual inertia is increased with different methods the settling time is also going to be longer, this leads to more energy required by the ESS for compensating the frequency deviation.

If SGs and inverter-based generators are combined in the same grid, according to Hossain et al. (2015, p. 5), if there is more SGs than inverter-based generators then the inverters would be controlled as they would be in a grid connection i.e., grid-following mode. Whereas SGs would be less than inverter-based generation, then the SGs would act as current sources and the inverters controls the bus voltage and frequency i.e., running in grid-forming mode. Another impact that inverter-based generators imply is the limitation on short circuit currents. Inverters are not as capable of providing high short circuit currents as SGs, thus leading to challenges for protection relays to detect faults in the system (Thakurta & Flynn, 2019).

Asset flexibility. The flexibility of an asset will decide how the asset can be used in the power system. If it is possible to use it for base load, peak load, or for balancing applications. This aspect was based on the work by Gagnaire et al. (2016) and changed a bit based on comments by the experts. Three classes are considered here: Time flexibility, power flexibility, and cycling limitations. The time flexible aspect can be linked to the dispatchability of the asset. If the asset is dispatchable or non-dispatchable, a non-dispatchable asset would have limitations in its time flexibility due to it will only generate power when, for example, the weather conditions are right, correct wind speed and direction, enough solar irradiance, etc., whereas a dispatchable asset could be dispatched whenever there is a need for it. Power flexibility could be linked to the minimum stable level of an asset or also the dispatchability of it. A non-dispatchable asset would likewise also have limitations in its power flexibility due to same factors mentioned above, however, with these assets you would have the possibility to decrease the generated power, in other words curtailing possible power. This is avoided though, often due to the objective function of maximising the amount of produced energy from RES.

Cycling limitations implicate limitations of how the asset is started and stopped, ramped up or ramped down. This is more related to thermal assets than RES, for example, gas turbines. Limitations in starting and stopping means that the asset must reach the right operating temperature before the asset could be ramped up or stopped. Likewise, it must cool down to a certain temperature before the asset could be started again. Limitations in the ramping of the asset could be that the ramping must be done in steps for ramping down or that the asset must have the right temperature before it can be ramped up to full load. This cycling limitation aspect could also, to a certain extent, be applied for ESSs. If the ESS would be a battery storage for example, then it would have limitations on for how long and with what amount of power it can be discharged or charged.

This view on flexibility limitations is supported in the work done by Varghese et al. (2021), where they look at flexibility constraints in gas turbines and how the utilisation of these could be increased if improving these limitations. According to Varghese et al. (2021), gas turbines would be limited in their operation by their maximum power output and minimum stable level, ramping rates at starting conditions, and ramping rates in normal operation. With these aspects, the asset would have limitations in its power flexibility and cycling limitations. According to expert C, when there is more RES in the system the flexibility of the rest of the assets becomes important. Assets with this flexibility are called balancing units and would have a fast response time to be able to follow the RES output fluctuations that RES have. The assets cannot only be fast acting, but the control system must also be fast enough, thus an automatic operation is important to be able to react to these changes.

Generation capacity. To get an understanding of how different assets interacts with the system you must know what the generation capacity is. However, the installed capacity alone does not tell what kind of system it is. It is related to the capacity of each generating asset and what the load demand is during base, peak and low load conditions. It is also good to know how often the demand changes, for example, does the peak occur once a week or even once a year. As already hinted, this is closely linked to the load demand and the load profile of the system. According to Klimstra (2014, p. 46), it is not ideal to operate a system with just few larger plants and especially in a setting with high amounts of RES with large variations. By having multiple generating units covering a set load, the fractional loss of generation would not be significant to the system as a whole. Furthermore, the individual generating units do not have to operate at low load, where the assets would become inefficient, in order to have sufficient spinning reserve.

Long term plans. Long term plans are linked to many different categories, for example decarbonisation potential, are there any CO2 goals or plans to expand the RES in the system; capacity adequacy, how is the system now meeting the demand and are there any plans on expanding the generation capacity; load profile, are they planning for any load growth in the system and how much and when. It is important to get a grasp of if the customer has long-term plans in place, to properly take them into account and be able to do a model as true as possible.

Level of operation. Often seen in customer microgrids is that there can be existing control systems in the grid, ranging from manual dispatch to full-fledged automated control of assets. As expert F describes it, in a manual dispatched system all the assets would be dispatched manually by a human operator, this dispatch would be based on the requested demand from the load users and to large extent on feeling. In a manual dispatch it is hard to run assets optimally because as a human operator you don’t have the speed to react to instant changes in the power demand or analytical skills to foresee the future and see what the need would be in short future. With these limitations the assets are often operated with some headroom so it would be easier to operate and that would lead to lower efficiency on the assets. Also, there could be instant changes where there would be need for more headroom but that the human operator cannot see. This view is also supported by Prostejovsky et al. (2019, p. 6), where the authors states that the increasing number of assets needing control and added complexity, due to more unpredictability in the system, leads to human operators do not cope with the monitoring and control that is required.

To cope with this more demanding task, automated operation can be utilised to different degrees. As expert F states, there are three different degrees of automation in a microgrid: a rule-based optimisation, an optimised scheduler, and an automated optimiser. The rule-based optimiser or a static decision support system (DSS), as Prostejovsky et al. (2019, p. 6) calls it, would react to changes in the system based on pre-defined rules and, according to expert F, this would mainly be used for keeping the power quality under control. However, due to frequent variations in the generation profile, this could lead to inefficient control of assets when constantly reacting to these changes. The next step in the automation would be to implement machine learning into the system (Prostejovsky et al., 2019, p. 6). With the machine learning algorithm, the system can make decision based on real-time measurements and forecasts. This degree of automation would be covered by the two last proposed levels: optimised scheduler and automated optimiser. The difference between these two levels is that in an optimised scheduler, the system has an advisory role and proposes how the system should be operated where the operator takes the final decision. In the automated optimiser, the system would take operation decisions and implement them.

A further comment made by expert F, is that if there are ready in place control systems, then it could be a challenge to get different systems to talk to each other, however, this means also that there would be some level of visibility in the system.

This view could be combined with the different levels of automation Prostejovsky et al. (2019, p. 6) adopts from Endsley and Jones (2016) (see Table 3). With this viewpoint, the rule-based optimisation could correspond to batch processing, where the system acts as the human have programmed. The optimised scheduler would be on the consensual decision making level where the system suggests and the operator decides what the system should do, whereas the automated optimiser corresponds to the automated control and decision support where the system choses what to do and the operator can intervene if needed.

Table 3. Levels of automation. Prostejovsky et al. (2019, p. 6) based on Endsley and Jones (2016).

Manual control	Human performs all tasks
Gathering and filtering	System gathers, filters, and highlights key information
Batch processing	System aids in action as instructed by human
Shared control	System and human generate decision options, human decides and carries out with support
Consensual decision making	System recommends options, human decides, system carries out
Automated control and decision support	System recommends options, selects best and system carries out, human can intervene if desired
Full automation	System carries out all tasks

Operation philosophy. When implementing an EMS, the system also must have an operation philosophy in place to work as intended. This category focuses on how the operators operate the facility and what rules are implemented in the system during e.g., contingencies. Both expert A and C emphasizes the importance of knowing what the level of reliability is required for the system. The reliability can be expressed as a percentage value and is calculated by dividing the scheduled operation time with the difference between the scheduled operation time and the unscheduled outage time (Hotakainen & Klimstra, 2011). According to expert A, in industrial microgrids, the reliability requirement is closely related to the value of lost load (VoLL). VoLL is the cost that a power outage would imply in regards of, for example, lost opportunity of producing a good, delay in production, damage to the produced good or production equipment, or employees getting hurt (Gorman, 2022, p. 2). If the VoLL is high, then a trip of the system would have a high financial impact and the operator could value a higher reliability more than an operator in a grid with a lower VoLL.

When the level of reliability is known, then the focus can be set on what the existing rules are in the system. These rules are put in place to mitigate any possible contingencies, for example, that the system should cope with one or two potential generator trips, called N-1 or N-2 generator trip. A mitigation alternative to this could be to have a certain amount of spinning reserve available in the system, questions related to that is then if these rules are followed and when. There is always a cost combined with the mitigation in place (Gorman, 2022, p. 2), therefore, it is always a trade-off between keeping costly spinning reserve or taking the risk of losing certain loads.

Co-optimised dependencies. This part takes into the consideration if there are any produced commodities other than electricity, for example heat. Gu et al. (2014) states that heat and cooling is often combined with thermal assets in industrial facilities, due to the cost savings done by taking advantage of the spare heat. There is also a possibility for these assets to run according to the electrical demand or the heat demand, these options introduce complexities to the optimisation. Expert F emphasize that it is important to get to know this in an early stage to be able to take it into consideration when doing optimisation modelling of the system.

The possibility is that if electricity demand from the asset is only considered, then the model will not keep assets in operation to provide sufficient heat. This would have big implications on the business case, especially in terms of fuel savings.

Capacity adequacy. The term generation adequacy is described by Billinton and Satish (1993, p. 1) and means if there is enough capacity in the system for meeting the demand with the possibility to do repairs or preventative maintenance. According to expert A, in a non-adequate system, in terms of generation capacity, there would be complications on how the load is met if some assets need unplanned maintenance compared to a system with more headroom. According to Billinton and Satish (1993, p. 2), there are several indices used for evaluating this adequacy, but the basic ones often used in power systems are the loss of load expectation (LOLE) and the loss of energy expectation (LOEE). LOLE is defined by the expected time during a set period when the load demand is higher than the available capacity, whereas the LOEE is the expected amount of energy not supplied due to the available capacity not meeting the demand. A LOLE less than 10 h per year is considered reliable by many countries (Kjær et al., 2021, p. 20).

According to expert F, a non-adequate generation capacity is not only related to the amount of installed capacity, but it can also be a consequence of badly maintained assets leading to a vicious circle, where badly maintained assets lead to a non-adequate system that in its turn lead to not being able to maintain the running assets. What is seemed as adequate can also differ from customer to customer. Expert F points also out that different customers have different comfortability levels. Some have a very tight system with demand and generation always head-to-head, leaving room for maintenance only few times a year. Others are never satisfied of the level of security and has many backup layers in place if something happens. Furthermore, these aspects can be linked to the operation philosophy and the long-term plans of the system. Depending on the generation adequacy, the operation philosophy must be according to the available assets and if the generation is not adequate, this is maybe considered in the long-term plans in regard of capacity additions.

RES penetration. The RES penetration is important to know how much they tap into it today and what the possibilities are today to expand to it. According to expert F, to understand the system there are two different figures that must be known: energy penetration and power penetration. The energy penetration describes how much of the total energy, over a set period of time, is covered by RES; with this figure you can for example get an understanding of what impact RES have on the total CO_2 emissions. The power penetration describes the momentarily coverage of RES in the system and the relationship between these two can have different implications.

For example, considering one day operation, with sunlight of 6 hours, of two different microgrids with similar demand. Microgrid A has an installed solar PV capacity of 10 MW and microgrid B has an installed solar PV capacity of 5 MW. Microgrid A will get a peak power of 10 MW while microgrid B gets a peak power of 4 MW. However, microgrid A gets only the 10 MW peak for an hour and the rest of the day only a constant production of 2 MW, while microgrid B gets to keep its peak for the whole day. This results in, that microgrid A will have a produced energy of 20 MWh while microgrid B will have a produced energy of 24 MWh. This way, the microgrid A has a higher power penetration with a lower energy penetration than microgrid B. In this case, microgrid B will have lower CO_2 emissions than microgrid A. Expert B pointed out that the question is then why there is such low penetration in microgrid A, is it due to the nature of the primary source or are there any limitations in the system that makes the system curtail the rest of the power.

There could also be limitations on what the maximum RES penetration is for the microgrid, in the article by Gwon et al. (2019), the authors go through different approaches for evaluating what the limit is on the RES penetration. These methods are used for the Korean power system, but the authors propose that they could also be used for other power system by adopting the limitations parameters for the grid in question. These limits are determined by the minimum power generation by SGs, primary frequency control capability of the RES, reserve requirements during a certain time period, dynamic limitations on the lowest allowable frequency nadir. These limitations are operational rules decided by the operator and would fit into the suggestion by expert A and C, that this is closely related to the flexibility of the other assets in the system and also what the level of operation is. For increasing these limits, Olivares et al. (2014) suggests that the adoption of ESSs is the key technology for this, however, this requires robust control systems, as discussed earlier.

The example above leads us to the next consideration in this category, what the tapped or untapped energy of the RES is in the grid. The aim of this is to get an understanding of if the grid utilises the installed capacity to its full extent. This could be checked by looking at how much of the available RES is curtailed. According to expert B, the curtailment can depend on different factors: there could be transmission bottlenecks in the network or there could be not enough consumption. Due to that power plants are not always near the demand, the power from the RES must be transmitted. In the transmission between the source and the load there could be a limitation on certain powerlines or substations. This would mean that there is enough consumption but due to these limitations a part of the produced electricity must be curtailed. If there are not any limitations in the system there could still be that during high peak RES production there is not enough demand to use the produced electricity, thus it must be curtailed. If there is a grid connection would there a be a possibility to transmit unused capacity to the main grid. This is strongly linked to the network topology of the system.

Resource availability. This category focus on the addition of RES in the system or switching to a less carbon intensive fuel for the thermal assets. For doing this, the availability of these resources must be checked. In regards of expansion of RES, land for installing these sources must be available, if not, then the question is if there are any possibilities to retrieve additional land and what would the implications of that be.

In terms of fuel, switching from crude oil-based fuels e.g., HFO, to a gaseous fuel, for example LNG, could be a way to decarbonise (Livaniou & Papadopoulos, 2022), but the following question is then what the availability is for this type of fuel.

Contractual constraints. This part refers to any contractual constraints for optimising and decarbonising the power system. Expert D pointed out that, if the existing generation assets could be optimised in such way that there would be substantial fuel savings, it must be checked if there is a high take-or-pay fuel agreement in place. A take-or-pay agreement stipulates that the buyer has an obligation to pay for a certain quantity of fuel whether taking it or not (Rogers & White, 2013). This could prohibit any optimisation, impacting fuel savings, by not being able to decrease the fuel consumption without paying for the same amount of fuel agreed on in the contract before the optimisation took place. If such agreement is in place, then the question is if there is a possibility to renegotiate the contract. Another constraint related to cost optimisation by utilising the main grid more, if the microgrid in question is grid connected, would be limitations in the connect in such a case, is there any limitations in the connection that would prohibit an increased offtake from the main grid.

Emission intensity. As expert A suggested, to be able to set a level of decarbonisation to a reference point, the emission intensity would be good to retrieve. If the RES penetration would be the only value of how decarbonised the system is, then it could give a false statement due to not considering the fuel used in the rest of the operation. A microgrid with relative high RES penetration but running its thermal assets on a carbon intensive fuel, for example HFO, could have a more CO_2 intensive grid than a microgrid with lower RES penetration, but is running the thermal assets on a low carbon fuel like natural gas. It was proposed by Expert A, that this would be expressed as g/kWh of CO_2, however, in the literature the CO_2 intensity for industries is often expressed as kg of CO_2 per amount of material produced.

For example, in gold mining, the unit used is kg of CO_2-e per troy ounces of gold produced, ranging from 129 to 2754 kg CO_2-e/oz (Ulrich et al., 2022). In Bernstein et al. (2007, p. 460), most industries are using the kg/tonne of produced good for the emission intensity.

5.2 Network

The network is a crucial part of the power system that lies between the generation and the load. The network cannot in the same way as generation be optimised but if overlooked it can lead to constraints that will have big impact on the final business case.

Topology. The topology of the network put limitations on how assets could be optimised, for example, where in the network different assets are located and how they are affected if a segmentation of the network would occur. According to expert B, the network topology can be set up in different ways and in a power system there is seldom one single topology throughout the system but often in a combination of topologies. Expert B explains that the most straight forward topology is the radial topology. This topology would have several branches and each branch goes from one end to another end of the network. This is a predictable topology that is relatively easy to predict the power flow of and the voltage profile in different parts of the network. This, however, would be more vulnerable to single point of failure due to only one direction for the power to flow.

The ring topology is a topology where the network would be starting and stopping at the same bus. For this topology, the predictions of power flow are harder and would require more measurements in the network to properly predict the state of the system. Protection coordination would also be more complex than a radial system. However, the network is less vulnerable to a single point of failure, due to becoming two radial networks, thus it is more reliable than the radial topology. A meshed topology is the most complex topology with many different directions of power flow from one single point in the network. Protection coordination is complex for this kind of system and with the possibility of multiple line switching alternatives, the control of the system is difficult. Due to the complexity, simplifications are needed when analysed by splitting the system into multiple radial and ring components. However, with complexity comes also more reliability. Due to many possibilities of power flow the reliability is high, and you also get a strong voltage profile.

According to expert C, in the present customer base microgrids there would be a mix of these topologies. Usually, the networks are based on a radial structure with meshed or ring components connected to it. For example, in an industrial facility the power feed from the generation would be made radial and the network in the facility premises would have a meshed structure. Expert C also emphasises the importance of getting a grasp of the network topology if there are any possibilities for a reconfiguration happening in the network. According to Thakar et al. (2019), reconfigurations could be done to optimise the system power flow and thus minimising costs. Reconfiguration may also happen due to faults in the system. Expert C points out the problem if an optimisation is done in the network with not having the possibility of reconfiguration in mind. If there are several plants located in the network with different efficiencies and the optimisation is concentrating operation to the plant with most efficient assets. A reconfiguration splitting critical load from the operating plant would most likely then trip the critical load. With this in my mind, the better approach would then be to spread out the generation on multiple assets for covering any reconfigurations in the network.

Hardware. This category covers any network hardware or physical elements that could influence the early assessment of a case. To this are underground cables and lines, especially HV lines, and any reactive power compensating devices considered. Expert C points out that, usually a microgrid would have a quite small area of operation but it has been seen that industrial islanded grids can have relatively long distribution feeders in form of overhead lines or underground cables.

This could have an impact on the reactive components in the system, thus also on the optimisation of efficient power transmission, also just the existence of several underground cables will have similar effect. Expert B mentions that HV line adds another dimension to the system with additional lines and substations that possibly must be controlled, thus adding complexity.

This corresponds with the work by Psarros et al. (2022). According to the authors, underground cables and HV overhead lines can have a great impact on the reactive components in the grid. These types of feeders have a high capacitance, and especially during low load conditions they will, if not compensated, lead to overvoltages, limited active power supply, and increased losses. When implemented in islanded grids, that typically have relatively small size, there are limitations in the generation assets of how much reactive power they can compensate. In the mentioned article, the available inverters are not capable of absorbing reactive power, thus leaving the thermal assets as the only assets available to compensate. Due to the limitations of each asset to absorb reactive power, there has to more dispatched thermal assets than during normal load conditions. This leads to that available RES must be curtailed due to the limited demand, which in turn leads to higher operational costs.

This could however be limited with the help of dedicated passive or power electronic-based reactive compensators, for example, fixed and variable shunt reactors (VSR) or static var compensators (SVC) and static synchronous compensators (STATCOM) (Song & Kim, 2022). This leads to another point that expert C emphasised, if there are any reactive power compensation devices installed in the grid that must be controlled by an EMS for example.

Grid connection. If there is a grid connection in place will have a strong impact on how the optimisation would be implemented. According to expert B, the different options are import / export only, or both import and export. Furthermore, expert C adds to this classing the possibility of zero exchange as well, used for grid stability. This corresponds to So

(2017), where they are implementing a microgrid with the possibility of a grid-neutral (connected with no power exchange), grid-supporting (grid export), grid-supported connection (limited import), or unlimited grid use. What is also emphasized in the literature is that if there is a grid connection there must be a seamless transition between connecting and disconnecting the microgrid to the main grid. To achieve this, robust control methods, extremely fast switching, and active synchronisation are needed. This is gone through in detail in De Souza and Freitas (2022).

Entity of power plants. With this category, it was suggested by expert A that a good thing to know about is if power plants are distributed in the grid or are centralised to one part. Furthermore, if RES, especially solar PV, are connected to the grid via one or multiple inverters if there is a possibility to lose the whole power plant due to inverter failure. Starting with inverter topologies. According to Cabana-Jiménez et al. (2022), the most used inverter configuration is the centralised inverter configuration, where the whole PV plant is behind one inverter. This system has the lowest maintenance cost but lacks reliability due to inverter trips cuts out the whole PV plant. The following configuration is an inverter chain configuration where the PV plant is divided into several chains of panels connected to the grid via individual inverters. This configuration has higher reliability but higher overall cost and higher maintenance cost. These two configurations would be the most used ones in an industrial or utility scale setting, with the chain configuration gaining more interest (Novergy Solar, 2020).

Regarding the placement of generation assets in the grid, it was said by expert C that a centralised implementation would ease operation but harder to keep a good voltage profile throughout the grid. In a decentralised approach, keeping a good voltage profile throughout the grid would be easier but harder to control the assets. This was simulated by Bandeiras et al. (2018) and they reached the same conclusion. Furthermore, they stated that a decentralised approach could also help sustaining critical loads with power during contingencies. Placement of ESSs was also discussed by the authors, in smaller grids, like microgrids, the placement of an ESS does not have similar impact as in larger grids, where ESSs are often placed near loads to keep losses at minimum, thus often placed where suitable. However, in a centralised approach the ESS would be placed near transformer substations and used for frequency regulation and balancing. Whereas in a decentralised approach, the ESS would be close to loads and generation assets helping in demand response.

5.3 Load

Proposed by expert B is that there could be classification done depending on the **type of industry**, which was agreed upon by several other experts. The most agreed aspect was that the industry type would have an impact on the microgrid load profile. This statement is also thought of by Sandhaas et al. (2022), who is trying to retrieve synthetic load profiles for different industries with the assumption that similar industries would have similar load profiles. There are many types of industries that could have implemented a microgrid but based on the customer base that this company has I am concentrating on the chemical, cement, and mining industry.

The characteristics of the mining industry's load demand is gone through in detail in the work by Gomez et al. (2020). Mining consists of three main processes: ore extraction, handling of material, and mineral processing. The ore extraction process is non-linear and cyclic, and the load demand depends on the type of drill rate and shovel loads, thus making the demand quite volatile. The material handling consists of hauling the material to the processing location, this is mainly done with trucks but there would be a possibility to use conveyor belts, thus enabling the possibility of regenerative power from decreasing speed in downhill situations. In the ore extraction process, there would also be the possibility to incorporate power electronics in the digging machinery, thus it also opens the possibility for regenerative power. Studies have shown that the amount of regenerative power can peak at 2 MW per cycle from shovel machines.

Gomez et al. (2020) continues, the mineral processing stage is the most energy demanding part with a 40 % of the total power demand. The grinding process would also have an unpredictable power consumption due to different hardness of ores. By splitting up different ores into different stockpiles, this unpredictability could somewhat be mitigated by using some DSM to control what ore is fed into the grinding process. Due to all different types of rotating machinery, there is a wide use of motors in mining. Highly variable energy consumption in mining depends on mineral, depth, and mining plan. Deep sea mines use often radial-based topology whereas open pit mines often use ring-based topology, furthermore, the distribution network itself would also change during mining operation.

In Olsen (2011) the cement production process is described. The cement production process consists of four main process stages: crushing of raw material, kiln feed preparations, clinker production, and finishing grinding. In the first step, limestone is crushed into and then fed to the kiln preparation. In the preparation before the kiln, the crushed material is milled and blended with other components into an even blend. Next step is the heating process that produces what is called clinker, which is later milled into cement. The cement industry reminds a bit of the mining industry, by having crushing and milling of raw and treated material. However, in the cement industry, the raw material is constantly the same material, this would imply that it does not have the same unpredictability in load demand as the mining industry would have, due to different hardness of the mined ores. A characteristic that differentiates a cement plant from a mine, is that a cement plant would also require a lot of heat to produce the clinker and this heating process is a critical continuous non-interruptible load that requires constant demand for keeping good quality. This would give a more levelized demand curve than in mining.

Chemical industry as a term is much broader than cement and mining, so it is harder to put a generalised characteristics of it, however, Riese et al. (2014) points out that one common trait is that the chemical industry is very energy and heat intensive. The demand for both electricity and heat are also constant in both the amount of energy and for how long the energy is needed, this is because chemical facilities have often a continuous production. Shoreh et al. (2016) states that chemical industries would also have high VoLL and therefore are run at full constant capacity. This would also mean that the load profile for these types of industries would be more predictable and even than both cement plants and mines.

The **load demand** covers what the difference is between low load, base load, and peak load. This was pointed out by expert A as a necessary distinction, for example, in the case of a peak load, there would be a large difference if the peak load would occur every day or few times a month. This would also reveal at what point of time is the generating capacity adequate for the system. As mentioned in an earlier chapter, if the power system would have capacitive properties there could be problems with overvoltages if there is a large difference between low and peak load.

Load flexibility. In (Golmohamadi, 2022), the authors go through the different load flexibility possibilities in different industries. It is stated that the ability for loads to be flexible depends on what type of industry it is in question, for example, mining industries would not have the same flexibility as in a cement as mentioned earlier. The flexibility levels could be split into three groups: long, mid, and short advance notices. On a long term notice the operator would look at the next 24 hours forecast and plan accordingly to what would be optimal processes for those hours would be, for example, the availability of RES. One conclusion could be not run certain non-critical loads at all for the next 24 hours. This viewpoint would be more of planning level than flexibility of a load, thus corresponding quite good with the suggestion by expert C. On a mid-term notice, the decision would be made on 60 to 10 min notice before planned dispatch and now certain non-critical loads could be decides not to be started. On short notice the decision would happen few seconds before dispatch and at this point could for example tune the power consumption for VSD controlled mills.

These mentioned flexibility measures would be used under normal operating conditions, furthermore, there could also be, according to Golmohamadi (2022), flexibility measures used during contingencies working on the same principle that spinning reserves, non-spinning reserves and supplemental reserves would do. Compared to a measure similar to spinning reserve would be to decrease the power consumption on allowable loads that wouldn’t affect the end product, for example, in an aluminium smelting pot. Non-spinning reserve would be to stop a crusher and allowing time for fast start up generators. Supplemental reserves would be to for example stop a batch after the ongoing process is ended. And continue after the contingency is over. These different measures correspond to the time flexibility, power flexibility and minimum running time that was suggested in the preliminary framework.

The **load profile** would be closely linked to the type of industry. As earlier stated, different industries would have different requirements in load demand and could either be predictable or unpredictable. Also, different industries would also have load profile that either could be volatile or even. Expert F states that a volatile load profile could be predictable, thus not causing any substantial problems. However, if the load profile would be unpredictable even if the demand would be mostly even it could have an effect on the implementation of an EMS, for instance, if load patterns are known from the get-go or if some time has to be reserved for the training of the EMS. Related to load profile is also if there is foreseen any load growth in system as proposed from expert D. In a grid with high RES penetration, a load growth could lead to less reliability. According to Kahrobaee et al. (2014), if the load increases with 10-20 % then a RES addition of 3-5 times the existing RES capacity in order to keep the same reliability in the system, if the added capacity should be RES and not thermal assets.

Load types. Expert C suggested the addition of what types of loads there are in the system, for example, large DOL induction motors could imply some certain considerations in reactive power and voltage control. This is off course related to the total load of the system. Han et al. (2017, p. 19) states that complex loads, for instance, dynamic loads, induction motors, pulsed loads and electric vehicles brings complications to the reactive power control. Large induction motors, for example, is common type of load in some industrial applications and due to the large amount of reactive power required at start up, it can cause serious local voltage drops in a weak grid (Sabbir et al., n.d.).

Load group priority. It was concluded by several experts that the different priorities that could be used in industrial grids could be just critical and non-critical loads. Furthermore, expert C proposes that instead of classifying individual loads, it would be more realistic to classify according to load groups. In the existing customer base, there are rarely any possibility to control individual loads, instead the control would be done by operating separate feeders or breakers. This off-course depends on the size of the individual loads, for example, a large DOL motor could be by itself behind one feeder.

5.4 System control

The system control type refers to where in the system the energy management system is located. If looking at this via the control hierarchy perspective, then this is about if the secondary control is implemented in a centralised or decentralised manner (Hatziargyriou et al., 2016, p. 2) (see Figure 8).

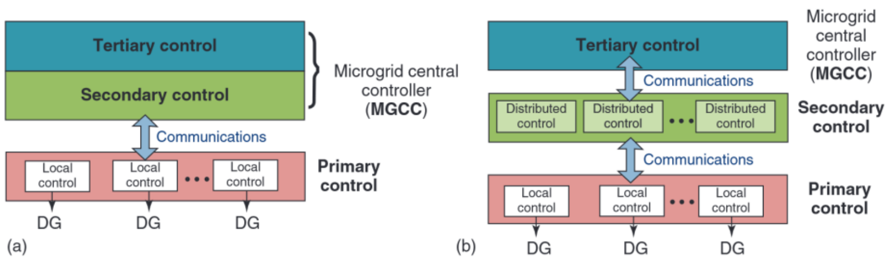

Figure 8. Hierarchical control – microgrid communications, local and centralized controllers: (a) centralized control architecture and (b) decentralized control architecture (Hatziargyriou et al., 2016, p. 2).

According to Meng et al. (2016), a centralised approach will ensure a good overall supervision and broad control of the whole power system. This requires though, powerful computing resources and a fast communication connection between devices to, in real-time, go through all data and do optimised decisions. The drawbacks are the vulnerability of a single point of failure and the inflexibility of expanding the system. Suitable implementations would be, for example, in smaller microgrids, in microgrids where there is a common understanding of the desired outcome, and where the system composition is mostly fixed. In a decentralised approach, some of the decisions and computations is done at the local control level, thus requiring less computational performance in the central controller. The central controller would perform more coordination and share information. It could enhance reliability because the optimisation would not rely on one device, thus becoming less vulnerable to a single point of failure. However, this approach would require a good synchronisation between the devices and the communication between these devices becomes vital. The cyber security aspect could also become of higher importance because of more devices capable to operate. This approach would suit larger grids in terms of distance (due to less need of central data acquisition, that could be costly to implement), grids with multiple stakeholders with different outcome goals, and grids requiring plug-and-play functionality.

As stated by several experts, the centralised approach would be the optimal solution. This is somewhat corresponding with the literature, as stated by Meng et al. (2016), the centralised approach would be suitable for smaller grids with a global optimisation goal. This is also stated by Dimeas et al. (2014, p. 34), that the centralised approach would be often used when the producer and user of the electricity is the same entity, for example, in an industrial microgrid. Furthermore, Thakar et al. (2019, p. 10) points out that for network reconfiguration possibilities in a microgrid there would also be a need for a central controller. However, as the grid becomes larger and there could be several stakeholders involved, the decentralised approach could become more relevant.

This topic summarises also all the control possibilities of each section in the microgrid. A suggestion by expert B, was to consider looking at the EMS as a central controller with three different components: an Automatic Generation Control (AGC), a network controller, and a demand side controller. Expert C is also emphasizing the possibility to check whether the customer has a network control in place or if the control of breakers and switches is done manually. This approach has to some extent been discussed in the literature, for example, both Pawar et al. (2020) and Wei et al. (2016) are considering a load management system inside of the EMS. This would also take into account the control philosophy suggestion by expert C; how is additions of loads communicated to the operator. Are they connected whenever or is it requested from the operator if the load is allowed to be connected. In the work by Litvinov et al. (2019), the authors propose an EMS with an AGC inside of it. As earlier mentioned, for the network control Thakar et al. (2019, p. 10) states that for a good network reconfiguration it should be located in a central controller. This approach would also go hand in hand with the visibility aspect of the microgrid discussed in chapter 4.2.2: in a microgrid with the controllers in place, there should be some visibility in the system. Then question is what data signals is collected and how is the system optimised.

6 Proposed method

In this section, the finalised classification framework is proposed. I have split up the framework into three sections: generation, network & control, and load. In each section there is sub-sections that covers different aspect of the different topics. In the sub-sections, I have grouped together categories that touch the same area and in these the main challenges or areas of concern are stated. In each category I have also added linked categories that would on some level be tied together. The categories are gone through briefly in this part, for more detailed analysis refer to chapter 5. The framework as a whole is attached to appendix 1.

In the generation section, the first sub-section is energy source reliability. In this part, the aspect of what the primary energy source is and the availability of it are covered. The primary energy source looks at where the main source energy is extracted from, this could be solar irradiation or fuel. Related topics are if there is a grid connection and if there are some limitations on that. The availability aspect is covered by the resource availability category and tries to map what sources of energy really is dependable at the grid in question (see Figure 9).

Energy source reliability	
Primary energy source	**Resource security**
What are the available primary energys sources, such as, • Solar • Wind • Fuel (e.g., LNG) • Main grid	**What is the availability of these sources** • Is the fuel supply unreliable • Varying wheather conditions • Unstable main grid
Links • Network, grid connection	**Links** -

Figure 9. Energy source reliability sub-section.

The following sub-section is generation characteristics. Here are the generation types converting the primary energy source into electricity covered. First category is the asset type, where the types of assets are covered. This could be an energy storage, reciprocating engine, etc. Next category is the prime mover interface which takes into consideration what the distribution between SGs and inverters are. This will have effect on the grid stability and would require a detailed evaluation for the impacts on the system. Asset flexibility looks at the prime movers and their capability for balancing RES, this would be related to the level of operation. The last category is the generation capacity, where the total capacity of the assets and the capacity of each asset is checked. This has tight connection to the load demand, what kind of interface, and the flexibility of these assets (see Figure 10).

Generation characteristics			
Asset types	**Prime mover interface**	**Asset flexibility**	**Generation capacity**

What assets are available in the grid, e.g.,
• Reciprocating engines
• Energy storage
• Solar PV plant
	What type of prime mover interfaces are there
	• Synchronous generator
	• Inverter-based interface
	  • Grid-following
	  • Grid-forming
		• Time flexible (D/ND)
		• Power flexible (MSL etc.)
		• Cycling limitations (starts/stop times)
			• Total generation capacity
			• Capacity of each generating asset

Links -	**Links** • Generation capacity	**Links** • Level of operation	**Links** • Load demand • Prime mover interface • Asset flexibility

Figure 10. Generation characteristics sub-section.

The third sub-section is called generation planning & energy management. This maps the areas how the operation of assets is done. The following categories are covered: are there long-term plans in the system and what are they in that case, what is the operation philosophy in the grid, are there any other commodities than electricity produced in the system and is there adequate capacity in the system and to what extent (see Figure 11).

Generation planning / Energy management			
Long-term plans	**Operation philosophy**	**Co-optimised dependencies**	**Capacity adequacy**

Are there any long term plans for the power system?
• Are there any CO2 reduction goals?
• Plans of replacements/additions of generating assets?
• Planning for load growth?
	• What is the level of reliability required?
	• Are there any existing rules in place
	  • How to operate during N-X generator trip
	  • Any spinning reserve requirements
	• How willing to take risks
	  • Trade-off between keeping costly spinning reserve or taking the risk of loosing certain non critical loads
		Other commodities produce other than electricity e.g.,
		• Heat
		• Cooling
			Is there enough capacity for meeting the demand
			• Possibility for maintenance
			• Different indices could be used e.g.,
			  • LOLE
			  • LOEE

Links • Decarbonisation potential • Capacity adequacy • Load profile	**Link** • Capacity adequacy • Grid connection	**Links** • Type of industry	**Links** • Operation philosophy • Long term plans

Figure 11. Generation planning & energy management sub-section.

The last sub-section is called decarbonisation potential, here the potential for further decarbonisation and the state of the system as of today is covered. Emission intensity and RES penetration looks at what the state is now. RES penetration maps the penetration in terms of energy and power and the aspect of if there is any untapped RES in the system. In the emission intensity the CO_2 emissions coupled to the produced energy or material is covered. Resource availability and contractual constraints takes into account the possibilities for further decarbonisation by looking at, for example, available land or greener fuel alternatives and if there are some agreements prohibiting optimisation of the system (see Figure 12).

Decarbonisation potential			
RES penetration	**Resource availability**	**Contractual constraints**	**Emission intensity**

What is the RES penetration
• Energy penetration
• Power penetration
 	
Is there any untapped energy from RES
• Curtailment
  • Transmission bottlenecks
  • Not enough consumption
• Unused capacity in powerlines or powerstations
• Islanded or grid-connected -> possibility to transmit unused capacity
	Addition possiblities of greener resources
	• Land for solar and wind
	• Water for extensive hydro power
	• Alternative fuels
	  • Are there any availability of carbon neutral or carbon free fuels.
	  • Possibility of using LNG if not already doing it.
		Are there any agreements prohibiting optimisation?
		• take-or-pay fuel agreement
		• limitations on grid off-take (if grid connected)
			Is there a emission intensity figure available
			• g CO2/kWh
			• kg CO2/tonne

Links • Hardware	**Links**	**Links** • Grid connection	**Links** • Type of industry

Figure 12. Decarbonisation potential sub-section.

The following section is the network & control section. This is split into two sub-sections: network characteristics and visibility & control. The network characteristics considers the four categories: hardware, topology, grid connection and entity of power plants. Hardware covers, for example, cables and lines, reactive power compensators or other hardware that would have an effect on the reactive power control in the system.

Topology considers if there are any other topology elements than radial topology in the system and if there are possibilities for any reconfiguration in the network. Grid connection considers limitations on the grid connection if there are one, and entity of power plants looks at if RES is behind multiple inverters and if the installed generation assets are centralised or decentralised in the grid (see Figure 13).

Network characteristics			
Hardware	**Topology**	**Grid connection**	**Entity of power plants**

Are there hardware in the system that can have impact on e.g., reactive power
• Cables and lines
• Reactive power compensators
• Online tap changers
	Is there other topology elements than radial topology e.g.,
	• Ring
	• Meshed
	
	Possiblity of reconfigurations in the network?
		• On-grid
		  • Import or export only
		  • Import and export
		  • Zero exchange
		• Off-grid
			Are RES behind one or more inverters?
			
			Is generation assets grouped or decenralised?

Links • Load demand • RES penetration • Control functionalities	**Links** -	**Links** • Contractual constraints • Operation philosophy	**Links** -

Figure 13. Network characteristics sub-section.

Visibility & control is the last sub-section in the network & control section. In this, the categories, system control location, control functionalities, level of operation and asset visibility are covered. System control location is considering if the secondary control level is centralised or decentralised, this would be linked to the locations of assets and what control functionalities are available. The control functionality looks at what part of the grid is controllable, and this tells also what kind of visibility there is in the system. The level of operation considers the degree of automation in the system, and this would for example be linked to the flexibility of assets due to more need of automation when assets has balancing capabilities. The visibility aims to get grasp of the visibility in the system, for example, is there communications in place for central controllers and generation to talk to each other and so on (see Figure 14).

Visibility & Control			
System control location	**Control functionalities**	**Level of operation**	**Asset visibility**
Where is the secondary control located? • Centralised • Distributed	What control functionlities are present • Automatic generation control • Network control • Load control	• Manual dispatch • Rule-based optimisation • Optimised scheduler • Automated optimiser	What is the visibility in the system?
Links • Control functionalities • Entity of power plants	**Links** • Visibility	**Links** • Asset flexibility • Visibility	**Links** • Control functionalities • Level of operation

Figure 14. Visibility & Control sub-section.

The load section is grouped into the sub-sections load characteristics and load management (see Figure 15 and Figure 16). What the analysis has shown is that the type of industry will have a large impact on the load characteristics in the system and these would be load flexibility, load profile, type of loads and load group priority. Load flexibility assess the possibility of demand response of loads and the load profile takes into account the day-to-day load demand and what the predictability, volatility and if there is any load growth. Type of loads aims to map if there are any relatively bigger loads that can have an effect on the stability of the grid and the last category looks at the priority of the load groups.

Load characteristics			
Load flexibility	**Load profile**	**Type of loads**	**Load group priority**
Possiblity for load flexibility • Time flexibility • Power flexibility • Minimum running time	What type of load profile is it in the system • Predictable / unpredictable • Stable / Volatile • Load growth	What are the different types of load e.g., • DOL induction motors	• Critical • Non-critical
Links • Type of industry	**Links** • Type of industry • Type of loads	**Links** • Load demand • Type of industry	**Links** • Type of industry

Figure 15. Load characteristics sub-section.

Load management covers the load demand and the type of industry the microgrid is part of. The load demand looks at the differences between, low load, base load, and peak load. The load profile would give more detail of what the actual load is from day-to-day, but by knowing these high level load stages can give some insight to if there is adequate generation or problems with reactive power. The type of industry for this thesis is covering chemical, cement, and mining industry. This is gone through in more detail in chapter 5.

Load management	
Load demand	**Type of industry**
• Low load • Base load • Peak load	• Chemical • Cement • Heavy industry (mining)
Links • Hardware • Generation capacity	**Links** • Load profile • Load flexibility • Load group priority • Co-optimised dependencies

Figure 16. Load management sub-section.

7 Discussion

This proposed framework tries to catch the most fundamental areas of concern where challenges could arise and how different aspects are linked together of decarbonising a microgrid through optimisation. This framework could be used as a guide or template for experts in an early stage to help them in the mapping process of different projects. Thus, helping them in taking into consideration the fundamental aspects before starting to implement different solutions, for example, additions of ESSs and installation of an EMS. Furthermore, this framework could also be used as a “canvas” in customer discussions for helping to ask the right question that will have an impact on the early assessment of a case, this way you could ensure you are not forgetting any important aspects.

However, to properly know if these topics touched upon in this thesis work are valid, a proper verification is needed to test to see if the framework catches the most fundamental aspects. This could be done by using the classification framework on projects already analysed without the framework and then comparing the results with each other. This way, it could be checked if the framework catches the aspects that was at least found important in the manual analysis. The following step, when several cases have been gone through, could be to have a clustering algorithm to see if there would be any unnoticed parameters that would have an effect on the characteristics on a microgrid. A further thing to consider is that the experts interviewed are working in the same company and have therefore not come across things that maybe other companies have faced, so this could also be a factor to consider when looking for additional parameters.

Based on the discussions and analysis done by reviewing relevant literature there are some topics that I see should need further research. According to the several authors Unamuno and Barrena, (2015); Pourbehzadi et al. (2019); Sarwar et al. (2022), the concept of AC/DC hybrid microgrids are getting more traction across the industry. There is a constant expansion of DC loads and inverter-based generation that could benefit from having a dedicated DC bus, thus removing many constraints and losses that would usually be found in an AC system. This type of microgrid would though bring other challenges to the system, thus it could be further researched what the requirements are to control loads and generation on DC and AC level together.

What was seen in the load section is that many categories are tied closely to the type of industry the microgrid is used in, and by understanding the type of industry, it will substantially help in mapping possibilities and constraints in the project in question. In the thesis three different industries was gone through very briefly with the chemical industry gone through at a very high level. When the customer base is expanding, the importance of knowing the industry and what characterises that industry will unlock the potential where the optimisation could be done. Closely linked to this is also the possibilities of load optimisation and demand side management. For a complete EMS, the load control should also be utilised and the possibilities for load management in different types of microgrids, in different industries, should be further studied. Related to this would also be the possibility for network control, according to Thakar et al. (2019) network control could be used for real-time congestion management, thus enabling to use the available RES to full extent by removing congestions in the microgrid.

Another topic that leaved me a little unsure is the system control type, whether a decentralised or centralised secondary control would be better. The experts were quite united in that a centralised secondary control would be the most optimal but, in the literature, the decentralised was often mentioned as a more optimal approach in many different conditions, for example, if the distances between generation assets and loads are long. This could be further looked in to for finding the boundaries for these two different systems. A topic that is related to this and would make the world of microgrid control easier to understand would be to get more consensus of all terms and functionalities used in the industry. As touched upon in chapter 2.4, there are many different terms for the same thing and according to different authors, the functionality could vary quite much. There could be done more research on standards and mapping of functionalities to decide what really does what, this could also help in customer discussions to ensure that the terminology used by different parts are corresponding to each other.

The communication is a monster on its own, it was revealed in the interview with expert E and G that there are many different challenges that can arise when trying to get different communications system to talk with each other. There is a vast combination of different standardised protocols and proprietary protocols used in different microgrids throughout the world, so there is a high probability that communication between devices can make a case complex. For getting better understanding of this topic, the functional layer approach touched upon in chapter 3 could maybe help in this.

The decarbonisation of power systems is getting more traction and a topic that is getting more interest due to that, is hydrogen production in combination with RES and, furthermore, the implementation of hydrogen in microgrids (Lee and Kim, 2022). This will add a whole other level to the optimisation of microgrids; to optimise the electrolyser production, with its constraints, to the rest of the system. It would be good to get an understanding of what impact the introduction of hydrogen production will have on the microgrid optimisation.

8 Conclusions

The aim of this thesis was to create a classification framework for assessing the possible areas of concern when starting to plan decarbonisation through optimisation for industrial microgrids. The work was done for a technology company in Vaasa, Finland focusing on decarbonisation of electrical power systems. The research process was based on qualitative study with literature reviews and interviews with experts across the company. The interview process was semi-structured and split into two different occasions, the first one focusing on general discussions on the possible fundamental areas that need to be assessed. The second occasion focused more on how different areas would be linked together and what would have an impact on what. The interview results were then analysed by comparing the answers with relevant literature.

The result was a proposed framework split into different sections: generation, network & control, and load. Each section had then different sub-sections focusing on different areas in each section and in each sub-section the relevant categories was listed. Every category was analysed, and the main findings were put into the framework, to these categories was also added links to other potential categories that would in some way be related to the category in question. These categories functions as pillars in the system, depending on what type of microgrid these pillars can have different weights, but they are there regardless of what type of grid it is. Some key findings were that the type of industry will have a great impact on the load profile of the system and different industries have different prerequisites for being able to implement load management.

The final framework could be used as a basis for assessing the possible areas of concern in a new microgrid project. It could be used both of experts and salespeople. For salespeople it could be used as a “canvas”, helping to ask the relevant questions for revealing any possible challenges in an early stage. For experts it could be used as tool for analysing cases when trying to create a solution for the project, furthermore, the framework could also be used to do further research on, for example, implementing some clustering algorithms for revealing unnoticed parameters that may have an impact on business case.

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Appendices

Appendix 1. Classification framework

Generation

Energy source reliability

Primary energy source	Resource security
What are the available primary energys sources, such as, • Solar • Wind • Fuel (e.g., LNG) • Main grid	**What is the availability of these sources** • Is the fuel supply unreliable • Varying wheather condtions • Unstable main grid
Links • Network, grid connection	**Links** -

Generation characteristics

Asset types	Prime mover interface	Asset flexibility	Generation capacity

What assets are available in the grid, e.g.,
• Reciprocating engines
• Energy storage
• Solar PV plant
	What type of prime mover interfaces are there
	• Synchronous generator
	• Inverter-based interface
	    • Grid-following
	    • Grid-forming
		• Time flexible (D/ND)
		• Power flexible (MSL etc.)
		• Cycling limitations (starts/stop times)
			• Total generation capacity
			• Capacity of each generating asset

Links -	**Links** • Generation capacity	**Links** • Level of operation	**Links** • Load demand • Prime mover interface • Asset flexibility

Generation planning / Energy management

Long-term plans	Operation philosophy	Co-optimised dependencies	Capacity adequacy

Are there any long term plans for the power system?
• Are there any CO2 reduction goals?
• Plans of replacements/additions of generating assets?
• Planning for load growth?
	• What is the level of reliability required?
	• Are there any existing rules in place
	    • How to operate during N-X generator trip
	    • Any spinning reserve requirements
	• How willing to take risks
	    • Trade-off between keeping costly spinning reserve or taking the risk of loosing certain non critical loads
		Other commodities produce other than electricity e.g.,
		• Heat
		• Cooling
			Is there enough capacity for meeting the demand
			• Possibility for maintenance
			• Different indices could be used e.g.,
			    • LOLE
			    • LOEE

Links • Decarbonisation potential • Capacity adequacy • Load profile	**Link** • Capacity adequacy • Grid connection	**Links** • Type of industry	**Links** • Operation philosophy • Long term plans

Decarbonisation potential

RES penetration	Resource availability	Contractual constraints	Emission intensity

What is the RES penetration
• Energy penetration
• Power penetration
 	
Is there any untapped energy from RES
• Curtailment
    • Transmission bottlenecks
    • Not enough consumption
• Unused capacity in powerlines or powerstations
• Islanded or grid-connected -> possibility to transmit unused capacity
	Addition possiblities of greener resources
	• Land for solar and wind
	• Water for extensive hydro power
	• Alternative fuels
	    • Are there any availability of carbon neutral or carbon free fuels.
	    • Possibility of using LNG if not already doing it.
		Are there any agreements prohibiting optimisation?
		• take-or-pay fuel agreement
		• limitations on grid off-take (if grid connected)
			Is there a emission intensity figure available
			• g CO2/kWh
			• kg CO2/tonne

Links • Flexibility • Level of operation • Hardware	**Links** •	**Links** • Grid connection	**Links** • Type of industry

Network & Control

Network characteristics

Hardware	Topology	Grid connection	Entity of power plants

Are there hardware in the system that can have impact on e.g., reactive power
• Cables and lines
• Reactive power compensators
• Online tap changers
	Is there other topology elements than radial topology e.g.,
	• Ring
	• Meshed
	
	Possiblity of reconfigurations in the network?
		• On-grid
		  • Import or export only
		  • Import and export
		  • Zero exchange
		• Off-grid
			Are RES behind one or more inverters?
			
			Is generation assets grouped or decenralised?

Links • Load demand • RES penetration • Control functionalities	**Links** -	**Links** • Contractual constraints • Operation philosophy	**Links** -

Visibility & Control

System control location	Control functionalities	Level of operation	Asset visibility
Where is the secondary control located? • Centralised • Distributed	What control functionlities are present • Automatic generation control • Network control • Load control	• Manual dispatch • Rule-based optimisation • Optimised scheduler • Automated optimiser	What is the visibility in the system?
Links • Control functionalities • Entity of power plants	**Links** • Visibility	**Links** • Asset flexibility • Visibility	**Links** • Control functionalities • Level of operation

Load

Load characteristics

Load flexibility	Load profile	Type of loads	Load group priority
Possiblity for load flexibility • Time flexibility • Power flexibility • Minimum running time	What type of load profile is it in the system • Predictable / unpredictable • Stable / Volatile • Load growth	What are the different types of load e.g., • DOL induction motors	• Critical • Non-critical
Links • Type of industry	**Links** • Type of industry • Type of loads	**Links** • Load demand • Type of industry	**Links** • Type of industry

Load management

Load demand	Type of industry
• Low load • Base load • Peak load	• Chemical • Cement • Heavy industry (mining)
Links • Hardware • Generation capacity	**Links** • Load profile • Load flexibility • Load group priority • Co-optimised dependencies