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Digitalization and energy flexibility of a battery manufacturing process

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Anni Ristola

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Author Anni Ristola

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Thesis supervisor Tanja Kallio

Thesis advisor(s) Malin Fuglesang, Jagruti Ramsing Thakur

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Abstract

The three D's (decentralization, decarbonization and digitalization) are the main drivers for the fourth industrial revolution, Industry 4.0. Furthermore, digitalization has a huge part in the future of energy as the demand and the available data are growing. Digitalization allows greater prediction, optimization and controlling of energy usage. Hence it creates an opportunity to lower energy costs and peak consumption as well as to integrate renewable energy sources.

Digitalization also enables energy flexibility (EF). Industrial sector is considered as an attractive candidate to EF operation due to its high consumption. Quantification of EF is done as energy flexibility potential (EFP) through energy flexibility measures (EFM). Adaptation of start of production in each process step is one of the most reasonable EFM for battery manufacturing, enabling peak shaving possibilities.

The objective of the thesis is to enable peak shaving within the manufacturing process through higher level of digitalization. The assessment process includes defining the characteristics of each industrial system, according to which the suitability for energy flexible operation is assessed. Each process step is graded in two categories: flexibility and power. Flexibility scores were given based on the information received from the process engineer, whereas power scores were given either by installed powers or according to the measured peak powers. Three scenarios to set up measurement points in the manufacturing process were created according to the given scores, and comparison of investment costs and level of digitalization was made between each scenario. Scenario 3 shows the most potential as the achieved level of digitalization is relatively high while the investment costs in relation to scenario 2 are not much higher.

It was observed that, battery manufacturing process does not have much EF. By adding energy storage solution (ESS) or renewable energy sources (RES) the flexibility can possibly be increased. However, more advanced modeling is needed to conclude economic analysis and calculate the practical and viable EFP. In order to do that, suggested real time measurement points should be set up and the data should be used for modeling different scenarios, e.g. with ESS and RES.

Keywords Industry 4.0, digitalization, Demand Side Management, Energy Flexibility Potential, Li-ion battery, RES, ESS

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Tiivistelmä

Kolme D:tä (hajautus, hiilenpoisto ja digitalisaatio, *engl. decentralization, decarbonization and digitalization*) ovat neljännen teollisen vallankumouksen, (*engl. Industry 4.0*), tärkeimmät edistäjät. Lisäksi, digitalisaation tärkeys energian tulevaisuudessa kasvaa kysynnän ja käytettävissä olevan tiedon kasvaessa. Digitalisaatio mahdollistaa paremman ennustamisen, optimoinnin ja energiankäytön hallinnan. Se luo mahdollisuuden alentaa energiakustannuksia ja huippukulutusta sekä integroida uusiutuvia energialähteitä.

Digitalisaatio mahdollistaa myös energiajoustavuuden (EF, *engl. energy flexibility*). Korkean kulutuksensa vuoksi teollisuuden sektoria voidaan pitää sopivana kandidaattina energiajoustavaan operointiin. Energiajoustavuuden kvantifiointi tapahtuu energiajoustavuuden toimenpiteiden (EFM, *engl. Energy flexibility measure*) kautta energiajoustavuuden potentiaalina (EFP, *engl. Energy flexibility potential*). Tuotannon ajoittaminen kussakin prosessivaiheessa on yksi mahdollisista energiajoustavuuden toimenpiteistä akkujen valmistuksessa, ja näin ollen mahdollistaen huipputehon rajoittamisen.

Tutkimuksen tavoitteena on alentaa tuotantoprosessin huippukulutusta digitalisaation avulla. Arviointiprosessissa tuotantoprosessin ominaisuudet määriteltiin, ja niiden perusteella arvioitiin soveltuvuus energiajoustavaan operointiin. Jokainen prosessivaihe arvioitiin kahdessa kategoriassa: joustavuus ja teho. Joustavuus arviointiin prosessi-insinööreiltä saatujen tietojen perusteella, kun taas teho arviointiin joko asennettujen tehojen tai mitattujen huipputehojen perusteella. Arvioinnin perusteella luotiin kolme skenaariota mahdollisten mittauspisteiden asettamiseksi tuotantoprosessissa. Investointikustannuksia ja digitalisaation tasoa verrattiin eri skenaarioiden välillä. Skenaario 3 vaikuttaa potentiaalisimmalta, koska saavutettu digitalisaatio on suhteellisen korkea, kun taas investointikustannukset suhteessa skenaarioon 2 eivät ole paljon suuremmat.

Tutkimuksen perusteella voidaan päätellä, että akkujen valmistusprosessi ei ole kovin energiajoustavaa. Energia joustavuutta voidaan mahdollisesti lisätä erilaisilla ratkaisuilla, kuten lisäämällä energiavarasto tai uusiutuvia energialähteitä, kuten aurinkopaneeli, tuotantoon. Käytännön ja toteuttamiskelpoisen energiajoustavuuden laskemiseksi sekä taloudellisen analyysin tekemistä varten tarvitaan edistyneempää mallintamista. Mallinnusta varten ehdotetut mittauspisteet tulisi toteuttaa ja data tulisi kerätä reaaliajassa.

Avainsanat Teollinen vallankumous, digitalisaatio, kysynnän hallinta, energiajoustavuus potentiaali, litium akku, energiavarasto, uusiutuva energianlähde

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Abbreviations

AI	Artificial intelligence
CAM	Cathode active material
CMC	Carboxymethyl cellulose
CNT	Carbon nanotubes
DHU	Dehumidifier
DI	Deionized water
DLT	Distributed ledger technologies
DR	Demand response
DSEF	Demand side energy flexibility
DSM	Demand side management
EF	Energy flexibility
EFM	Energy flexibility measure
EFP	Energy flexibility potential
ESS	Energy storage solution
EV	Electric vehicle
GHG	Greenhouse gas
HEPA	High-efficiency particulate absorbing
ICT	Information and communication technology
IEF	Industrial energy flexibility
IoT	Internet of Things
Li-ion	Lithium-ion
LV	Low voltage
MV	Medium voltage
NMC	Lithium-Nickel-Manganese-Cobaltoxide
NMP	N-Methyl-2-pyrrolidone
NV	Northvolt
OCV	Open circuit voltage
PP/PE	Polypropylene/Polyethylene
RES	Renewable energy source
SBR	Styrene-butadiene
SEI	Solid electrolyte interface

Symbols

x_{ln}	input/output interdependence
x_C	control mode
x_O	operational concept
x_i	installed power factor
$P_{i,\ IS}$	installed power of the industrial system
$P_{inst,\ total}$	total installed power of the manufacturing segment
x_p	peak power factor
$P_{peak,\ IS}$	measured peak power of the industrial system
$P_{peak,\ total}$	total measured peak power of the manufacturing segment
x_{ld}	level of digitalization,
P_m	installed power that can be measured with the suggested measurement points

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1 Introduction

As we are living in the age of climate change, society is moving towards more sustainable solutions within all sectors. Energy systems are evolving at a high pace while new innovative materials are being researched actively by aiming to obtain a higher recyclability rate and endurance than currently used materials. Conventional energy forms are left behind or reshaped as the use of renewable energy and electricity is increasing. However, the increased use of renewable energy sources, such as wind and solar power, is creating further problems such as grid instability. (Pina et al., 2012) Furthermore, with daily and seasonally variable demand load both in the industrial and residential sector, the investments for peak generation are increasing since the installed capacity for electricity generation should be able to meet the maximum peak demand (Strbac, 2008).

In addition to an increased share of renewable energy sources in the grid, the electrification of different sectors on the end-use side creates challenges to match the demand. By 2050, almost 50% of total final energy consumption is expected to consist of electricity. (IRENA, 2019a) Electricity systems can be divided into four sectors: generation, transmission, distribution and consumption (Strbac, 2008), and the change in electricity generation profile requires the demand profile to change and create new roles (IRENA, 2019a). As an example, several energy storage options offer solutions for the unpredictable supply load but are not always available or are too expensive (Pina et al., 2012).

When looking into global energy transformation, electrification should be encouraged. The reason for this is that electrified demand load can be regarded as flexible demand, and therefore, can enable better integration of renewable energy sources to the grid. (IRENA, 2019a) There is substantial research focusing on Demand Side Management (DSM) which could offer “viable alternatives to a further expansion of peak power generators” (Ramin et al., 2018). DSM includes different strategies of which energy efficiency and energy flexibility, or more precisely, demand side flexibility are examples. Energy efficiency can be increased with more efficient processes and appliances on the demand side. (IEA, 2019) Furthermore, the use of waste heat and other excessive energy increases the overall efficiency of the process. Demand side flexibility however is one of the key enablers of better matching between supply and demand. It can be defined as a portion of energy demand that can be shifted, decreased or increased within a certain period of time. In this way, it is possible to reshape load profiles to correspond with renewable energy generation to minimize electricity cost by responding to fluctuating electricity prices and shifting the load from high price period to lower price period, as well as enable peak shaving. Additionally, demand side flexibility of industrial processes is considered as a suitable and competitive solution in the future. (IRENA, 2019a)

When discussing DSM, and especially, demand side flexibility, one key enabler cannot be neglected: digitalization. With smart digital technologies it is possible to collect an increased amount of data with greater connectivity and analytics which enable better optimization and controlling of energy usage in real-time, leading to lower energy costs and better integration of renewable energies. In addition to energy data, other measurement data can be collected, such as climate, allowing even better energy optimization. (IEA, 2019)

Digitalization has an impact on both energy supply and demand, and therefore, it is expanding the end-use efficiency to energy system efficiency. However, there is some complexity on the impacts: as efficiency increases and improvements can be made, so does the amount of electric appliances and servers. This can lead to even higher energy consumption if not considered in the system planning and managed appropriately. (IEA, 2019)

1.1 Objectives

The objective of the thesis is to investigate the suitability of a battery manufacturing process for energy flexible operation, and to define where measurement points should be located in order to achieve peak shaving of the electricity consumption through high level of digitalization.

1. What is the suitability of each process step for energy flexible operation?
2. Where to set up the measurement points in the process?
3. What is the level of digitalization that can be achieved?

1.2 Scope and Limitations

In order to conclude the suitability study for energy flexible operation, the Li-ion battery manufacturing process in Northvolt Labs facility and related possible measurement equipment are studied. The control system used in the facility will be only discussed in relevance to enable digitalization of data. The other limitation is set by the data availability since the production has not been running steadily for long, thus, there is not much existing measurement data available.

1.3 Methodology

The methodology starts with assessing the literature about demand side management and its tools in the industrial sector, and how it is affected by digitalization. Following this, in order to evaluate the suitability of a battery manufacturing process for energy flexible operation, the following steps were considered (Figure 1):

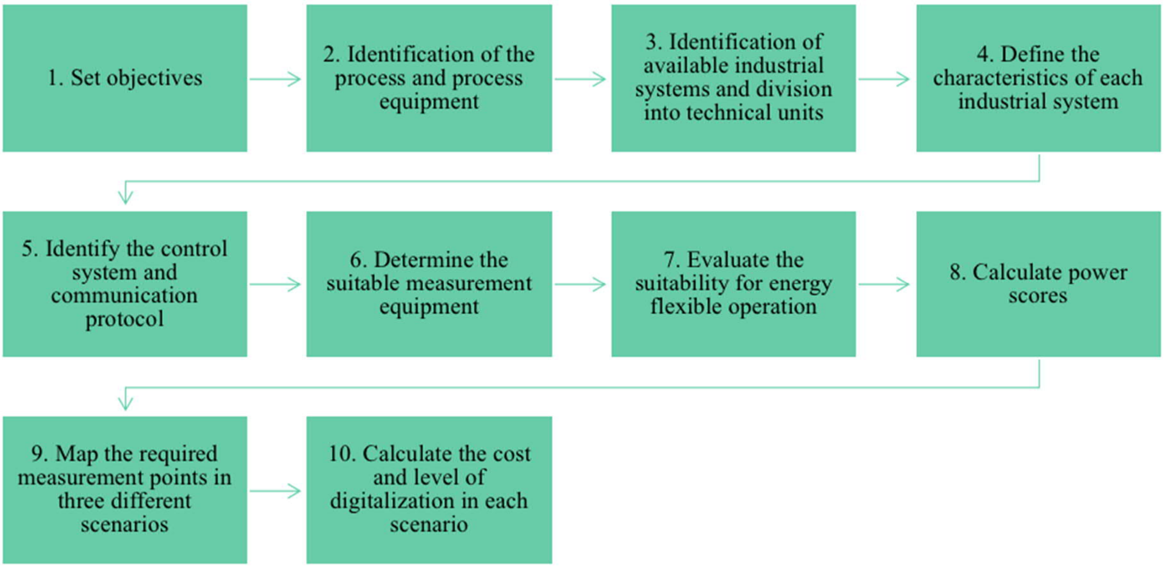

Figure 1. Methodology of the research.

1. Set objectives

According to the Figure 1, the methodology starts with setting up the objectives for the assessment process. Some examples are presented in chapter 4.

2. Identification of the process and process equipment

The next step is to get familiar with the production process and identify the process equipment. By using the energy auditing data, the most energy intensive process parts are identified.

3. Identification of available industrial systems and division into technical units

Once the process and process equipment have been identified, they can be identified as industrial systems which then can be divided into technical units. In addition, connections between industrial systems should be defined.

4. Define the characteristics of each industrial system

When the technical units and industrial systems have been identified, the physical, operational and production characteristics should be identified.

5. Identify the control system and communication protocol

Before the suitable measurement points can be determined, the control system and the communication protocol in the facility should be identified. By this, the amount of the data and the duration during which the data can be stored will be identified.

6. Determine the suitable measurement equipment

In order to ensure a fast and efficient data collection, the measurement equipment should be compatible with the control system and the communication protocol.

7. Evaluate the suitability for energy flexible operation

After concluding all the previous steps, each industrial system can be evaluated in four different categories and the flexibility score can be given which is discussed in section 4.4.

8. Calculate power scores

Power scores are given based on installed and peak power factors of each industrial system. The equations are presented in section 4.5.

9. Map the required measurement points in three different scenarios

According to the flexibility and power scores, three scenarios were established with a different number of measurement points each resulting to a certain level of digitalization.

10. Calculate the cost and level of digitalization in each scenario

After the scenarios have been established and the amount of measurement points in each scenarios has been decided, the cost and the level of digitalization in each scenario can be calculated.

2 Literature review

2.1 The fourth industrial revolution

During last few decades the world has been undergoing the fourth industrial revolution, i.e. Industry 4.0. The focus is mainly on interconnectivity, blockchain technology, real-time data collection, automation, machine learning, the Internet of things (IoT), and advanced digital manufacturing technologies. There are three acknowledged drivers for Industry 4.0: decarbonization, decentralization and digitalization, or in other words, the three D's. They are highly connected to each other, enabling efficiency and security in power systems. (Rhodes, 2020) The three D's are explained more in detail in the following chapters.

2.1.1 Decarbonization

When taking a deeper look in the first D – decarbonization term can be described as reducing the primary energy sources' carbon intensity over time and exploiting cleaner energy sources (Rhodes, 2020). It targets the majority of the world through international and national policies, such as Paris COP2 agreement, by supporting the low carbon energy generation and encouraging the use of renewable energy sources. The goal of COP21 has been to "keep a global temperature rise well below 2 °C", and 17 sustainable development goals (Figure 2) were determined to support this overall goal. (Di Silvestre et al., 2018) A few of the 17 sustainable development goals is directly related to decarbonization: goals 7, 9 and 11. Goal 7 concentrates on ensuring the energy access, goal 9 promotes sustainable industrialization, and goal 11 aims to support of building sustainable cities. (United Nations, 2021) Most of the sustainable development goals signify the importance of increasing the "access to information and communications technology" and encourage to provide not only universal but also affordable access to the Internet. Hence, new business models and technology improvements were needed. Furthermore, many countries have set up different targets on reducing their greenhouse gas (GHG) emissions by 2030, and many of them are being supported by financial incentives. (Di Silvestre et al., 2018)

Figure 2. Sustainable development goals. (United Nations, 2021)

2.1.2 Decentralization

The second D, decentralization, indicates the decentralization of energy sources, and it is driven by the increased consumption of goods and energy demand. It creates several new needs at distribution level as the amount of measured data is increasing, such as reduced complexity of the infrastructure and advanced data storage. Especially in power systems, decentralization implies that the electricity is generated and managed close to the load centers with generators which are connected to low voltage (LV) and medium voltage (MV) grids. One of the biggest promoters for decentralization has been public incentives worldwide, encouraging the use of off-grid RES solutions for consumers, e.g. premium tariff for electricity produced from RES and tax credit. (Di Silvestre et al., 2018)

2.1.3 Digitalization

Digitalization is the final main driver of Industry 4.0 which ties all of them together. There are two terms which are usually mixed together when discussing about digitalization: digitization and digitalization. Digitization means transforming existing data into digital form, e.g. transforming paper files into pdf form, whereas digitalization describes the process where digital technologies are used to change business models. (Ritter et al., 2020) Together with urban development, they create new digital business models to exchange services and other goods. For examples, electricity companies can have access to real-time measurement data, e.g. from buildings or electric vehicles (EV) which gives the opportunity to analyze and store it. In relation to Industry 4.0, many countries in the EU have adopted digital manufacturing initiatives and other strategic plans to promote digitalization. (Di Silvestre et al., 2018)

Rhodes (2020) describes digitalization of energy in his paper as “the act of incorporating digital systems and information and communications technology (ICT), along with the new business models and interaction opportunities these support, into the energy system.” Researches have paid a lot attention into digital technologies connected to Industry 4.0 which are influencing the performance and efficiency while encouraging the sustainable development in the environmental and economic sectors. (Borowski, 2021) There are four technologies which have been raised in different research: big data, artificial intelligence (AI) and machine learning (ML), IoT and blockchain (Rhodes, 2020). These technologies are presented in the following chapters 2.1.3.1, 2.1.3.2, 2.1.3.3 and 2.1.3.4.

2.1.3.1 Big data

It is used to describe datasets that cannot be analyzed with conventional techniques due to their enormous size as well as their advanced analytics and information possible to be extracted from the raw data. Research shows that three V’s are used to describe big data: velocity, volume and variety. Velocity refers to the generation speed of the data, volume refers to the quantity of the data, and variety refers to all the different formats in which the data can be collected. Due to these qualities, it can enable advanced decision making tools and process automation if the information is processed in an innovative and cost-effective way. In energy systems, there are many examples of big data analytics, such as improving the reliability, asset utilization and DSM. (Rhodes, 2020)

2.1.3.2 Artificial intelligence and machine learning

Both AI and ML technologies are major enablers of the digitalization in Industry 4.0. AI and ML terms are often confused together. AI refers to the machine's ability to make decisions based on the given information through three steps: assessing the data, processing and learning from the data, and responding to that data. ML on the other hand, is one of the subcategory of AI and refers to computer systems' ability to automatically improve by experience when performing tasks. Hence, the ML program learns quicker when more data is fed into it. Together with big data, they form a powerful combination which can improve business agility through analyzing large amounts of data in real-time. In energy systems, AI offers great opportunities, e.g. in decarbonization. (Rhodes, 2020)

2.1.3.3 Internet of Things

Rhodes (2020) describes IoT as "the increase in appliances and objects with embedded sensors and internet connections." During the recent years the processors and sensors have reduced in price and in size while increasing in energy efficiency, which allows them to be interconnected with other appliances. In energy systems, many Internet-connected devices are being used, such as smart meters providing real-time data of energy use. Furthermore, sensors can be connected to the electricity networks and enable monitoring of the electricity flow and different conditions. (Rhodes, 2020)

2.1.3.4 Blockchain

Blockchain links different operations together in a globally accessible system. In addition, it is one example of the distributed ledger technologies (DLT), which enables "storing multiple synchronized and identical copies of a ledger across a network of devices". (Rhodes, 2020) It combines different flows such as energy, data and business. According to Borowski (2021), big data, AI, ML and IoT together form a blockchain which enables development and integration of RES. In decentralization, blockchain allows communication within the power grid as well as monitoring the consumption and generation of energy (Borowski, 2021). Some possible applications of the four technology in the value chain of energy are presented in the Table 1.

Table 1. Applications of energy value chain. Adapted from Rhodes (2020).

	Generation	Transmission	Distribution	Consumer
Big data	Analytics to optimize operational efficiency	Predicting of price and load fluctuations	Analytics to optimize off-grid and storage solutions	User patterns, energy saving possibilities
AI & ML	Optimize solar farms by forecasting solar radiation	Automated energy trading	Avoid defaults in the network through optimization	Automated demand response
IoT	Inspection of process or equipment with drones	Monitoring and smart grids	Enable off-grid solutions	Smart sensors, Evs
Blockchain	National certificates, e.g. for emissions	Direct energy trading	National markets and microgrids	DSM, metering

2.2 Demand side management

Due to Industry 4.0, the processes of digitalization, decarbonization and decentralization are global phenomena. However, the effects on the demand side are complex: decarbonization and decentralization both increase the penetration of RES in the grid which can create challenges to the grid stability. Hence, creating an urgent need for demand response programs which is a better alternative than expanding peak power generators. Furthermore, the amount of data and sensors is increasing rapidly with digitalization, thus, AI and ML are needed to process all the data efficiently. Fortunately, it creates a possibility for improved demand side management. (IEA, 2019)

In industrial systems, the demand varies both daily and seasonally. In addition, any interruptions in the energy supply can damage the productions and the final product, and therefore, be very costly. Hence, the supply must be able to meet the peak demand at any given time. (Strbac, 2008) Many strategies both on demand and supply side have been proposed to tackle these challenges, such as flexible energy generation, energy efficiency and energy storage solution (ESS), and more (O′Connell et al., 2014). In addition to these, demand side energy flexibility (DSEF) has been increasing its interest among researches as it offers a potential solution to challenges within industrial sector both on power generation and demand sides. According to Tristán et al. (2020), "DSEF, comprises the capacity of the demand sectors within the electrical grid to adapt (increase, reduce or shift) their electrical consumption over a specific duration to balance variations in the electrical supply." DSEF on an industrial level is usually referred as industrial energy flexibility (IEF), which is defined as industrial system's capability to adapt to changes in the electricity markets as quickly and cost-effectively as possible without damaging the process or final product. (Tristán et al., 2020)

Demand Response (DR) is one of IEF's applications, and it has been existing for some decades. Yet, its implementation especially in industrial sector has been very little, even though it represented nearly 40% electrical consumption in 2017 in the EU, and it is expected to grow. This makes it an attractive candidate for energy flexible operation. (Tristán et al., 2020) There are some existing demand response approaches, such as time of use and critical peak pricing. Both of these examples are related to the pricing of electricity: lower prices during off-peak hours, e.g. night time, and expensive tariffs during high peak hours. Hence, the consumer is encouraged to adjust their consumption to off-peak hours in order to lower the electricity cost while enabling peak shaving. (O′Connell et al., 2014) As can be concluded, usually DR describes the adaptation of the electrical consumption into profit through grid operators' financial incentives (Tristán et al., 2020). What is more, if the objective of the study is to reduce electricity cost, including an off-grid RES solution can be seen as demand response strategy, by which the industry can possibly achieve higher level of flexibility and reduce the dependency on the grid (IREAN, 2019b). Nevertheless, the IEF can be driven by other objectives as well than financial ones, as will be presented in chapter 4.

2.2.1 Energy flexibility potential

As described above, there are different types of energy flexibility approaches. However, it needs to be formulated in a usable form in order to be evaluated. Thus, Tristán et al. suggest energy flexibility measures (EFM) for this purpose. It is described as a conscious action to execute a defined change in industrial system's operative state at a specific time, and it can be quantified as energy flexibility potential (EFP). It can be defined through "a power component, the flexible power, and the active duration" of the change of the operative state. In order to quantify the EFP, the characteristics of the industrial system needs to be defined. (Tristán et al., 2020) More detailed explanation on how to conclude the characterization is presented in Chapter 4. There are different types of EFP which are presented in Figure 3.

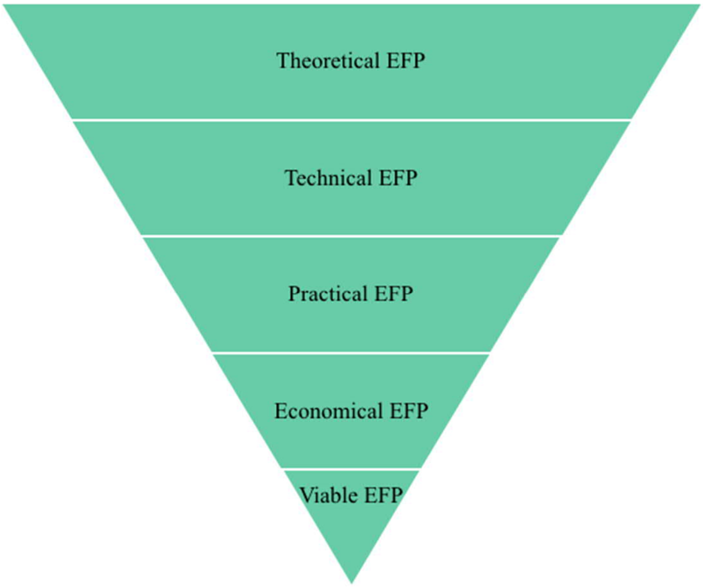

Figure 3. Different types of EFP. Adapted from Tristán et al. (2020).

Theoretical EFP takes only the physical characteristics of the industrial system into account, thus, only the installed power and the operation time are included in the calculation. Operational characteristic of the industrial system, e.g. actions that needs to be taken during the full cycle of completing the task, are included in the technical EFP. Strategics and production planning of the facility, e.g. production goals per week, are included in the practical EFP. As significant investment, such as sensors or change of infrastructure, might be required to enable IEF, the economical EFP calculates the share of economically feasible practical EFP. Hence, the savings in energy cost through IEF outperform the required investment costs. Lastly, viable EFP takes into account the company goals and investment plans, which is calculated as a share of the economical EFP supporting those goals and plans. (Tristán et al., 2020)

2.2.2 Energy flexibility measures

As mentioned in the previous chapter, EFM transforms IEF into usable form. They can be classified as operational (O) or technical (T). Operational EFM is usually related to strategic planning of the facility, hence, they might not have a direct effect of the energy load.

Whereas technical EFM usually has a direct effect on the load profile of the industrial system. (Tristán et al., 2020) Following list of EFM has been presented in the research:

Table 2. Energy flexibility measures and their classification. Adapted from Tristán et al. (2020).

EFM	**Classification**
Adjustment to staff working shifts and free time	O
Variation of production sequence of orders	O
Capacity planning	O
Delay of start of production	O
Hiatus of manufacturing order	O
Resource allocation	O
Adjustment of operation parameters	T
Hiatus of operational	T
Variation of the operational sequence	T
Inherent or dedicated energy storage	T
Simultaneous operation	T
Change of energy carrier	T

The suitability of each EFM for industrial system is considered throughout the methodology presented in Chapter 4. The action of EFM is triggered as a response to a certain event or defined constraint, such as peak consumption or a change in electricity price. This can be enabled through digital blockchain technologies, such as big data, AI and ML, measuring and processing the data in real-time. After the digital response, the physical part is executed as a change of industrial system's operational state. Even though the current digital technologies offer rapid and efficient solutions for data processing and automated decision making, there is a certain reaction time between the triggering event and the termination of the change in the operational state. This why, active duration of EFM is included in the EFP, as described in the previous chapter. (Tristán et al., 2020)

3 Battery manufacturing process and smart meters

Northvolt (NV) is a battery manufacturing company, and it was established in 2016. They produce high-performance Li-ion batteries, for example, for Evs. NV uses Lithium-Nickel-Manganese-Cobaltoxide (NMC) chemistry as their cathode active material (CAM). Northvolt's goal is to enable the future of energy by producing world's greenest battery with 10 kg $CO_{2,eq}$/kWh carbon footprint and with 50% recycled material by 2030. They have operations both in Sweden and in Poland. (Northvolt, 2021)

Battery manufacturing process can be divided into two main processes: upstream and downstream. Raw materials are manufactured in the upstream process. In Li-ion battery manufacturing, the upstream process usually refers to the manufacturing of the CAM. As the main component of Li-ion batteries, CAM determines many properties of the battery: the cell voltage, capacity, power and energy capabilities, cycle life, and operation temperature. There are different existing chemistries to be used as CAM in Li-ion batteries but this study will concentrate on $LiNi_{0.4}Mn_{0.4}Co_{0.2}O_2$. (Dunn et al., 2014) Afterwards, the manufactured CAM is used as one of the raw materials for the downstream process. Downstream process describes the production of battery cells from raw materials, such as cathode and anode active materials, and other components. (Heimes et al., 2019) Both upstream and downstream processes are presented in the following chapters.

3.1 Upstream

As mentioned earlier, CAM is produced in the upstream process of battery manufacturing. Process flow chart for upstream process is presented below:

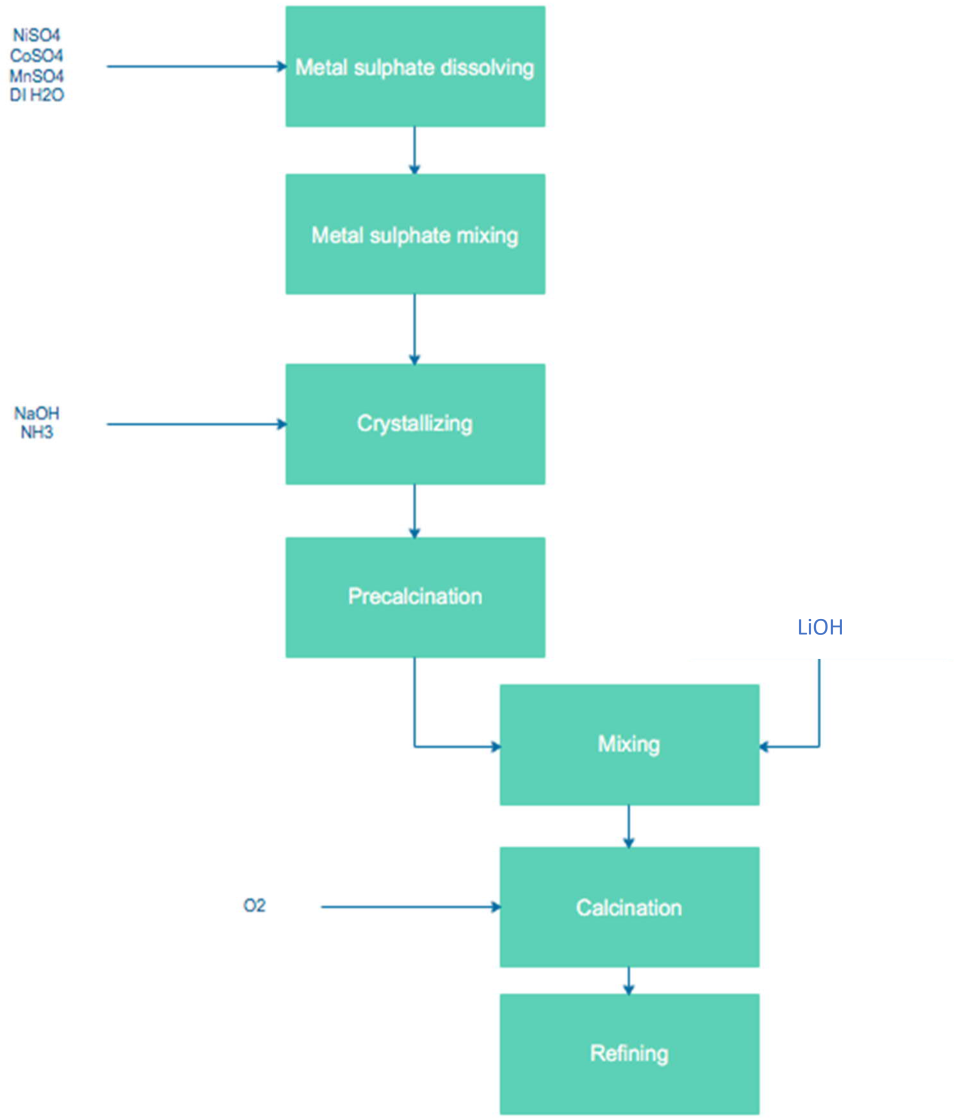

Figure 4. Upstream process flowchart. (Dunn et al., 2014)

3.1.1 Raw material preparation

After the metals have been mined, the upstream usually starts with dissolution of metals with sulphuric acid or metal sulphates with deionized (DI) water. As the focus is on $LiNi_{0.4}Mn_{0.4}Co_{0.2}O_2$, metal sulphates conclude $MnSO_4$, $NiSO_4$ and $CoSO_4$. In this study, raw material preparation includes both metal sulphate dissolving and mixing. (Dunn et al., 2014)

Metals or metal sulphates are dissolved in three separate dissolving tanks at approximately 40-50 °C. If the temperature is set higher, the dissolving is faster. It is important to dissolve the particles properly since the undissolved particles will cause blockages in the process. Metal sulphates are mixed in a predetermined ratio in a continuous mixing tank depending on the desired chemistry. In order to ensure appropriate mixing of the metal sulphate dissolutions, the temperature is set at 60 °C. Reactants for crystallizing, NH_3 or NH_4OH and NaOH are prepared by dilution with DI water in order to achieve the desired molarity, and then stored in a feed tank. (Dunn et al., 2014)

3.1.2 Manufacturing of precursor and precalcination

The manufacturing of precursor concludes the crystallization of metal sulphates to metal hydroxide. Metal sulphates, NaOH and NH_3 or NH_4OH are led to a reactor in a predetermined ratio. The temperature is kept at 60 °C. (Dunn et al., 2014) NH_3 is used to form metal complexes which then react with NaOH forming a precursor ($Ni_{0.4}Mn_{0.4}Co_{0.2}(OH)_2$) according to the following reaction:

$$Ni_{0.4}Mn_{0.4}Co_{0.2}SO_4\ (aq) + 2\ NaOH\ (aq) \rightarrow Ni_{0.4}Mn_{0.4}Co_{0.2}(OH)_2\ (aq)\ +\ Na_2SO_4\ (aq) \quad (1)$$

Precursor is fed to a pre-calcination kiln which is heated up to 400-500 °C to form a powder. According to Dunn et al., precalcination takes 12 hours and requires 12.5 kW. Afterwards, the mixture is mixed with LiOH before the calcination. (Dunn et al., 2014)

3.1.3 Calcination

Mixing is followed by calcination at approximately 800 °C with pure oxygen gas. According to Dunn et al., calcination requires 100 kW for eight hours. It is important to achieve as high temperature in order to synthetize all the metal hydroxide to metal oxide. (Dunn et al., 2014)

3.2 Downstream

Battery cells are manufactured in the downstream process from several raw materials. Each process step is explained in the following chapters. Process flow chart for downstream process is presented below. (Heimes et al., 2019)

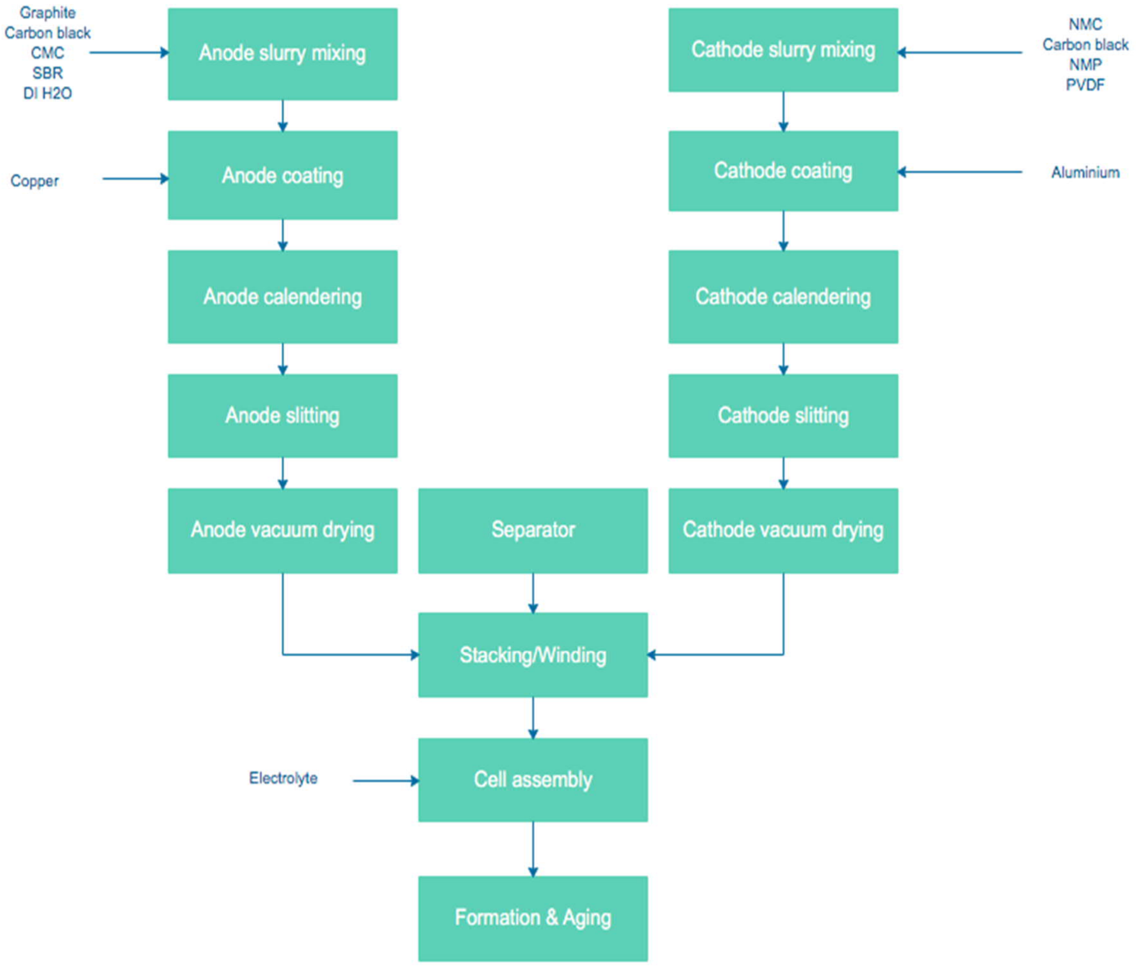

Figure 5. Downstream process flowchart. (Heimes et al., 2019)

3.2.1 Slurry mixing

Downstream process starts with preparation and mixing of both cathode and anode slurries which are prepared in separate production lines. The process can be batch production or continuous mixing. Mixing is divided into two sections: dry and wet mixing. In dry mixing, an active material, a conductive material and a binder are mixed together. Solvent is added in wet mixing and a homogenous mixture is formed. (Heimes et al., 2019) Specific substances are presented in Table 3.

Table 3. Specific substances added in each production line in slurry mixing. (Heimes et al., 2019)

	Anode	Cathode
Active material	Graphite	NMC ($LiNi_{0,4}Mn_{0,4}Co_{0,2}O_2$)
Conductive material	Carbon black	Carbon black
Binder	CMC	PVDF
Solvent	DI water	NMP
Additive	SBR	-

It is possible to perform the process under vacuum in order to avoid gas formation. The sequence of mixing and dispersing as well as the mixing time and temperature are determined according to cell design requirements. Mixing time can vary between 0.5 to 5 hours, and temperature can vary between 20 °C and 40 °C. After mixing, the slurry is filtered to remove any impurities. The particle size, purity, homogeneity and viscosity are measured for quality control. As the slurry is very sensitive to moisture, both process lines take place in a dry room. Slurry mixing is crucial process step in battery manufacturing and any error can decrease the performance of the battery cell. (Heimes et al., 2019)

3.2.2 Coating

In coating, the slurries are coated on current collectors and dried. Similarly to slurry mixing process, coating consist of two production lines: anode and cathode coating. Foils can be coated sequentially or simultaneously from top and bottom. Coater ovens are usually connected to solvent recovery, especially when the substance is hazardous. Both processes take place in clean and dry room. (Heimes et al., 2019)

In cathode coating, an aluminum foil is coated with cathode slurry consisting NMC as an active material and NMP as solvent. In anode coating, a copper foil is coated with anode slurry consisting graphite and DI water as solvent. Thereafter, the coated foil is led through drying chambers which can be up to 100 meters in total. (Figure 6) The foil is fed to the chambers on a set speed (usually between 35 m/min and 80 m/min) which then defines temperatures in each oven as the foil behaves differently in different temperatures and can cause wrinkles if temperature is set too high and then cooled down. Temperature usually varies between 50 °C and 160 °C. Depending on the cell design, the foil thickness varies between 5 µm to 25 µm. On cathode side, the ovens are connected to NMP recovery whereas anode side can be connected to a condenser. Residual humidity, surface quality and thickness are controlled for quality. (Heimes et al., 2019)

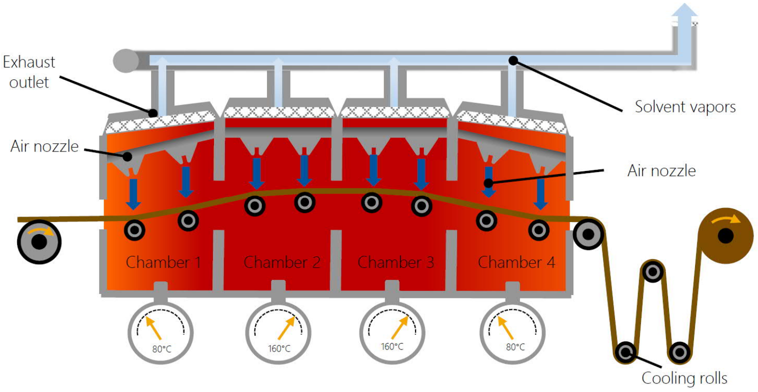

Figure 6. Example of coating ovens. (Heimes et al., 2019)

3.2.3 Pressing, slitting and vacuum drying

Also pressing, slitting and vacuum drying are done in two different production lines: anode and cathode. All the processes take place in clean and dry room. Before the pressing, any dust and magnetic impurities are removed from the electrode. In pressing, the electrodes are compressed with two cylindrical rolls and reducing the thickness of the electrode, and by that increasing the density of the active material. (Figure 7) The roll speed varies between 60 m/min and 100 m/min. The porosity is reduced from 50% to somewhere between 20% and 40%, which affects the energy density of the cell. In order to avoid breaking the foils and increase the ductility of the active materials, the foils and rolls can be heated. Porosity and surface quality are controlled for quality. (Heimes et al., 2019)

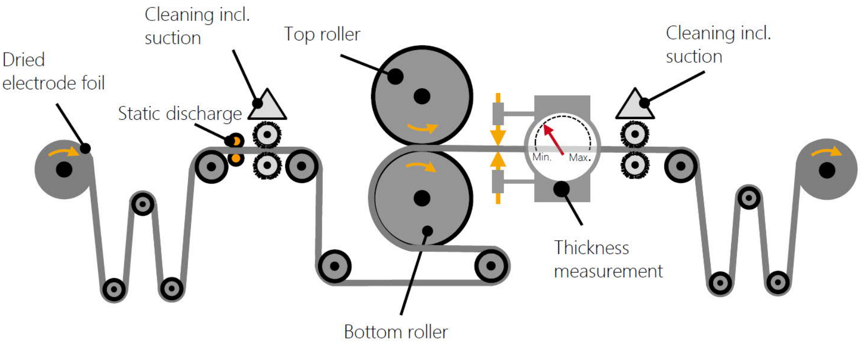

Figure 7. Pressing of the electrodes. (Heimes et al., 2019)

In slitting, the electrode is cut into several smaller electrodes (Figure 8). Gap between electrodes can be controlled, and varies between 60 mm and 300 mm depending on the cell design. The roll speed varies between 80 m/min and 150 m/min. After the slitting, the electrodes are brushed and impurities are removed. Contamination might lead to short circuits in the battery cell. (Heimes et al., 2019)

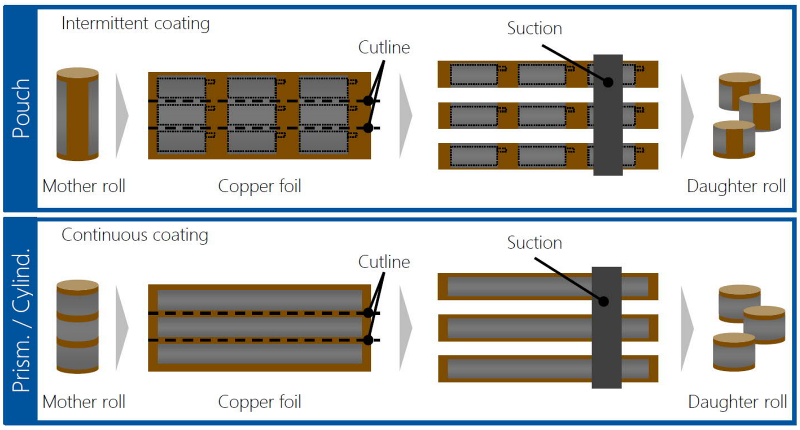

Figure 8. Slitting of electrodes. (Heimes et al., 2019)

Vacuum drying of the electrodes is divided into several compartments where solvent and residual moisture are removed. The temperature and drying time (up to 30 hours) in each compartment are determined according to cell design. Temperature varies between 60 °C and 150 °C, whereas the pressure varies between 0.07 mbar and 1000 mbar. Inert gas can be used to avoid corrosion. (Heimes et al., 2019)

3.2.4 Cell assembly

After the vacuum drying, the process continues with cell assembly that consists of multiple steps. The process takes place in a clean and dry room. Depending on the cell design, the cell assembly differs. This study concentrates on prismatic and cylindrical cells. Cell assembly starts with winding, where both anode and cathode electrodes are winded with a separator as a jelly roll. Winding can be done around a center pin (for cylindrical cells) or around a mandrel (for prismatic cells). (Figure 9) Separator is usually made out of plastic compounds such as PP or PE. The electrodes and separator are kept clean from dust and any metallic particles during winding. After winding, the cell is secured with adhesive tape. (Heimes et al., 2019) According to Heimes et al. (2019), the machine output is up to 30 cells/minute (for cylindrical cells) or 6 cells/minute (for prismatic cells).

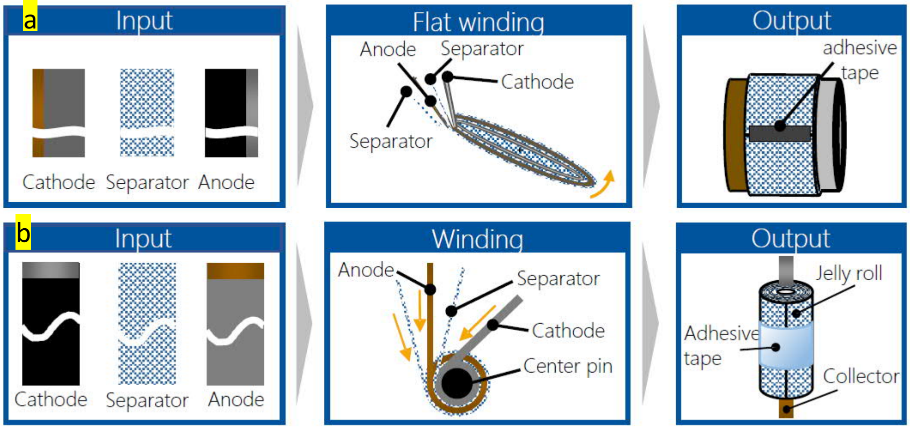

Figure 9. Winding of a) prismatic cells and b) cylindrical cells. (Heimes et al., 2019)

The stacks are placed inside metal cans which are then welded from the bottom. An insulation ring is placed on top of the jelly roll, and the cells are filled with electrolyte, which contains several chemicals, such as $LiPF_6$ (Figure 10). (Heimes et al., 2019)

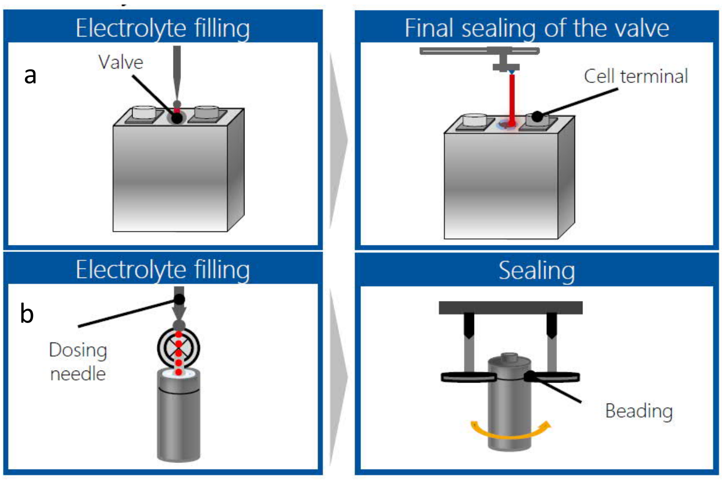

Figure 10. Electrolyte filling of a) prismatic cells and b) cylindrical cells. (Heimes et al., 2019)

3.2.5 Formation and aging

The final manufacturing cell of the downstream production, formation and aging comprises of multiple steps during which the voltage and the temperature are changed. The aim is to activate the materials and transforming them into their usable forms through one fully controlled cycle of charging and discharging. For example, the essential passivating layer of solid electrolyte interface (SEI) is created. The percentage of charging and discharging states have been defined beforehand in each step, and it varies between 20% and 80%. The duration of formation can be up to 24 hours, and the parameters vary according to cell design impacting the performance of the cell. (Heimes et al., 2019)

The design of the cell defines the ageing time and temperatures. The prismatic and cylindrical formation and ageing can differ in terms of both maximum current and total duration which can be up to three weeks during which the open circuit voltage (OCV) is measured regularly. Temperature is varied between 22 °C and 50 °C. The data of the cell performance, e.g. voltage, can be collected and stored to ensure quality and traceability. (Heimes et al., 2019)

3.3 Suitable measurement equipment

When choosing a suitable measurement equipment, the desired parameters to be measured should be defined. Most advance power loggers measure current, voltage, reactive power, active power, and more. What is more, the equipment should be compatible with the used control system. (Janitza.com, 2021)

Measurements can be done as three-phase measurements or single-phase measurements. According to the supplier, single-phase measurement should be only done with the equipment that have almost constant load, such as pumps and compressor. Hence, if the energy consumption of the equipment varies a lot, three-phase measurement should be used. Single-phase measurement requires one channel in the measurement equipment, whereas three-phase measurement requires four channels, three for active measurement and one for zero measurement. (Janitza.com, 2021)

3.3.1 Janitza electronics

One suitable option to measure the desired parameters would be modularly expandable energy measurement device UMG 801 from Janitza electronics (Figure 11). It uses “direct data transmission to higher-level systems via OPC UA”. There are two units: base unit and additional unit. Each base unit measures all the required parameters, such as current, voltage and active power, whereas additional unit measures only current. The price of the additional unit is approximately 8% of the price of the base unit. (Janitza.com, 2021)

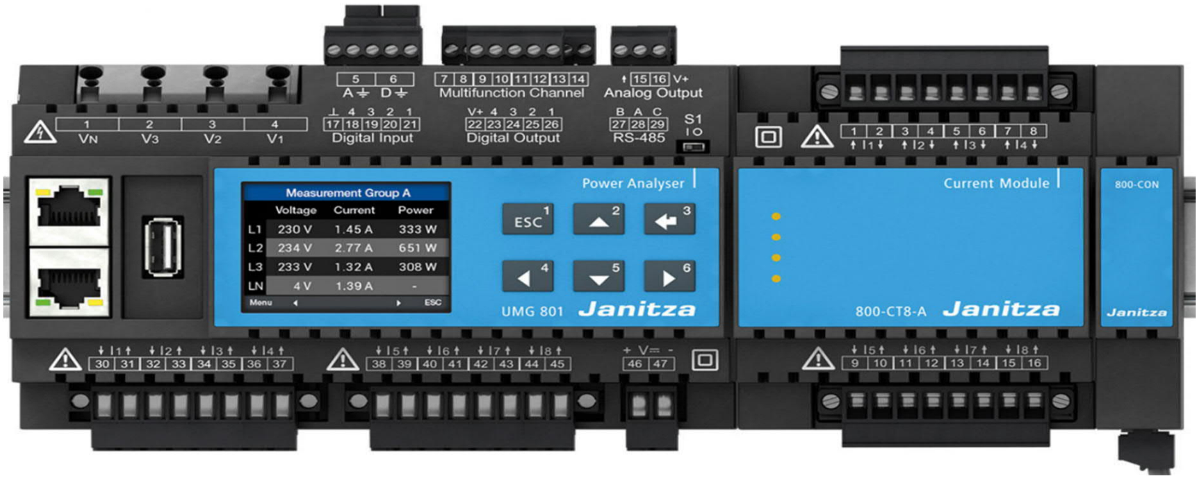

Figure 11. Base and additional units of modularly expandable energy measurement device UMG 801 from Janitza electronics. (Janitza.com, 2021)

Each base unit has eight channels, thus, they can be connected to either eight single-phase measurement or to two three-phase measurement. Up to 10 additional units with eight channels in each can be connected to one base unit within 100 meter radius. What is more, it makes the integration of new measurement points easier and less costly in the future. (Janitza.com, 2021)

3.3.2 ABB

Another suitable option to be used as measuring equipment in industrial process would be M4M30 Network analyzers from ABB (Figure 12). Each unit measures all the above mentioned desired parameters.

Figure 12. M4M 30 Network analyzer from ABB. (ABB, 2021)

Each unit has four channels for current measurement and it can be easily configurated with ABB systems. It can be connected to mobile app via Bluetooth and it has many embedded communication protocols, such as Modbus RTU. (ABB, 2021) The comparison between ABB and Janitza measuring equipment is presented below:

Table 4. Comparison of ABB and Janitza electronics measurement equipment.

	Modularly expandable energy measurement device UMG 801 (Janitza electronics)	M4M 30 Network analyzer (ABB)
Size (mm)	144*90*76	96*96*77.5
Measured parameters	Voltage, current, power (reactive, active), harmonics, etc.	Voltage, current, power (reactive, active), harmonics, etc.
Current measurement channels	8	4
Display	Yes	Yes
Bluetooth	No	Yes
Connectivity	High	High
Expandable	Yes	No

As can be seen from Table 4, both of the devices are very advanced and considered as smart meters. Whereas ABB equipment is smaller in size and uses Bluetooth, the Janitza base unit has eight current measurement channels and it can be expanded with additional units. Price depends on the supplier offer which is highly related to the amount of required meters.

4 Research material and methods

As mentioned earlier, it is more beneficial to have more measurement point which measure the energy data in the process in real time. However, this might increase the total energy consumption as the data need to be processed, and depending on the size of the measurement equipment, it can consume a lot of energy. Furthermore, there might be a resource issue as well: some of the measurement equipment have a quite significant price tag. (IEA, 2019) In order to define where to set up the absolutely needed measurement points in the battery manufacturing process, two assessments where made. First, each process was assessed whether it could be suitable for energy flexible operation, and a grade between 0 and 9 was given. (Tristán et al., 2020) Secondly, each process was given a power score between 0 and 3 depending on the measured peak consumption in relation to the total average consumption of the facility. Also, the installed power was taken into account. According to these measurement points, a ground work for a mathematical algorithm was made in order to quantify the estimated amount of energy flexibility in the future. The method for both of the assessments are presented in the following chapters.

4.1 Objective of the energy flexibility assessment

The assessment process starts with setting up the objectives for energy flexible operation. In industrial sector, the following examples can be potential outcomes of EF operation (Tristán et al., 2020):

- Peak shaving: peak shaving and other possible ways to manage the load profiles are reducing the amount of peak loads, and therefore, reduce the momentary demand to supply high peaks.
- Increase the amount of renewable energy sources in the industry’s energy portfolio: the production and the energy consumption can be adopted to match the off-grid RES. It also increases the energy self-sufficiency of the production site, and it can reduce the carbon footprint of the facility.
- Optimize the energy costs: It is possible to reduce the energy cost with an intelligent response to the electricity price fluctuations.

4.2 Identify technical units and industrial system

After the objective or objectives have been defined, the processes and process equipment should be identified, as described in detail in chapter 3, as well as the energy consuming components which are directly or indirectly connected to the production process. The discussed energy consuming components constitute of industrial systems, which are then grouped under five main technical units within the factory boundaries according to the Figure 13. (Tristán et al., 2020)

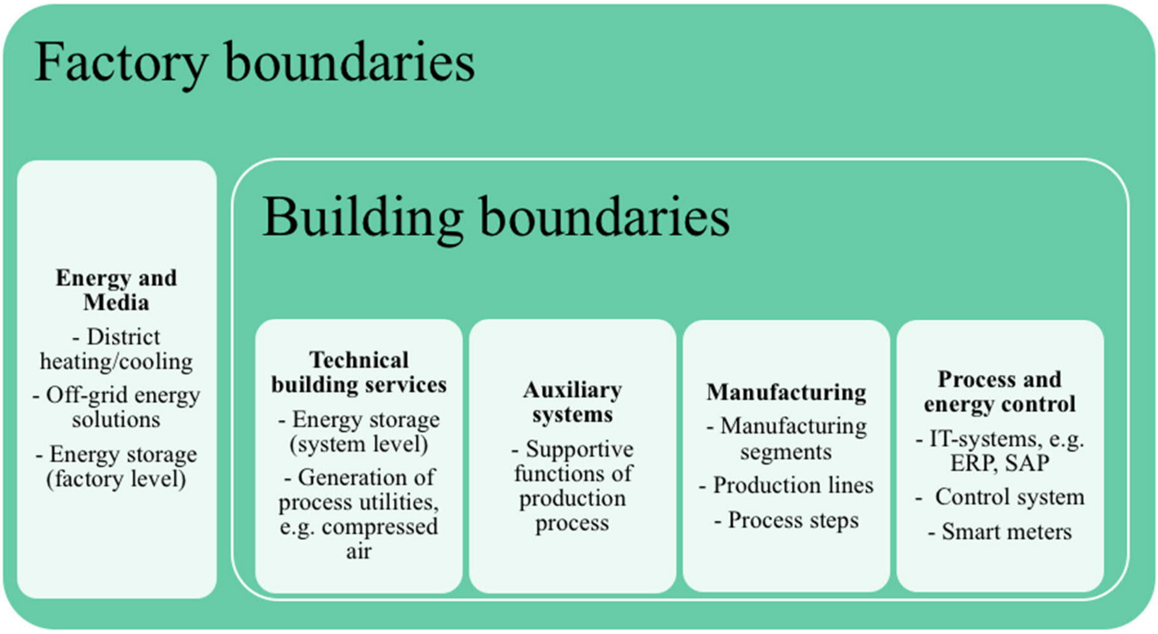

Figure 13. Industrial system (factory) and its technical units. Adapted from Tristán et al. (2020).

The main focus is on three technical units: manufacturing, technical building services and auxiliary systems. Manufacturing consist of the main manufacturing segments (upstream and downstream) which can be divided into production lines (e.g. anode and cathode) which can further be divided into process steps, such as coating. Technical building services consist of generation of useful energy forms, such as steam or compressed air, and energy storage at system level. Finally, the Auxiliary system concludes all the operative support for the manufacturing system, such as logistics when transporting product from one manufacturing line to another. (Tristán et al., 2020)

In addition, energy and manufacturing control technical unit includes other supportive system, such as IT-system controlling and storing the data from the process. Outside the physical building, the fifth technical unit, energy/media, concludes all the off-grid energy sources, such as on-site solar panels, as well as district heating and cooling. Also, an energy storage on a factory level would be grouped under this technical unit. (Tristán et al., 2020)

4.3 Characteristics of industrial systems

Once the industrial systems have been grouped into technical units, the physical and operation characteristics of each industrial system should be defined. On an energy system point of view, physical characteristics consist of the following (Tristán et al., 2020):

- Technical unit – defined in the previous step as described above.
- Layout of the industrial system – especially including the energy consuming components.
- Operation time – how long the industrial system takes time to finish a task when operated under normal conditions.

- Installed power and the maximum output of the process – installed power is usually given by the equipment supplier, and the maximum output is usually specified in the process description as the maximum capacity.
- Control concept – what task and in what sequence are included in the operation when operated under normal conditions.

However, the physical characteristics do not quite give a full description of the operation dynamics of the industrial system. Hence, the operation characteristics offer more detailed information, such as energy consumption patterns. The some of the operation characteristics to be described are the following (Tristán et al., 2020):

- Energy load profile – a typical load profile under normal operation conditions.
- Continuity of the operation – whether the operation state stays the same throughout the action or if it changes in intervals.
- Control variables – operation parameters which define the operation state, thus, the energy consumption.
- Shiftability and interruptible – the system's ability to adopt if part of the operation cycle is operated at earlier or later state, or if it is stopped and finalized later.
- Flexibility of the output – whether the industrial system can be operated to result different output levels.

Once the physical and operation characteristics are identified, it is necessary to get a better understanding of the production characteristics in order to be able to meet the required output of the product. Some of the relevant production characteristics are the following (Tristán et al., 2020):

- Manufacturing principle – whether it is Make-to-Stock (MTS), Assemble-to-Order (ATO), Make-to-Order (MTO) or Engineer-to-Order (ETO).
- Method of the production – whether the production is continuous or batch operated.
- Variety of energy carriers – which different energy carriers are able to meet the energy demand in the industrial system.
- Related costs – define the related energy and maintenance costs.

4.4 Suitability for energy flexible operation assessment

After all the characteristics are defined, it is possible to begin to evaluate which industrial systems are suitable energy flexible operation. The evaluation is done in three categories: controllability, criticality and input/output interdependence, of which the latter is further divided into two subcategories: control mode and operational concept. Each of the categories is graded between 0 and 3, where 0 indicates the lowest level of flexibility. The evaluation is recommended to be done in collaboration with the personnel working in the production with an adequate level of knowledge of the process. (Tristán et al., 2020) The evaluation criteria is presented in the Table 5.

Table 5. The evaluation criteria in each category. Adapted from Tristán et al. (2020).

Grade	Controllability (Co)	Criticality (Cr)	Input/output interdependence (In)
3	Unrestricted	Neutral or positive impact	Comprehensive decoupling capabilities
2	Time-dependent	Moderately negative impact	Limited decoupling capabilities
1	State variable dependent	Significantly negative impact	Inherent decoupling capabilities
0	Process-dependent	Quality reducing or failure inducing influence	Direct input-output correspondence

Controllability indicates how much the industrial system can adapt to the any changes in its operational state, and it is usually evaluated according to its physical characteristics. Process-dependent (Cr0) indicates that the operation is "fully defined in time and quantity", thus, there is no possibility to operate it in an energy flexible way. The industrial system's flexibility can be reduced if it is dependent on any state variables (Cr1), such as temperature or pressure. If the operational state of an industrial system can be changed over fixed intervals, it can be defined as time-dependent (Cr2) allowing a decent amount of flexibility. When the tasks of an industrial system can be executed "continuously and unrestricted in time and quantity" (Cr3), the control concept can be considered suitable for energy flexible operation. (Tristán et al., 2020)

The second category, criticality, describes how much the quality of the final "product or the continuity of the production" would be affected if the operational state of an industrial system is changed. If the change of an operational state changes causes a failure in the production or reduces the quality of the final product (Cr0), the industrial system can be considered unsuitable for energy flexible operation. There might be a slight possibility for flexibility if the change causes significantly negative impact on the quality of the final product or production (Cr1). Moderately negative impact (Cr2), which is usually related to the increased operating costs, indicates a decent amount of flexibility whereas neutral or even positive impact (Cr3) indicates industrial system's suitability for energy flexible operation. (Tristán et al., 2020)

The third category, input/output interdependence, indicates the decoupling capabilities "between the energy input and the output of the industrial system along its operative cycle". (Tristán et al., 2020) It is further divided into two subcategories which are evaluated according to the following table:

Table 6. The evaluation criteria in each subcategory. Adapted from Abele et al. (2016).

Grade	Control mode (C)	Operational concept (O)
3	Virtually uncontrolled	Buffer capacity covers the load
2	Process independent time-based control	Uncritical process and the load is not covered with buffer capacity
1	Process dependent time-based control	Critical process and the load is not covered with buffer capacity
0	Fully controlled in time and quantity	Load via real-time energy conversion

Both subcategories describe the operation of the equipment in the industrial system. The first subcategory, control mode, describes the control system commands. When the equipment is rarely turned on/off, it can be considered virtually uncontrolled (C3). Within fixed time intervals, the equipment can be turned on/off either independently (C2), or dependently (C1) from the main production. In addition, the equipment "can be fully controlled in quantity and time" (C0). (Abele et al., 2016)

The second subcategory, operational concept, describes the buffer capabilities of the equipment. According to Abele at al., the energy buffers can be conventional, such as pressure reservoirs, or operational buffers, such as tanks. If the buffer capacity is capable of meeting the demand of equipment's operation cycle (O3), it increases the industrial "system's suitability for energy flexible operation". If the equipment has some buffer capacity but not enough to cover the full operation cycle, the equipment can be considered as uncritical (O2) or critical (O1). Finally, the operation cycle is fully covered "on a real-time energy conversion" (O0) if the equipment has no buffer capabilities. (Abele et al., 2016)

The input/output interdependence grade is given as a combination of the grades in two subcategories according to the following equation:

$$x_{In} = \frac{x_C + x_O}{2} \quad , \tag{1}$$

where x_{In} is the grade of the input/output interdependence,
x_C is the grade of the control mode and
x_O is the grade of the operational concept.

4.5 Power score

In addition to flexibility score, each industrial system was given a power score. The power score indicates which industrial systems consume the highest amount of energy in the manufacturing process, making them attractive for real-time energy measurement. The power score of an industrial system was calculated in two different ways according to the following equations:

$$x_i = \frac{P_{inst,\ IS}}{P_{inst,\ total}} * 100\% \quad , \tag{2}$$

where x_i is the installed power factor,
$P_{i,\ IS}$ is the installed power of the industrial system and
$P_{inst,\ total}$ is the total installed power of the manufacturing segment.

$$x_p = \frac{P_{peak,\ IS}}{P_{peak,\ total}} * 100\% \quad , \tag{3}$$

where x_p is the peak power factor,
$P_{peak,\ IS}$ is measured peak power of the industrial system and
$P_{peak,\ total}$ is the total measured peak power of the manufacturing segment.

Both categories were graded according to the following Table 7.

Table 7. Power scores according to the installed and peak power factors.

Score	x_i, x_p (%)
3	≥ 9
2	4 – 8.9
1	1 – 3.9
0	≤ 0.9

The highest score between the two power factors will be given as the power score for the concerning industrial system.

4.6 Scenario description

Three scenarios were created according to the flexibility and power scores. The grades in each category (Table 5) given to each industrial system are summed together and the flexibility score is given between 0 and 9. If the industrial system is graded as 0 in any of the categories described in Table 5, it is not considered suitable for energy flexible operation, and the flexibility score is given as 0. As described in previous section, the power score is given between 0 and 3 according to the higher power factor. The scenarios were created according to the following Table 8:

Table 8. Grading criteria for each scenario.

	Scenario 1	Scenario 2	Scenario 3
Flexibility score	≥ 5	≥ 4	≥ 3
Power score	3	≥ 2	≥ 1

The scenarios were created so that at least one of the criteria in Table 8 was fulfilled. Thus, if the flexibility score was given as 6 and the power score was given 2, the industrial was included in scenario 1.

The number of measurement points in each scenario were defined according to number of electrical consumers in each industrial system, such as pumps, mixers and electrical heaters. For example, if an industrial system would include three pumps, one mixer and two electrical heaters, the required number of measurement points in the concerning industrial system would be 6. As described in section 4.3, the electrical consumers are defined as part of the characteristics of each industrial systems.

4.7 Level of digitalization

The level of digitalization was calculated according to the following equation:

$$x_{ld} = \frac{P_m}{P_{inst,\ total}} * 100\% \quad , \tag{4}$$

where x_{ld} is the level of digitalization,
P_m is amount of installed power that can be measured with the suggested measurement points and
$P_{inst,\ total}$ is the total installed power of the manufacturing segment.

5 Results

5.1 Suitability for energy flexible operation

The objective for the assessment was defined as peak shaving, i.e. minimizing the peak consumption. The main focus was on the following technical units: manufacturing, technical building services and auxiliary systems. The characteristics of each industrial system is described in chapter 3.

Each industrial system was evaluated and flexibility scores were given according to the criteria presented in chapter 4.4. Evaluation was done in collaboration with process engineers through unstructured interviews and walk-throughs of the manufacturing process. Processes 1-13 represent process steps of the manufacturing process, whereas the process 14 represents a supportive process and processes 15-17 represent the generation of process utilities. The scoring is presented in Table 9.

Table 9. Flexibility scores of each industrial system.

Technical unit	Industrial system	Flexibility score
Manufacturing	Process 1	5
	Process 2	3
	Process 3	3
	Process 4	3
	Process 5	3
	Process 6a	2
	Process 6b	2
	Process 7a	3
	Process 7b	3
	Process 8a	6
	Process 8b	6
	Process 9a	6
	Process 9b	6
	Process 10a	4
	Process 10b	4
	Process 11a	6
	Process 11b	6
	Process 12a	1
	Process 12b	1
	Process 13a	1
	Process 13b	1
Auxiliary Systems	Process 14	3
Technical Building Services	Process 15	4
	Process 16	5
	Process 17	5

More detailed evaluation in each category is shown in appendix 1. The detailed justification for the evaluation cannot be presented here owing to confidentiality of the information.

5.2 Power consumption

The total installed power of the considered technical units (manufacturing, auxiliary systems and technical building services) is approximately N in Northvolt Labs facility. The total energy consumption as well as the upstream and downstream energy data cannot be presented here owing to confidentiality of the information. Furthermore, the energy consumption comprises of electricity, cooling and heating. The measured peak powers of each industrial system and the facility in March 2021 were used for the study. To illustrate the calculations, made-up numbers are used in the following example.

Total installed power of the facility is 100 MW and measured peak power in March was 75 MW. Process 1 has installed power of 10 MW and measured peak in March was 4 MW. The installed and peak power factors were calculated with equations (2) and (3):

$x_i = \frac{10\text{ MW}}{100\text{ MW}} * 100\% = 10\%$ and

$x_p = \frac{4\text{ MW}}{75\text{ MW}} * 100\% = 5.3\%$.

According to Table 7, installed power factor would give a power score of 3, whereas peak power factor would give a power score of 1. As described in chapter 4.5, the highest score will be given as the power score, thus, in this example, Process 1 would be given a power score 3. The actual power scores of a battery manufacturing process are listed in the Table 10.

Table 10. Power score of each industrial system.

Technical unit	Industrial system	Power score
Manufacturing	Process 1	0
	Process 2	1
	Process 3	1
	Process 4	0
	Process 5	2
	Process 6a	1
	Process 6b	1
	Process 7a	3
	Process 7b	3
	Process 8a	0
	Process 8b	1
	Process 9a	0
	Process 9b	0
	Process 10a	0
	Process 10b	0
	Process 11a	0
	Process 11b	0
	Process 12a	1
	Process 12b	1
	Process 13a	2
	Process 13b	2
Auxiliary Systems	Process 14	2
Technical Building Services	Process 15	3
	Process 16	3
	Process 17	3

The power scores of each industrial system in both categories are presented in the appendix 2.

5.3 Scenario comparison

Three scenarios were created as described in chapter 4.6. According to the flexibility and power scores shown in previously, the most attractive processes for stationary measuring points were defined. The number of electrical consumer in each of these processes was studied together with process engineers and electricians working in the facility, and the suggested measurement points in each scenario were determined and listed the Table 11.

Table 11. Suggested measurement points in each scenario.

Technical unit	Industrial system	Scenario 1	Scenario 2	Scenario 3
Manufacturing	Process 1	6	6	6
	Process 2	-	-	7
	Process 4	-	-	6
	Process 5	-	24	24
	Process 6a	-	-	2
	Process 6b	-	-	2
	Process 7a	5	5	5
	Process 7b	4	4	4
	Process 8a	1	1	1
	Process 8b	4	4	4
	Process 9a	1	1	1
	Process 9b	2	2	2
	Process 10a	-	1	1
	Process 10b	-	1	1
	Process 11a	1	1	1
	Process 11b	1	1	1
	Process 13a	-	7	7
	Process 13b	-	7	7
Auxiliary Systems	Process 14	-	3	3
Technical Building Services	Process 15	7	7	7
	Process 16	2	2	2
	Process 17	1	2	2

When calculating the amount of measurement units and the cost of the scenarios, modularly expandable energy measurement device UMG 801 from Janitza electronics (Chapter 3.4.1) will be used in the example. There are several transformers at Northvolt Labs and each transformer requires a base unit. More detailed description of how many measurement points is needed for each transformer cannot be presented here owing to confidentiality of the information. The required amount of meters is presented in the Table 12.

Table 12. The amount of measurement units in each scenario.

Measurement unit	Scenario 1	Scenario 2	Scenario 3
Base units	n	n+1	n+1
Additional units	a	a+20	a+27

The investment costs of each scenario is calculated according to the price per unit given by the supplier and multiplied with the number of units. The level of digitalization is calculated with equation (4). To illustrate the calculations, made-up numbers are used in the following example.

Total installed power of the facility is 100 MW. In scenario 1, the total installed power that can be measured with suggested measurement point is 37 MW. The level of digitalization was calculated with equation (4):

$$x_{ld} = \frac{37\ \text{MW}}{100\ \text{MW}} * 100\% = 37\ \%$$

Thus, the level of digitalization would be 37%. The actual investment costs and the level of digitalization in each scenario is presented in the Table 13.

Table 13. The cost and level of digitalization in each scenario.

	Scenario 1	**Scenario 2**	**Scenario 3**
Total costs (%)	100	138	146
Level of digitalization (%)	46.9	66.4	71.4

6 Discussion

As a conclusion, battery manufacturing process cannot be considered very suitable for energy flexible operation, especially without energy storage solution (ESS) or off-grid renewable energy sources (RES). Adaptation of start of production in each process step is one of the most reasonable energy flexibility measure (EFM) for battery manufacturing process which could enable peak shaving of the total consumption of the facility.

As can be seen from the Table 13, in this study there are no measurement points connected to one of the transformer, hence, one less base unit is needed in the scenario 1. As the base unit has much higher cost than additional units, the scenario 1 is relatively much lower in cost than scenarios 2 and 3. However, the achieved level of digitalization is only 46.9%. Nevertheless, there might be a need for more measurement point in the future, e.g. due to expansion projects, thus, it could be beneficial to invest in one base unit connected to each transformer.

When comparing scenarios 2 and 3, there is no significant difference in the cost. Hence, scenario 3 could be seen as most attractive option since the level of digitalization is above 70% while the cost is not significantly higher. Moreover, the energy flexibility potential and possible savings in energy costs were not calculated in this study, thus, the cost of each scenario would be even lower.

6.1 Shortcomings

Energy flexibility, and especially demand side energy flexibility, is being experimented in industrial sector. Hence, the novelty of the topic and the lack of comparable research was seen as a shortcoming. In addition, the real-time energy measurement data from longer period is needed for the mathematical model. As the battery manufacturing was evaluated to have a very low level of suitability for energy flexible operation, the scenarios were created with relatively low limit values.

6.2 Future recommendations

In order to evaluate energy flexibility potential and the related cost savings, an advanced mathematical model should be created. The model could be used to model current status of energy flexibility potential but also with ESS and off-grid RES to compare the results. Also, an economic analysis of each possible scenario should be done. What is more, also planned process steps or changes in the process should be included in the evaluation.

7 Conclusions

The main drivers for Industry 4.0, the three D's (decentralization, decarbonization and digitalization) are described in the literature review. Some of the example solutions were presented, and technologies and their applications under digitalization were presented. Also some challenges related to all three D's were presented.

As digitalization was considered as the key enabler for demand side management, some of the existing and possible future strategies were discussed, especially the ones related to industrial sector. Energy flexibility was introduced and its types of EFM and EFP were presented. Adaptation of start of production in each process step was considered as one of the most reasonable EFM for battery manufacturing.

Assessment process to evaluate suitability for energy flexible operation was constructed and conducted on a battery manufacturing process. Each process step was graded in two main categories (flexibility and power), and three scenarios were created based on the given gradings. Assessment was concluded in collaboration with process engineers to get support on the grading of the categories. Peak power measurement were concluded by energy engineer due to the lack of existing measurement points. It was determined that scenario 3 shows the most potential since the highest level of digitalization can be achieved without significant increase in the investment costs in comparison to other scenario

All in all, it was concluded that battery manufacturing process does not have much EF. It was suggested that some level of EF could be achieved with ESS and RES. Furthermore, it was stated that more advanced modeling is needed in order to conclude EFP calculations and the economic analysis in different scenarios, e.g. with ESS.

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Appendix 1. Suitability scores in each subcategory.

Technical unit	**Industrial system**	**Co**	**Cr**	**C mode**	**O concept**	**In**
Manufacturing	Process 1	2	2	C2	O3	1
	Process 2	1	1	C2	O3	1
	Process 3	1	1	C2	O3	1
	Process 4	1	1	C2	O3	1
	Process 5	1	1	C2	O3	1
	Process 6a	1	1	C1	O3	1
	Process 6b	1	1	C1	O3	1
	Process 7a	1	1	C2	O3	1
	Process 7b	1	1	C2	O3	1
	Process 8a	2	3	C1	O3	1
	Process 8b	2	3	C1	O3	1
	Process 9a	2	3	C1	O3	1
	Process 9b	2	3	C1	O3	1
	Process 10a	1	2	C1	O3	1
	Process 10b	1	2	C1	O3	1
	Process 11a	2	3	C1	O3	1
	Process 11b	2	3	C1	O3	1
	Process 12a	0	1	C1	O3	0
	Process 12b	0	1	C1	O3	0
	Process 13a	1	1	C1	O3	0
	Process 13b	1	1	C1	O3	0
Auxiliary Systems	Process 14	1	1	C1	O3	3
Technical Building Services	Process 15	1	1	C1	O3	2
	Process 16	1	3	C2	O3	1
	Process 17	1	3	C2	O3	1

Appendix 2. Installed and peak power scores of each industrial system.

Technical unit	Industrial system	Installed P score	Peak P score
Manufacturing	Process 1	0	-
	Process 2	1	-
	Process 3	1	-
	Process 4	0	-
	Process 5	2	-
	Process 6a	1	1
	Process 6b	1	1
	Process 7a	3	3
	Process 7b	3	3
	Process 8a	0	0
	Process 8b	1	1
	Process 9a	0	-
	Process 9b	0	-
	Process 10a	0	0
	Process 10b	0	0
	Process 11a	0	-
	Process 11b	0	-
	Process 12a	1	1
	Process 12b	1	1
	Process 13a	2	2
	Process 13b	1	2
Auxiliary Systems	Process 14	1	1
Technical Building Services	Process 15	3	3
	Process 16	2	3
	Process 17	2	3