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Transitions to renewable energy systems: A case study of sustainable transport on Posten/Bring terminal as a part of Digerneset business park.

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Abstract

The transition to decarbonized and sustainable transport in Norway is connected to electrification. In this context, renewable sources of energy can provide the clean energy needed for this process.

This thesis explores the possibility of developing a renewable energy system in the Digerneset business park to decarbonize the transport on Posten/Bring terminal. Hereby making it more sustainable. For this purpose, defining the dimensions of the energy demand for transportation combining it with the suitable dimensions of the potential renewable energy production and energy storage.

Three different scenarios have been constructed, one fully electric, others with a different share of hydrogen-based vehicles. This created three different demand profiles for the analysis. The scenarios were further divided into different versions based on battery storage and different logic behind electricity import. The method used is the energy demand and supply analysis based on hourly, daily, and monthly comparisons.

Results show that the energy system based on self-produced renewable energy is facing challenges related to the alignment of production with consumption. The modeled system overproduces energy during the summer, while the highest demand is during the winter months. The modeled system is further overproducing energy on the yearly balance in the fully electric scenario but underproduces in the case of hydrogen-based scenarios. Based on the intraday and hourly analysis, there is a need to import energy from the grid to meet the demand in all of the analyzed scenarios. The battery storage is improving the efficiency of the system and utilizes more of the produced energy. It can reduce the extra demand peaks during the charging of vehicles, reducing the cost of charging. Although the fuel-cell hydrogen trucks are seen to be more suitable for the longer distances with the heavy freight, the scenarios including hydrogen are further increasing the energy demand, so there is a need for a higher import of the electricity from the grid. They are also connected to significantly higher investment into electrolyzer cells. Because of the disproportion between production and consumption, there is a need for long-term storage of a high capacity to transfer and utilize the produced electricity. Hydrogen is a more suitable and cheaper solution for this, although there is a relatively high energy loss during the production. Storing the higher amount of energy in the battery is nearly 20 times more costly than storing it in hydrogen. Although the price of storage technology for both batteries and hydrogen is expected to decrease in the future, they will still be connected to high investment and need, therefore policy support and subsidies to become competitive.

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Abbreviations

AC – Alternating current

AEC - Alkaline electrolysis cells

BEV – Battery-electric vehicle

CCS – Carbo capture and storage

DC – Direct current

DEA – Danish energy agency

DNV - Der Norske Veritas

EEA – European Environment Agency

ENTSO-E - European Network of Transmission System Operators

EU - European Union

EV - Electric vehicle

FCV - Fuel cell vehicle

GHG - Greenhouse gases

GWEC - Global wind energy council

IEA - International energy agency

IRENA - International Renewable Energy Agency

LCOE - Levelized cost of Electricity

LCO - Lithium cobalt oxide

LFP – Lithium iron phosphorus

LIB – Lithium battery

MLP - Multi-level perspective

NCM - Nickel, Manganese and Cobalt

NVE - Norwegian Water Resources and Energy Directorate

PEM – Proton exchange membrane

POX - Partial oxidation

PV - Photovoltaic

RE – Renewable energy

SDS – Sustainable development scenario

SMR - Steam methane reforming

SNM - Strategic Niche Management

SOEC - Solid Oxide Electrolysis Cell

UN – United Nations

Units

GW - Gigawatt

kW - Kilowatt

kWh - Kilowatt hour

kWp – Kilowatt peak

MW - Megawatt

MWh- Megawatt hour

NOK – Norwegian krone

TWh – Terawatt hour

1.Introduction

One of the greatest challenges that society is facing in modern times is climate change. The main issue is closely connected to the energy usage in society and the greenhouse gas (GHG) emissions related to this. As a response to this challenge, the Paris Agreement was achieved in 2015. The goal of the Paris Agreement is to implement measures that would reduce carbon emissions, aiming to limit global warming well below 2 °C, preferably below 1.5 °C (UN, 2015). The main challenge in achieving these targets is finding a common strategy while considering the cost of energy and resource availability in different parts of the world and the national interests. The success of this effort is hence dependent on solidarity and cross-country cooperation. Further on a local level, it is the development and transition to clean and sustainable energy systems based on the carbon clean technologies, that have to be designed, implemented, and used appropriately.

In order to reach the targets of the Paris Agreement, the European Commission has proposed the net-zero GHG emission targets to achieve a climate-neutral EU by the year 2050 (Tsiropoulos et al., 2020). To achieve this, an urgent transition in all sectors is necessary. Because of its heavy reliance on fossil fuels, transport is responsible for a high level of GHG emissions. Therefore, the decarbonization of the transport sector presents an opportunity to reduce GHG emissions heavily and is necessary to achieve the Paris Agreement targets. The transport sector in Norway is one of the biggest sources of GHG emissions, being responsible for approximately one third of the country`s emissions (IEA, 2016). However, Norway has the largest share of electric cars in private transport thanks to strong policy support. Public and heavy transport electrification is more challenging because of the high distance and extreme weather conditions in certain areas. Despite this, many Norwegian counties have incorporated electric buses into the public transport systems, and further electrification of the overall transport is planned. To fulfill its` obligation to the Paris agreement, governmental strategy corresponds with the European one, and Norway plans to become a low-emission society by 2050. Dividing the emissions reduction into two phases, first by 40 percent until 2030, and by 80 to 95 percent until 2050, referring to the 1990 emission levels (Klimaloven, 2017). The decarbonization of the transport sector is therefore necessary for Norway to meet this objective.

A wide range of technologies is needed to reduce the overall emissions related to energy and transport: focusing on increased energy efficiency, renewable sources of energy, replacement of fossil fuels with alternative ones, and carbon capture and storage. This transition to the decarbonized energy systems is driven by wind and solar photovoltaic (PV) power, while the availability of geothermal, hydro, and bioenergy is limited in many countries. The case of Norway is specific because of its abundance of natural resources, such as wind and hydropower, and the low population density. This makes Norway the country with the highest share of electricity produced from renewable sources in Europe while having the lowest emissions from the power sector (NVE, 2020). The variable characteristics of PV and wind power generation present challenges in the right constellation of the energy system and its` flexibility, as much as the grid capacity and layout (Faraji et al., 2017). Renewable energy incorporation into the transport sector presents an opportunity in order to reduce GHG emissions, hence reducing the penalty of the carbon tax in the future.

The transition to energy systems based on renewable power resources presents opportunities for the niche innovation to flourish with the dissemination of new technologies, from energy generation and storage to power system regulation and management. However, on the side of the alternative fuels, the green hydrogen produced from excessive renewable energy may play a significant role, especially for heavy transport. The choice of the right constellation of the energy system is also relevant for economic feasibility. Investment in the "wrong" technology may result in the companies and actors involved in the stranded assets. The scope, feasibility, and success of this transition depend on the correct policy support.

This paper investigates the possibilities for a transition to a system based on renewable energy, where the energy produced will be used to reduce the GHG emissions of the Posten/Bring logistics terminal in the Digerneset business park.

2. Background

2.1. Digerneset business park

Digerneset Business Park is situated ca. 26 km west from Ålesund in Møre and Romsdal county, in the proximity of the E 39, which is the European road connecting Trondheim to Denmark. The Digernes intersection has a strategic location concerning adopted and future road projects in the region. At the same time, Digerneset is a vital connection point for collective traffic. This will mean that there will be a demand for the charging of electric buses, cars, and trucks in the light of electrification. The new ferry-free E39 and the possible future "Storfjordsambanden" will be passing around Digerneset. Different companies use the fully developed area of approximately 25,000m2: Posten/Bring logistics, Tesla, Maxbo, Rema 1000, Circle K, and Sparkjøp. Digerneset Business Park is prepared and aims to become a new regional hub in Møre and Romsdal for both companies and their customers. The central location of the park and the quality of the area provide the best conditions for sustainable growth in the region, combining the creation of local workplaces with short-distance trade and public services and locally produced renewable energy.

Figure 1: Digerneset business park[1]

In 2020 Digerneset Busines Park, with its main partners Posten/Bring, SINTEF, BKK, Ålesund municipality, etc., established Digerneset Innovation to further develop the business park in the sustainable direction and become the business area of the future. The main goal is balancing the economic viability and sustainability with the help of smart and renewable energy system, reducing the GHG emission in the region which includes those from transportation. There exists a plan to build up a smart microgrid based on renewable energy production and energy exchange between buildings, utilizing the roof surface of the buildings for solar PV power production, combining this production with battery storage, smart energy system and perhaps with the wind power production.

[1] foto capture from https://digerneset.no/#hvorfor

2.2. Posten/ Bring environmental strategy

The environmental strategy of Posten/Bring is based on the sustainable development goals: 8- decent work and economic growth; 9- industry innovation and infrastructure;11- sustainable cities and communities; and 13- climate action[2]. The company is continuously working on phasing out the old cars, replacing them with electric alternatives, resulting in the average age of car in the fleet being merely 2 years old. Further, 1200 vehicles have already been electrified (January 2020), and another 200 are using advanced biodiesel, biogas, or bioethanol. Posten and Bring are the first in the Nordic countries to test hydrogen truck Nikola 3 (expected delivery in 2022/2023), and among the first, order the Tesla Semi electric truck (expected delivery 2021/2022) for transportation between terminals in Norway. Part of the overall strategy is the cooperation and establishment of strategic partnerships to develop new technological solutions and new electric vehicles that are suited for the different delivery routes to reduce the GHG emissions inside the cities.

The strategy's primary focus is the continuous work on reducing energy consumption and the efficiency of the routes and number of kilometers driven. In 2018 the energy consumption was reduced by 19 percent. The focus of the infrastructure investments is in terminals and renewable sources of energy, solar PV and wind, and alternative sources such as geothermal energy and energy storage.

The new main target for the Posten/Bring group is to use only renewable energy sources for vehicles and in the buildings in 2025 (Posten Norge, 2018).

[2] Posten Norge (2018): https://www.postennorge.no/baerekraft/miljo/miljomal-visjon-og-strategi

2.3. Problem statement

Based on the goals from previous chapter the following research problem statement has been formulated:

How to make the Post/Bring terminal in Digerneset more sustainable with the help of available renewable energy resources.

Research questions:

1. What is the energy demand related to the terminal and transportation

2. What is the potential of the available renewable energy sources in meeting this demand?

3. What type of scenario is more suitable and profitable

This study aims to investigate the possibility of developing a renewable energy system for the Posten /Bring terminal in the Digerneset business to make it more sustainable. Define dimensions of the energy demand for transportation and the possibilities to produce renewable energy as a supply. The aim is to utilize this locally produced renewable energy to decarbonize the transport fleet. An additional aim is to investigate the effect of hydrogen technology incorporation into this system to store the possible surplus of renewable electricity into the hydrogen, which can be further used as a renewable fuel.

2.4. Previous research

The literature on renewable energy systems is growing in tandem with heavy increase in renewable energy generation connected to GHG emissions reduction. Integrating this energy into the existing power systems presents several challenges stemming from the variable and intermittent nature of wind and solar power production. The demand for storage and balancing power requires smart planning and smart regulation of the energy systems based on renewable energy (Gils et al., 2017).

Choice and dimension of energy storage concerning renewable energy production contributes to substantial proportion of research literature. The proper energy storage capacity dimensioning has been studied by Al-Ghussain et al. (2020) and Yang et al. (2018). Zhang et al. (2017) are studying efficiency of hydrogen storage, in comparison to battery storage, both connected to photovoltaic power production.

The role of renewable energy in the decarbonization of transportation is a focus of García-Olivares et al. (2018). The authors were analyzing the possibility of a future transport system based on renewable electricity and hydrogen. Acar and Dincer (2020) further investigated the role of hydrogen on GHG emissions and the sustainability of transportation. Most of the literature on sustainable transportation focuses on comparing different types of available technologies and renewable fuels (Adnan et al.,2018; DeSouza et al. 2018) or upon the electrical charging infrastructure (Joseph et al., 2019; Enany et al.,2021).

Several software tools have been developed in order to model the proper capacities of renewable energy systems, an example of these are e.g. Homer or EnergyPLAN. Lund et al. (2015) developed energyPLAN in 1999 to study renewable systems optimization on national and local levels, balancing demand with supply and utilizing excessive renewable energy for transportation or district heating. The EnergyPLAN has been used in many subsequent analyses, the majority of which focus upon analyzing the incorporation of renewable energy into national energy systems. Bartha et al. (2017) use it to model the optimal structure of the energy supply for electric vehicles in the Romanian energy system. Prina et al. (2019) use an advanced version of the energyPLAN to analyze possible transition pathways towards renewable energy systems, incorporating the electric vehicles into the Italian national energy system. Bellocchi et al. (2019) using it to compare the role of electric vehicle deployment on the transition to the renewable energy system in Italy and Germany. Dorotić et al. (2019) use EnergyPLAN to highlight the optimization of the energy and transport system on the island of Korcula based on 100 percent renewable energy supply.

3. Theory

3.1 Technological transitions

Geels (2002) defines technological transitions as: “major technological transformations in the way societal functions such as transportation, communication, housing and feeding are fulfilled.” (p.1257). They present the change in the sociotechnical configuration that is connected to the technological substitution as much as to the changes to other system elements.

Technological transitions are based on the interaction between societal, technological, political, and economic factors that define the whole process (Geels, 2011). Contrary to historical technological transitions that were usually business opportunity-based and emergent, the sustainable (low carbon) transitions, are goal-oriented and emerging under the pressure of environmental and social problems (Smith et al., 2005; Geels, 2011; Sovacool and Geels, 2016).

The transition from fossil fuels to the low carbon society is mainly the transformation of the energy system. Energy has a societal function that is a product of the socio-technological energy systems (Verbong and Loorbach, 2012). These are embedded in the geographical, political and economic context (Sattich, 2018). The embedment plays an important part in slowing down the transition because of the resistance provided by incumbent system elements controlling the market. Transitions, therefore, do not come about easily. Furthermore, the existing systems(regimes) are characterized by stability, state of lock-in, and resistance to the change (Verbong and Geels, 2010). The transitions depend on the techno-economic variables. The new technology needs large changes to existing infrastructure or development of new infrastructure, requiring both time and huge financial investments. Hence the economic competitiveness of the new technology on the market is lower at the beginning of the transition, but this situation should improve over time (Grubler et al., 2016; Smil, 2016; Sovacool and Geels, 2016).

The public interest and political will behind the transition to sustainability open the possibility for speeding up the transitions through the policies that can change the market and selection environment, enabling the phase-out of the “unwanted” technology (in this case the fossil fuel) even before its turn-off (Kern and Rogge, 2016; Bromley, 2016; Sovacool and Geels, 2016; Stedronsky, 2019).

Energy transitions depend on actors and the forces, that are creating new paths (Fouquet, 2016). Politics, supported by the wider public, finding the common grounds while facing the urgency of the environmental problems, may increase the speed of the transitions to the low carbon society (Sovacool and Geels, 2016).

3.2 Multi-level perspective (MLP)

MLP is a tool that is useful to study how the technological transitions can occur. It is a middle-range theory providing a heuristic device for understanding of the different dynamics before and during the transitions. MLP sees the transition as a non-linear process, as an interaction and dynamics between three different analytical levels: niches, socio-technical landscape, and socio-technical regimes (Geels, 2011).

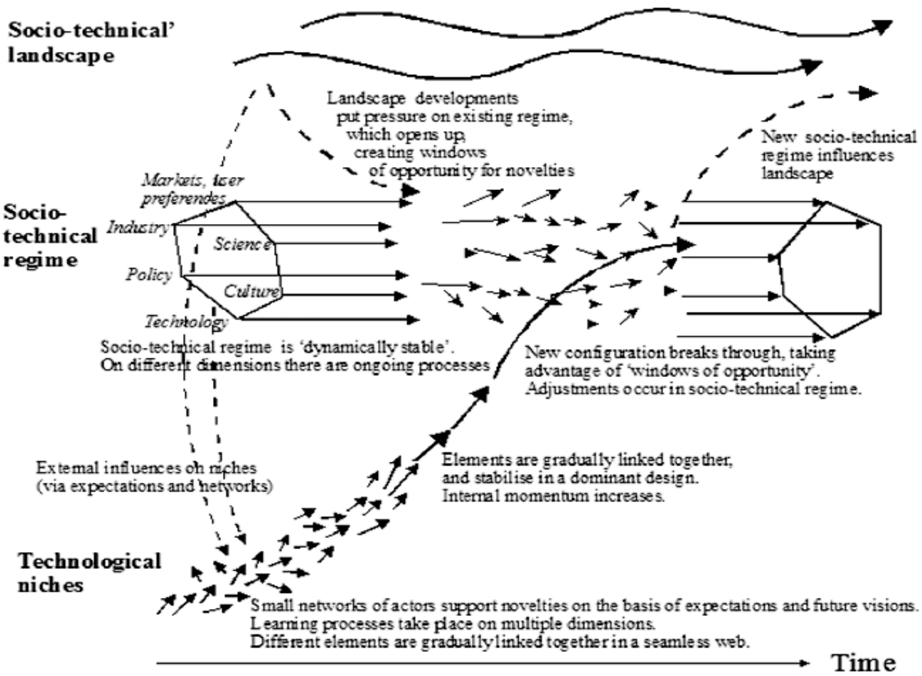

Figure 2: Multi-level perspective (Geels, 2002)

Socio-technical landscape

The socio-technical landscape is an external broader context influencing the regimes and niche innovations, highlighting the physical and technological patterns creating the society; including "demographic trends, political ideologies, societal values, and macro-economic patterns" (Geels, 2011:28).

MLP suggests that most socio-technical transitions happen when external landscape changes put pressure on existing regimes, creating "windows of opportunity" for broader change. Hence, enabling the niche-innovations, with built-up internal momentum, influences and fundamentally changes the existing regimes (Markard et al., 2012).

Socio-technical regime

According to Geels (2011), "socio-technical regime forms the 'deep structure' that accounts for the stability of an existing socio-technical system" (p. 27), referring to a set of rules and practices that are coordinating the actors, and establishing their relations inside of the system. Examples of such rules are shared beliefs, lifestyles and user practices, and forms of regulations. These are used and followed by the regime actors guiding their actions and perceptions (Geels, 2011; Geels, 2012). Such rules and laws are helping to create the lock-in state of the regime and the path dependency for the incremental innovation, that is creating the barriers for the transition to happen (Geels, 2010).

Therefore, there is a need for a force from the outside of the regime to change it, and such pressure is creating the space for the niche innovation to flourish (Geels and Schot, 2010).

Niches

Niches are considered to be crucial for technological innovation, they exist as safe havens, operating outside of the economic influence of the existing regime. Niches provide the direction of the innovation by articulating its vision and expectations (Geels, 2011). Niches are arenas for the interaction of many actors, creating space for learning processes to happen and open the possibilities for expanding the network, involving more actors, and building strategic alliances between them. This all to try to breach the existing regime with the goal of eventually replacing it (Geels, 2002).

Political landscape

The MLP has been criticized for its lack of agency (Smith et al., 2005). The study of the political dynamics on the landscape level may be the answer to this problem. Politics may have a significant effect on the energy transition. To address its role in regime destabilization, there is a need to take a closer look at its placement and its effect on the dynamics between the different levels.

Geels and Kemp (2007) divide the socio-technological landscape into a more static material and more dynamic political landscape. Although the political landscape can be very stable and conservative, it can change fast under the right constellation. Standing both on the inside and outside of the regime and niche environment where it is "*mediating and socially constructing the other landscape factors*", by doing so, influencing the policies and their implications for niches and regimes (Langhelle et al., 2018: 12; Stedronsky, 2019).

Politics are influencing all three levels in different ways. Niches need supportive and protective policies that create a safe zone for innovation; regimes are constituted and defined by the rules and policies, possible core alliances between policymakers and incumbents are happening on the regime level with the main emphasis on maintaining the status-quo (Geels, 2014; Langhelle et al., 2018, Stedronsky, 2019).

3.3. The Strategic niche management (SNM)

Strategic niche management explores the processes and actors needed to shape and apply new technologies (Weber et al., 1999; Hoogma et al., 2002).

Kemp et al. (1998) described the main barriers to the introduction of the use of new technology.

- technical barriers

- governmental policy and regulatory framework

- social and institutional barriers

- economic barriers

SNM is based on the development and introduction of new technologies through setting up niches as protected experiments; those are further used by actors helping them learn about the design, user needs, cultural and political acceptability, and so on (Schot and Rip, 1996). The further development of niches is regulated by the legislation, focusing on the regulation of the actors. Policies are taking over the central actor role in initiating experiments, improving learning, and shaping the feasibility of the new technologies (Hoogma et al., 2002).

3.4. Sustainability and decarbonization in the transportation sector

The concept of sustainability is based on the interaction of social, economic, and environmental dimensions, creating what Elkington (1992) calls for a triple-bottom-line (Evangelista et al., 2018). Therefore, the sustainable development applied to the transport system is dependent on the proper linkages between environmental protection, economic efficiency, and social progress (Rodrigue, 2020).

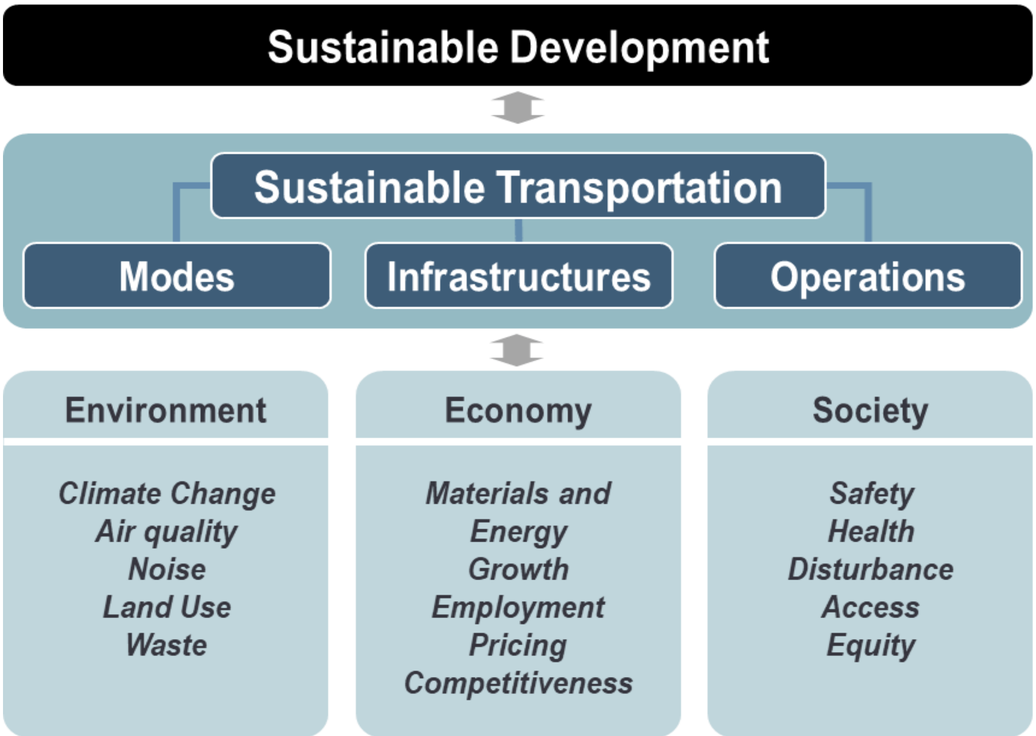

Figure 3: Sustainable transportation (Rodrigue 2020)

Rodrigue (2020) defines sustainable transportation as: "*the capacity to support the mobility needs of a society in a manner that is the least damageable to the environment and does not impair the mobility needs of future generations.*"

The environmental dimension here involves all activities and decision-making to minimize environmental pollution caused by the company (Oberhofer and Dieplinger, 2014). In this context, the main environmental issue is carbon emissions, where goods transport has a significant negative impact. For example, light- and heavy-duty trucks are responsible for 27,9 percent of transport emissions in the EU (EEA, 2019).

Based on this, making transport more sustainable is through carbon emissions reduction, a process called decarbonization. This process is an interaction between economics, infrastructure, regulatory environment, innovation, and application of information technologies and is shaped by the dynamics in the political landscape. Decarbonization aims to reduce, mitigate, and potentially eliminate carbon emissions by changes in transportation infrastructures, the type of energy(fuel) used for transportation, and management of transport operations (Rodrigue, 2020). The main trend in Norway in achieving the carbon emissions reduction goals is through the electrification of the transport sector. The availability of relatively cheap renewable electricity in the grid and the potential for local renewable energy production, together with the availability of electric-based vehicles and niche innovation, are creating bases for this. The electric-based vehicles are divided between battery electric vehicles (BEV) and hydrogen fuel cell vehicles (FCV) as an alternative to these. The FCVs are more suitable for heavy trucks and for longer distances, with a much shorter time for re-fueling than the BE trucks (Unterlohner, 2020).

4. Literature review

4.1. Renewable energy systems

Renewable energy systems are systems utilizing renewable energy sources. The large-scale deployment of renewables, like wind and solar, present two main challenges when integrated into the power grid; first is the instability in the energy system because of the intermittency of the wind and solar energy production, where the power production strongly depends on the local weather and climate (Mahmud and Zahedi, 2016). The problem with the system's instability will grow stronger with the higher share of wind and solar energy; there is a connection to the second challenge, which is the capacity of the conventional power system to accommodate the increased renewable energy generation (Yang et al., 2018). One of the possible solutions to these problems is the right composition of such a system, integration of various renewable energy sources, together with the choice of suitable energy storage (Yang et al., 2018). The need for optimizing the electricity supply network can be solved by smart grid technology, where the energy storage systems play an essential role (Faraji et al., 2017).

4.2. Renewable sources of energy

For the purpose of this paper, the main focus will be mainly on wind and photovoltaic (PV) power. Those seem to be the most relevant and widely available sources of electricity (aside from the grid import) for the local and niche innovative projects in the transport sector.

4.2.1. Photovoltaics (PV)

Solar energy is the energy produced by the sun in the form of heat and radiation. The tremendous amount of potentially partly accessible energy and its availability throughout the year in most regions on Earth makes it the most sustainable, reliable, prime, and green energy source (Sharma and Goyal, 2020). Solar energy can be converted directly into electricity with the help of solar cells, using the photovoltaic effect. Therefore, this type of renewable electricity is called photovoltaic solar energy (PV) (Sharma and Goyal, 2020; Sampaio and González, 2017).

The PV industry is one of the most growing ones worldwide and is considered one of the most promising markets in the field of renewable energy (Sampaio and González, 2017; IEA, 2020). It became more popular in the last decade, growing exponentially both in homes and commercial buildings, that all with the help of strong policy support in Europe, the USA, and Japan (IEA, 2020). The growth in power generation is estimated to have increased by 22 percent in 2019, to 720TWh, becoming the second-largest (behind the wind power) among renewable technologies and standing for almost 3 percent share in global electricity generation (IRENA, 2020; IEA, 2020). Levelized cost of electricity (LCOE) is the average net present cost of electricity generation over the lifetime of generating plant, it is used for comparison of different methods of electricity generation. The LCOE of the new PV projects has globally fallen by 82 percent over 2010 to 2019 period (e.g., Figure 4), primarily driven by the reduction of the price of the PV module (IRENA, 2020). As a consequence, the global installed capacity of solar PV has heavily increased.

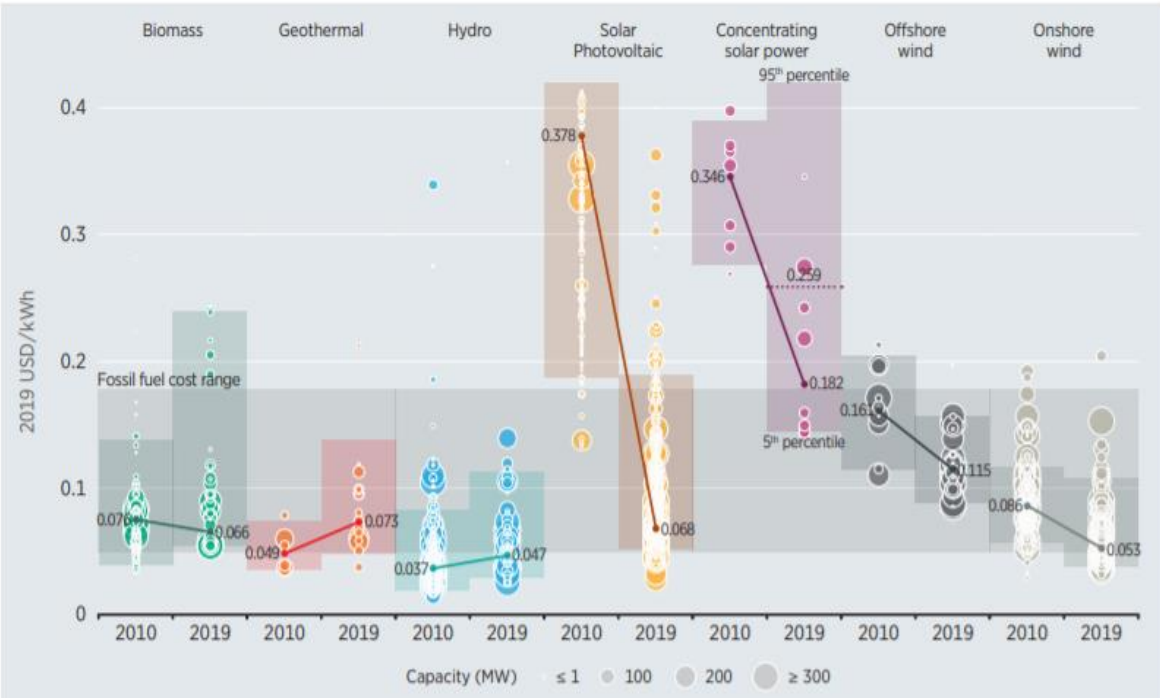

Figure 4: Global LCOEs from newly commissioned utility-scale renewable power generation technologies, 2010-2019 (IRENA 2020).

This growth seems to be well on track with the Sustainable Development Scenario (SDS) that expects it to generate almost 3 300 TWh in 2030, meaning that the annual electricity generation by PV should increase by 15 percent each year (IEA, 2020). In order to keep this pace, there is a need for innovation and further development when it comes to price reduction, device design, production technologies, materials, and energy consumption during the manufacturing of those, and also new concepts to enhancing the global efficiency of the solar cells (Sampaio and González, 2017).

Solar energy stands for a small share of the power production, but at the same time, it is the source that is the fastest growing one (e.g., Figure 5) (NVE, 2020).

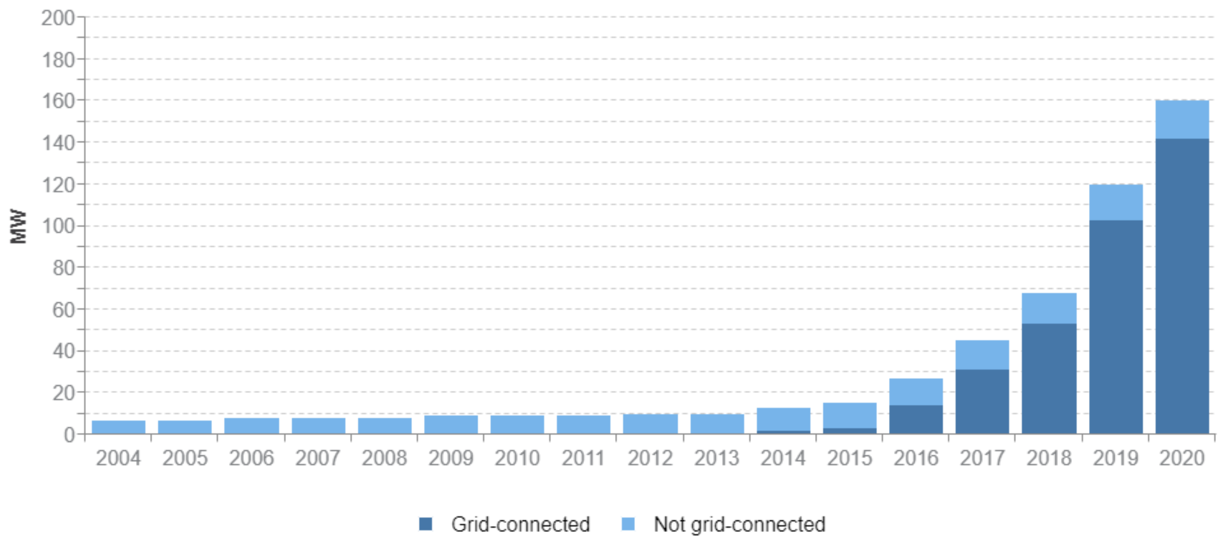

Figure 5: Development installed capacity for solar power in Norway[3]

The potential production of the PV installation may be between 650-1000 kWh per year in optimal conditions (NVE, 2020). This level of production is comparable to other places in Europe situated due south of Norway. The comparison in Figure 6. shows that the PV installation has a relatively high potential, also in Norway.

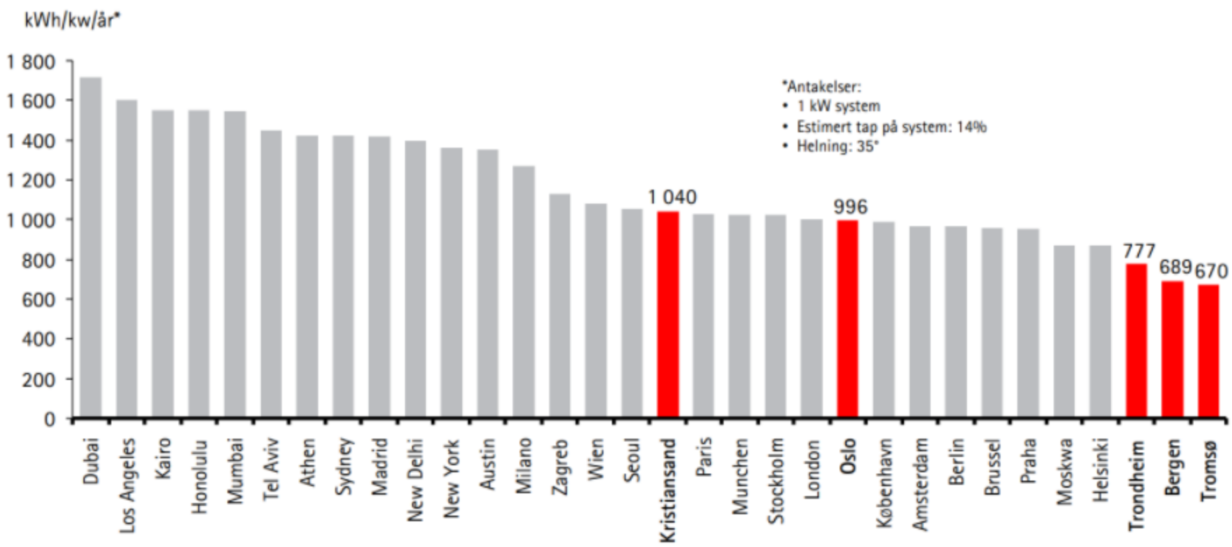

Figure 6: Comparison of energy generation potential of PV at various locations (NVE 2020).

[3] Energi fakta Norge(2021): https://energifaktanorge.no/en/norsk-energiforsyning/kraftproduksjon/

A solar cell is an electronic device based on the materials known as semiconductors that generate electricity when exposed to solar irradiation (Sampaio and González, 2017; Sharma and Goyal, 2020; DEA, 2020). The most used semiconductor is silicon, the second most abundant element on Earth (Sampaio and González, 2017).

The amount of power generated by the PV cells depends on the amount of the irradiation received, installed generation capacity, material, and quality of the components, minus the losses related to installation site (shading, etc.), losses related to conversion from sunlight to electricity, losses connected to DC/AC (direct current/alternating current) conversion, grid connection and transformer losses (DEA, 2020).

Based on the material used, PV cells can be divided into four categories, also referred to by some as generations, where the main aim of each generation is the cost reduction costs and improved conversion efficiency of the cells (Sharma and Goyal, 2020).

First-generation PV cells are silicon and germanium-based solar cells. These cells are capable of electricity generation from different wavelengths. Silicon-based PV cells are the most commonly used PV cells. Because silicon's qualities, such as its easy availability as a material, nontoxic and nonhazardous for the environment, it is a stable material with long life, low maintenance cost, and the efficiency in the range between 15 -24 percent (Sharma and Goyal, 2020). The second generation is based on thin-layer– film technologies using the amorphous silicon, cadmium telluride/cadmium sulfide cells (Sampaio and González, 2017). The aim here is to reduce the high costs of the cells of the first generation (Sharma and Goyal, 2020) and utilizing new space and surfaces that wouldn't be suitable for the previous generation. The third generation is based on nanomaterials' usage to increase the PV cell efficiency further. For example, a high-quality film of silicon nanoparticles integrated into silicon solar cells can improve the conversion efficiency by 50–60 percent in the ultraviolet range of the spectrum (Sharma and Goyal, 2020). This generation of cells is characterized by higher design flexibility, reduced recombination losses, and further, low material usage leads to cost reduction.

Solar cells of the fourth generation are characterized by flexibility and further cost reduction. These cells are based on combining the inorganic nanostructures with organic-based nanomaterials like carbon nanotubes, graphene, and their derivates. This technology can become cheaper and more efficient than conventional silicon solar cells (Sharma and Goyal, 2020). While still in development, the usage of carbon nanotube-based technology presents potentially potent technology for further renewable energy development.

Advantages:

The electricity generation through the PV does not consume any fuel. It is modular and relatively easy to install and has a long lifetime of around 30 years (DEA, 2020). The power is produced during the daytime when demand is usually higher, covering the electricity demand peaks happening during the daytime. It must be combined with the proper type of energy storage system if energy is supposed to be consumed later. PV power generation daily and seasonal profile complements the wind power because of opposite production profiles (e.g., Figure 7). Another advantage of the PV cells is that the installation on the roofs does not require ground space (DEA, 2020).

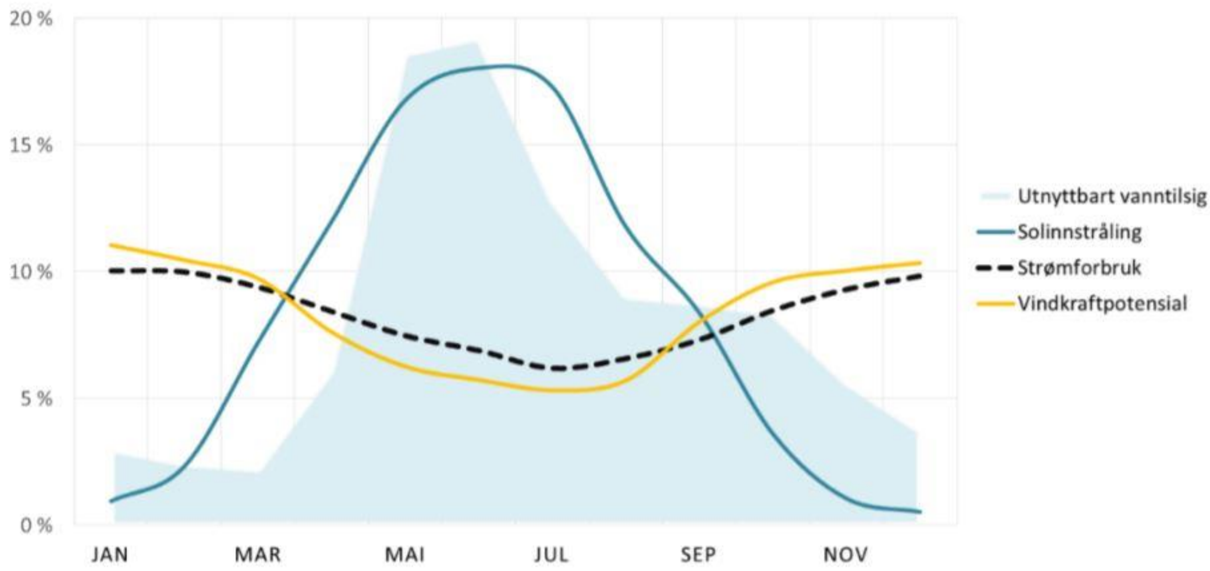

Figure 7:Example of monthly distribution of Norwegian renewable power production compared to profile of annual electricity consumption, as a percentage of the sum over the year (Lundsbakken 2019)

Disadvantages:

PV systems have a high upfront cost and relatively low capacity factor (DEA, 2020). The electricity generation follows the daily and yearly variation in solar irradiation; this may eventually create problems with the power generating system reliability because of the unpredictability of the weather. For example, in future there may be more days with rainfall during the summer season and potentially more extreme weather events related to climate change. Further, the generation often does not correspond with the consumption during the day.

For transportation most of the traffic happens during the day, so the cars are away from the terminal when the electricity is available.

Moreover, on another side, the charging of the vehicles is mostly happening overnight. Hence there is a need to combine PV production with storage to utilize the produced electricity. However, energy storage is expensive, thus increasing the whole system cost.

Some of the thin-film technologies depending on the rare minerals may be limited in market deployment by the scarcity of these rare minerals (DEA, 2020). Further, some of the materials used for the manufacturing of PV films are toxic.

4.2.2. Wind power

The renewable energy of wind has become an attractive energy resource because it is considered to be clean, socially justifiable, environmentally friendly, and it became economically competitive (Vargas et al., 2019). It is also the fastest-growing renewable energy technology (IRENA, 2019). However, wind power is a practically inexhaustible and clean energy source, while its unpredictability and abrupt variations in speed and density negatively affect the stability and uniformity of electricity generation (Barbosa de Alencar et al., 2017).

According to the Global Wind Energy Council (2018), wind power is becoming fully competitive in the marketplace against fossil and nuclear incumbents (GWEC, 2018). The global average cost of electricity generated from the onshore wind decreased to 53 USD per MWh in 2019 (IAE, 2020). The reduction in the cost and advancements in the turbine design have led to worldwide growth in the past two decades, all with the proper policy support. As a result, the global installed capacity of both offshore and onshore grew from 7,5 GW in 1997 to 564 GW by 2018 (IRENA, 2019). This growth is expected to continue. According to the International Energy Agency’s outlook, wind power should stand for 18 percent of global power generation in 2050 (Vargas et al., 2019). While the cost reduction and policy support are seen as the main drivers of the global wind power deployment during the coming five years, there is also expected increase in the share of wind power that is not subsidized (IEA, 2020).

In Europe, the wind plays a significant role in the energy mix; wind energy contributed nearly 9% of Europe's energy production in 2016: a third of the total renewable energy production (ENTSO-E, 2016).

The wind is the air in motion; this kinetic energy is captured by the turbine's blades and converted into mechanical energy, which drives the rotor of the wind generator, which produces electricity through electromagnetism (Barbosa de Alencar et al., 2017; IRENA, 2019). The annual energy output of the wind turbine depends on the average wind speed, the hub height, and the surface roughness (DEA, 2020). The turbines are designed to operate in the optimal wind speed range, starting to operate in “cut in” wind speed, while the rotor blades are controlled to maximize electricity production at the lower wind speeds, maintaining constant power output and decreasing the mechanical stress under the high speeds. When the wind is too strong, reaching the “cut out” speed, the turbine starts to operate on reduced power or is shut down to prevent mechanical damage (DEA, 2020).

In wind-based electrical systems, there is essential to predict the future values of the wind behavior and evaluate the potential energy production in the next period, affecting the dispatch of the generating units and the overall system's overall stability (Barbosa de Alencar et al., 2017).

According to Wang et al. (2017) the accurate forecast is very difficult, because of the nonlinear and non-stationary characteristics of the wind.

This fluctuating wind power poses challenges for the grid stability when the wind power is integrated into the grid (Vargas et al., 2019). Therefore, the increased share of the wind power connected to the electric grid demands a higher level of planning, coordination, and flexibility. Accessing the future values of the wind production, there exist three different time horizons: short, medium, and long term (Vargas et al., 2019). Short-term forecasts are mainly useful for operational purposes; medium-term forecasts increase the operational security of day-ahead electricity markets and the decisions about going online or offline. The long-term forecasts provide information when accessing wind power generation potential in specific areas and serve for the power system risk assessment (Soman et al., 2010).

Norway belongs to the countries in Europe with the best availability of wind power (e.g., Figure 8). With the wind production being higher during the autumn and winter months than during the summer ones.

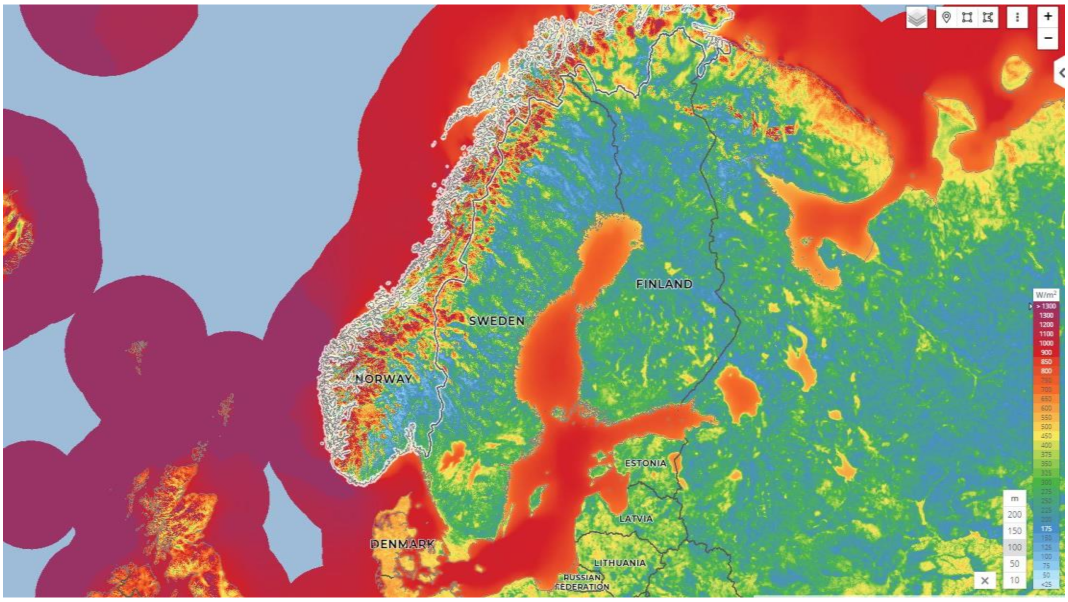

Figure 8: Map of mean power density of wind power in Norway (Global wind atlas)

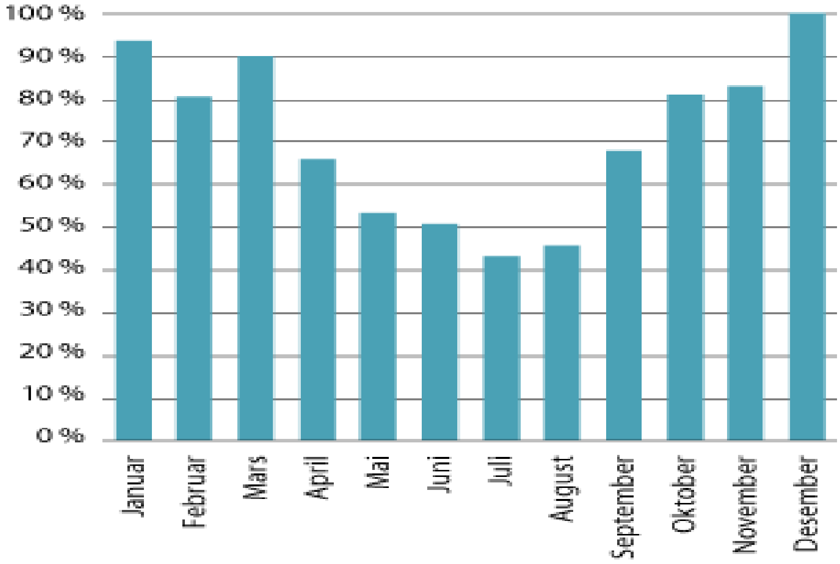

Figure 9: Selected wind turbine production through in Norway 2019, measured against the month with the most production (December = 100 percent) (NVE, 2020)

Wind power in Norway becomes competitive with other energy sources and will add to the carbon emission reduction from the power production sector (Lundsbakken, 2019). As a result, the LCOE of wind power in Norway has decreased by more than one-third since the year 2012 (Lundsbakken, 2019).

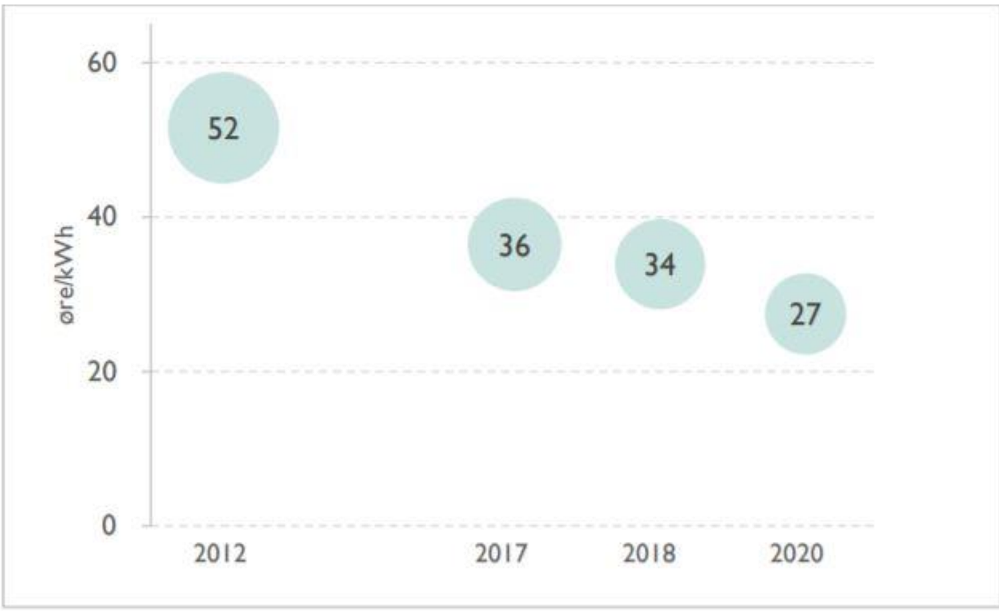

Figure 10: Development in the LCOE for the Norwegian wind power (Lundsbakken, 2019).

Advantages of the wind power are zero emissions from the operation and low operational cost (DEA, 2020). In addition, the availability during the night and colder months, together with lower production during the summer, is creating the possibility for balancing PV power production.

The main disadvantages are high investment cost, the need for regulating power, visual impact and noise, and the variability in power production (DEA, 2020).

Although wind energy is seen as a clean energy source, it is connected to several environmental concerns. First is the risk of collisions of the blades with bats and birds, potentially affecting the whole ecosystem around the wind farms and the damage to the environment under construction (DEA, 2020). Second is the bulk waste from the tower construction and hazardous waste from components in the nacelle and carbon emissions connected to the production of the power plant components.

Wind power, especially the onshore one, has been facing many problems regarding social acceptance. There is a range of factors behind this resistance (Huijts et al., 2012; Elis and Ferraro, 2016). Suskevics et al. (2019) summarize the main reasons behind this resistance in Europe: encroachment into the landscape, lack of trust, and environmental concerns. A significant role also plays the social justice and control over and participation on the benefits from the wind power.

4.3. Renewable fuels

4.3.1. Electricity

Based on NVE (2020) data, Norway has the total installed capacity of the power supply system of 371 680 MW, producing ca. 153 TWh annually. Renewable energy sources dominate this production. First, hydropower is the biggest from the energy sources and stands for approximately 90 percent of the production in Norway (Koestler et al., 2020). The potential of hydropower power is based on the reservoirs that have a capacity of 87 TWh to handle the seasonal and annual rainfall variation. The second biggest renewable source is onshore wind, with a share of approximately 10 percent, or 13 TWh of electricity produced yearly (NVE, 2020; Koestler et al., 2020).

Solar power had over 6500 solar installations at the end of the year 2020 with the production of 0,1 TWh (Koestler et al., 2020). Wind and solar power are rapidly growing in Norway, with wind power being recently the dominant investment (NVE, 2020).

This constellation makes Norway the country with the highest share of electricity produced from renewable sources in Europe while having the lowest emissions from the power sector (NVE, 2020).

The energy consumption in Norway in 2020 was 137 TWh (NVE, 2020). Because of the electrification of the transport sector and petroleum industry, it is expected to increase to ca. 163 TWh in 2040. The electrification of the transport sector is happening fast, and in 2025 there is planned to have 95 percent of new passenger cars and 45 percent of new vans and trucks should be electric (Finansdepartement, 2020). For the decarbonization of heavy transport, hydrogen will play a significant role in the future, but more time for developing the infrastructure on a larger scale is needed (NVE, 2020). Further, there is also an expected increase in the energy consumption related to hydrogen production.

Electricity as a fuel

In order to mitigate the carbon emissions from the transportation sector, the broad adoption of alternative fuels such as electricity is necessary. However, the extent of the emission reduction depends on the carbon intensity of the electricity production, electric vehicle and battery technologies, and the charging profiles of the vehicles (Keller et al., 2019).

The limiting factor for the widespread switch to electric vehicles is the preparedness of the national grid to supply sufficient power for the increased level of demand as much as developing the network of the charging points with sufficient power (Monios and Bergqvist, 2019). To ensure sufficient effect available for changing, the utility companies need to reinforce and upgrade the grid, which may be very costly (NVE, 2020). In addition, to successfully transition to the electrical-based transport system, there will most probably be necessary to expand generation capacity (Keller et al., 2019). However, these capacity and effect problems may be solved locally with the right combination of renewable energy production and storage capacity, dimensioned to cover the extra loads connected to the charging of electric vehicles.

Electricity is an energy source that can be considered an alternative to petroleum fuels (Rodrigue, 2020). The combustion engines are less energy-efficient than electromotors because between 60 to 75 percent of energy from the fuel is lost during the combustion (Holmberg and Erdemir, 2019). Electric vehicles use electricity directly from the batteries. Consequently, the electromotor of an electric car is smaller and less complicated compared to the combustion engine. That makes the construction of electric cars cheaper and easier, but the main expenses and challenges are related to the battery (Monios and Bergqvist, 2019).

The capacity of the batteries, the style of charging, and the developed charging infrastructure are the limiting factors from the operational perspective (Teoh et al., 2018; Monios and Bergqvist, 2019). The battery's capacity is limiting the routes of the delivery vans and trucks, while the most common range is between 180 to 300 km, with some single unit trailers up to 800km (Chung, 2020). The basic relation between and range and the battery capacity is as follows, the larger range, the larger, and hence heavier battery is required. This means that it will automatically occupy a significant percentage of the potential payload of the vehicle (Teoh et al., 2018; Monios and Bergqvist, 2019).

The potential range is further affected by the weather conditions, terrain, and driving style (Keller et al., 2019).

If the battery electric vehicles drive at a speed under 60km per hour, their range increases considerably (Furtado, 2018). However, this will significantly decrease the efficiency of the delivery increase the number of working hours for the drivers. Such a problem may be solved using autonomous electric vehicles (Monios and Bergqvist, 2019).

For the purpose of reducing emissions from transport, the battery-electric trucks were not seen as a viable solution because of their high energy consumption per kilometer and low capacity of the battery (Den Boer et al., 2013). However, the recent development in battery technology and market development is turning them into commercially and technically viable solution (Liimatainen et al., 2019). Moreover, with the expected decrease in the battery price, should the life cycle cost of the heavy battery trucks lower than diesel heavy-duty trucks (Liimatainen et al., 2019).

Several researches conclude that while the electric trucks have approximately three times higher purchasing price, they will become competitive with the diesel trucks if annual mileage is high enough and the battery life can match the vehicle lifetime (Sen et al., 2017; Liimatainen et al., 2019).

According to Liimatainen et al. (2019) the medium-duty electric trucks are already a commercially viable solution. However, the viability of heavy-duty electric trucks depends on improvements to battery capacity and the development of recharging infrastructure. Lastly, the heavily articulated truck trailers don’t seem to be suitable for electrification with the battery technology. Therefore, hydrogen may present a better solution here.

Charging of the electric vehicles

There main operational difference between charging of electric car and trucks, where cars can use regular charging during the time when they are not in traffic, for the trucks there is more economical to utilize the trucks as much as possible, hence stopping to charge when on the route is less attractive (Monios and Bergqvist, 2019). This problem may be solved by battery swapping or fast charging during the breaks for the drivers if the infrastructure for fast charging is available (Chung, 2020; Keller et al., 2019).

The charging technology is divided based on the energy transfer into conductive and inductive (Tie and Tan, 2013). Conductive charging is used for the power transfer through the metal connection between the charger and the vehicle. Inductive charging uses magnetism for the power transfer; hence no physical connection is needed (Chung, 2020).

Based on Chung (2020), four main types of charging exist plug-in, catenary system, battery swap, and wireless charging.

The plug-in system is a type of conductive charging, using cables connected to the charging station as a medium for the power transfer. The power station may be connected to the grid or the battery storage.

The catenary system is conductive charging using the power transfer from above through the pantograph. This type of charging is suited for electric buses and trucks because of their height.

The battery swapping is also based on conductive charging, where the depleted battery is exchanged for a fully charged one at the battery swap station (Den Boer et al., 2013). This type of charging may be utilized on long routes that the battery's capacity cannot cover. And for the heavy electric trucks.

Wireless charging is a type of inductive charging, where the vehicle is parked on the charging unit that is built under the surface of the road and is charged by induction. This type of charging has low efficiency and is not yet market-ready (Chung, 2020). Wireless charging has relatively low efficiency in comparison to conductive charging. The main technical challenge is distance and proper alignment between the plates of the charging pad and the vehicle (Ahmad et al., 2020). In addition, the surface of plates has to be kept clean, which may be problematic during winter, when they can be covered by snow or ice.

4.3.2. Hydrogen

Hydrogen is the most abundant element in the universe, but because of its` high reactivity, it does not exist in its 'free form in nature, but it is present in water, fossil fuels, etc. (Birol, 2019; World Energy Council, 2019). Therefore, hydrogen is available everywhere, it can also be potentially produced anywhere by extracting it from these, but the efficiency and feasibility of the production depends on the ability to produce large volumes for a reasonable cost on a large scale and on the smaller or local scale using the excess energy from the renewable energy sources, that is available locally. Therefore, the economic feasibility of such production depends on the resources available and the potential local usage of the produced hydrogen, hence reducing the expenses connected to its transportation (DNV, 2019).

Higher energy content compared to natural gas and gasoline makes hydrogen an attractive fuel for the transport sector and application in other sectors with high energy demand (Birol, 2019).

The transportation system based on using hydrogen as a fuel consists of hydrogen production, compression or conversion it into the liquid, transfer, and storage on the board of the vehicle, and finally generation of electricity with the help of fuel cell in order to propel the electromotor of the vehicle (Rodrigue, 2020).

The nature of the extraction process varies according to the type of feedstock used. The source of energy for the extraction of more than 95% of the hydrogen produced globally is based on fossil fuel, with steam methane reforming (SMR) being the most common production method (around 48%), followed by partial oxidation (POX) of crude oil products (30%) and coal gasification (18%) (Birol, 2019; World Energy Council, 2019).

Climate-friendly hydrogen is divided into so-called blue and green hydrogen (Statkraft, 2018). The blue hydrogen is produced by extraction from natural gas (usually through the process of SMR), in combination with the capture of the carbon. Therefore, the climate effect of this production depends on the efficiency and development of carbon capture and storage (CCS) technology. There is also present a danger of leakage of natural gas (methane) during the production and processing. Methane has higher impact on climate than carbon dioxide (Balcombe et al., 2018). On the other hand, the green hydrogen is produced by electrolysis of the water, using renewable energy in the process. Nevertheless, this method accounts just for approximately 4 percent of the current global production of hydrogen (Taibi et al., 2018).

There exist three main types of water electrolyzers: alkaline (AEC), proton exchange membrane (PEM), and solid oxide one (SOEC), with an electric efficiency between 56 (PEM) and 81 (SOEC) percent (DEA, 2021). Alkaline electrolyzers being the most matured technology, are dominating the market of electrolysis. PEM electrolyzers are younger technology in an earlier stage of development. However, because of their higher flexibility, they are becoming more popular, mainly through their ability to react to variations in renewable electricity generation (DEA, 2021). Although the alkaline electrolyzers have been available on an MW-scale (6MW), the scale-up of PEM has been realized in the last few years and is up to 2 MW, driven by the growth of renewable energy and the reduced plant footprint, at the same time, SOEL is still in a laboratory phase and on a scale up to 10 kW[4].

The large-scale incorporation of hydrogen in different technologies depends on reliably producing large quantities of green hydrogen (Thomas et al., 2020). This has been the greatest barrier to the development of a sustainable hydrogen society. However, the increased efficiency of green hydrogen production in combination with higher penetration of the renewable energy into the energy systems should replace the hydrogen produced by the SRM, hence reduce the carbon emissions related to SRM and the need for CCS capacity.

Electrolyzers have been long seen as inefficient, but the recent rapid progress made them more efficient and hence more competitive with other hydrogen generation technologies. As a result,

[4] Janzen (2021): https://www.greensight.no/2021/01/03/technology-electrolysers-part-3

it is expected that the cost of hydrogen production by electrolysis with the help of renewable energy sources may fall by up to 80 percent by the year 2030 (Thomas et al., 2020).

Electrolysis is a modular technology that can be easily installed and scaled up and down based on the required capacity of generation (DNV, 2019). The only requirements are access to water and a source of electricity. These qualities make electrolysis good suitable for local production of hydrogen, where the expenses related to transport and storage will be reduced, thereby increasing the electrolysis competitiveness. Investment can start with a single module that can be gradually increased later depending on the demand for transportation (DNV, 2019).

Hydrogen is often seen as the energy source of the future (Rodrigue, 2020). Green hydrogen could significantly reduce global carbon emissions and the dependency on fossil fuels in the sectors that are hard to decarbonize. One of them is the transport sector. At the same time, it also presents a unique opportunity for research and innovation (European Commission, 2020). In Norway, the carbon emission from the transport sector that the hydrogen can potentially reduce is around 500 000 tons per year, standing for approximately 1 percent of national carbon emissions (DNV, 2019).

In order to incorporate the hydrogen into the transport system, hydrogen-fueled vehicles have to be in place together with the fueling infrastructure network. The most promising are those that are using hydrogen-based fuel cells. The most used fuel cells at the moment are the PEM ones. Fuel cells are electrochemical devices that transform hydrogen and oxygen directly into electricity and heat (Thomas et al., 2020). This transformation is emission-free and more energy-efficient than gasoline (Rodrigue, 2020). The fuel cell electric vehicle market started to flourish in recent years, and big car manufacturing companies have started to offer their models even for heavy transport e.g. Nikola (DNV, 2019).

The climate change ambitions are creating momentum for low-carbon hydrogen, where an increasing number of countries have published their hydrogen strategies and roadmaps for hydrogen technology deployment (IEA, 2020). However, there is a need for governmental support during the establishment period of the hydrogen infrastructure, especially the hydrogen filling stations' network is essential for further adoption of the hydrogen vehicles (DNV, 2019).

Hydrogen storage

Hydrogen storage technology is necessary to ensure the stability and security of supply. Hydrogen can be stored in the form of gas, liquid, or in a solid-state. In order to achieve higher energy density, hydrogen has to compressed or liquified before it is stored (van Cappellen et al., 2018). The storage can be short-term in order to respond to intraday demand on a smaller scale, and the long-term storage on a larger scale for seasonal storage.

The hydrogen storage model based on incorporation with the renewable energy source consists of an electrolyzer, hydrogen tank, and a fuel cell (Zhang et al., 2017). The produced hydrogen is compressed in the storage tank and can be used as a fuel for hydrogen vehicles or converted later back into electricity through the reverse process in the fuel cell when needed. Hydrogen storage is suitable for seasonal storage, where the hydrogen stored from warm months is used for peak shaving during the cold months.

Vehicles using hydrogen fuel cells are more energy-efficient than those using gasoline (Rodrigue, 2020). When it comes to carbon emissions, hydrogen is seen as a clean energy source, but it is clean as much as the electricity it has been produced from. The main challenge with hydrogen is the loss of energy during the electrolysis, where 20 to 40 percent of energy will be lost. The storage and compressing further require more energy.

4.4. Energy storage

Energy storage is a crucial technology for the successful energy transition to a sustainable and renewable energy system (DEA, 2020b). The main focus here will be on the most actual two electricity storage technologies: Flywheel and battery storage. The potential of storing the energy into the hydrogen was looked upon closer in the hydrogen part of the paper.

4.4.1. Flywheels

Flywheels represent the oldest, dynamic, and highly reliable technology (Faraji et al., 2017). It is a type of mechanical battery, storing the energy mechanically as kinetic energy in a high-speed rotational disk connected to the shaft of an electric machine and releasing it back to the network when necessary. The amount of stored energy depends on the form, mass, and rotational speed (Faraji et al., 2017). The energy can be stored for seconds up to years, while the most common use is for shorter periods (DEA, 2020b).

In order to reduce aerodynamical drag, modern flywheels are operating in a high vacuum. In combination with the contactless magnetic bearing, it reduces the energy losses during the storage cycle (DEA, 2020b)

The fast reaction time makes flywheels helpful in providing ancillary services to the grid and helping to maintain the grid frequency (Buchroithner et al., 2018). This makes them the best energy storage alternative in combination with wind power. In the wind farm, an adaptable speed generator can quickly control output and input, reducing the variations in grid voltage and output (Faraji et al., 2017). The flexibility and short reaction time make flywheels optimal for applications like peak shaving during the charging of electric vehicles, where they make be used to reduce the costly investment into the grid upgrade (Buchroithner et al., 2018). Compared to the battery storage system, the flywheels are less costly, and their energy storage capacity degrades at a slower rate over time. They are also not affected by the style and depth of charge and discharge (DEA, 2020b).

Advantages:

One of the main advantages is the fast power response, short recharge time, high specific energy, and high cycle and calendar life (DEA, 2020b).

Disadvantages:

Flywheel storage systems are limited by the material they are made of and derived from it by the mechanical stress these materials can withstand. Typical is the short discharge time and relatively high parasitic losses while also present potentially hazardous failure modes (DEA, 2020b).

4.4.2. Battery energy storage

Lithium-ion batteries (LIB)

Lithium-ion batteries dominate the market for energy storage and electric vehicles (Lee et al., 2020). There exist several types of these with different properties, based on the material used. Currently, the most prominent ones are lithium-cobalt-oxide (LCO) nickel-cobalt-manganese (NCM), and lithium-iron-phosphorus (LFP) (Olivetti et al., 2017).

The variety of technologies and rapid development make the future development of the energy storage market challenging (Lee et al., 2020). However, NCM batteries are becoming increasingly popular for transport thanks to their wide range and the decline in costs during the last decade. They are also expected to stand for 90 percent of the market share in the period 2025 to 2030 (Lee et al., 2020). Although battery storage has been showing rapid global growth in recent years, while this growth is expected to continue, there is a high level of disagreement about its direction (Figgener et al., 2020).

Battery production is demanding when it comes to the usage of energy and rare minerals and materials. Lithium itself is highly reactive, which creates a technological challenge in the production of safe battery cells, but in praxis, different compounds capable of donating lithium ions are used instead (Zubi et al., 2018). Lithium is used in electrolyte and sometimes in the anode (while most of the anodes are made of graphite), cathode consists of layered metal oxide composed of lithium compounds with cobalt, manganese, nickel, phosphorus, and iron, but there is also a need for copper, aluminum and steel during the production and assembly (Gratz et al., 2014; Lee et al., 2020).

The material used is responsible for the most relevant characteristics of a battery: specific energy and power, durability, and safety (Zubi et al., 2018). The specific energy depends on the type of cathode and anode materials and on their nano and micro-structures. Durability depends on the speed of battery degradation, caused by the operating conditions (mostly low or too high temperature) and overcharge and deep discharge (Zubi et al., 2018).

Lithium-ion batteries present huge global potential towards energy sustainability and substantial reductions in carbon emissions, both as a part of the renewable energy system and the transition in the transport sector. Firstly, by supporting the integration of high PV and wind energy shares in the power mix by providing storage capacity and ancillary services. This should later create a healthy basis for the large implementation of electric vehicles (Zubi et al., 2018).

Another function of the battery storage systems can be peak load shaving. The power profile of the customers of the electrical system has uneven electricity consumption during the day, with the demand spikes resulting in load peaks in the electric system (Uddin et al., 2018). Therefore, the energy system must be dimensioned for those peaks. Further, the power generators responding to the sudden demand increase are more costly than those that are responsible for the baseload (Mahmud et al., 2018). The extra cost is imposed on the consumers in the form of the power fee (Uddin et al., 2018). Battery storage systems are used to reduce this extra cost with peak shaving. The stored energy is used to cover the peak demand, reducing the variation in the electricity consumption and consequentially the cost (Mahmud et al., 2018). The challenge with peak shaving is to detect peaks on time and discharge the battery without missing the peak or using it on smaller peaks instead of the main one (Uddin et al., 2018).

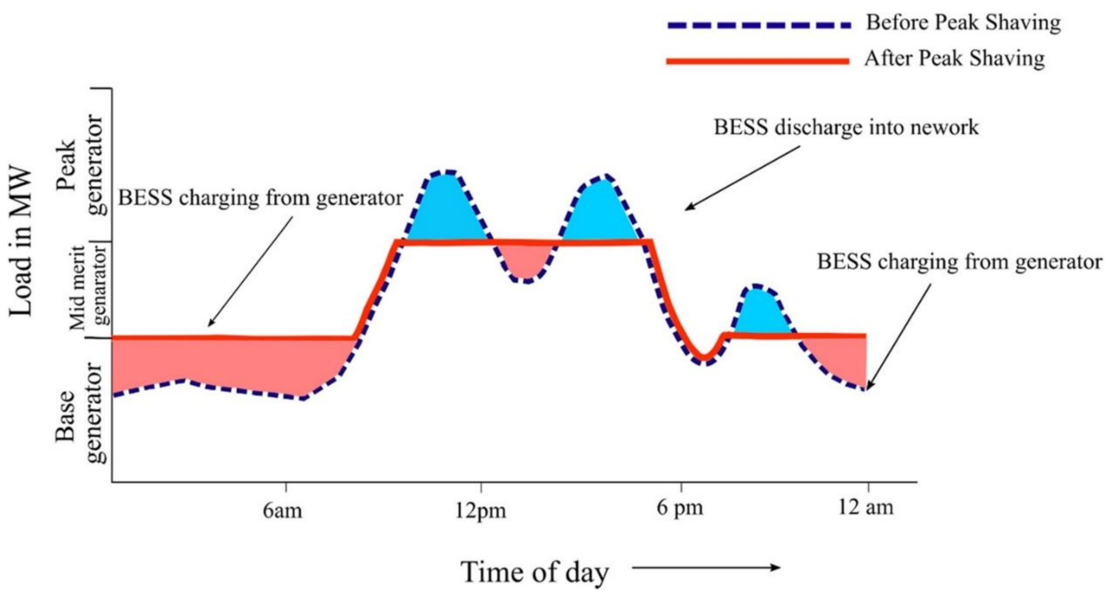

Figure 11: Peak shaving (Uddin et al. 2018)

Disadvantages of LIB:

LIB requires direct current (DC) during charging, and it also provides DC when discharged. However, for a connection to the grid, or application using alternate current (AC), the DC has to be converted with the help of an inverter. This loss caused by this conversion is around 2 to 5 percent (DEA, 2020b).

The storage period of the LIB is limited by the self-discharge rate of the batteries, making the long storage of energy unfeasible. Also, the unwanted chemical reactions are degrading the battery, decreasing its lifespan (DEA, 2020b).

The battery technology has demand for potentially critical materials such as indium, dysprosium, neodymium, cobalt, tellurium, tin, lithium, nickel, gallium, etc. (Moss et al., 2011). The potential of bottlenecks of those materials make affect the further energy transformation. Therefore, recycling these rare materials from old batteries is an important, maybe essential part of the transition to electrical transport (Zubi et al., 2018). Cobalt is already considered a critical material because its limited supply and mining are connected to potentially serious environmental damage. At the same time, mining is also connected to child labor in the Republic of Congo and other ethical concerns entering public debate. This led to increased press to develop cobalt-free batteries (Zubi et al., 2018; Lee et al., 2020).

5. Methodology

5.1. Research design

This thesis is a case study based on the mixed methods research design. Mixed methods research combines the elements of qualitative and quantitative methods for the purposes of a broader and deeper understanding of the studied problem (Clark and Bryman, 2019).

The qualitative part of the research is explorative, and it was based on the extensive market analysis, document analysis, deep content analysis of the current development on the market of renewable energy and storage technologies, hydrogen, charging technologies. And finally, the state of the art of the transition of the traffic sector in Norway. Further on the potential production patterns for the wind and solar PV power production. This qualitative data collection and content analysis build a foundation for further quantitative research.

The quantitative part of the research is descriptive and comparative, is further based on the data provided by the Posten/Bring Norge and Digerneset business park.

The quantitative research is divided into four main parts: First is mapping the demand for energy consumption for the potential electrification of the transport. The second part focuses on the available renewable energy sources. The third part focuses on building up the scenarios based on qualitative research and the supply and demand data connection. The fourth part is the scenario comparison.

The first two parts are based on the energyPLAN. EnergyPLAN is a freeware software used for the analysis of energy systems. It is used for the country and local energy systems, comparing the demand and supply on an hourly basis, incorporating renewable energy production with the right time of storage and import/export from the grid (Lund, 2014).

The third part is based on scenario development. The scenarios are based on the same supply of renewable energy and three constellations of electric vehicles. The first one is entirely battery-electric - scenario A, second one battery-electric incorporating fuel cell vehicles in order to replace the trucks with the highest energy demand - scenario B. Third scenario is based on replacing all the trucks with FCV, and the rest delivery cars and vans with BEV - scenario C. The scenarios are constructed in the same manner, with a slight difference in the hydrogen-based scenarios B and C. Because of the higher system flexibility in terms of storing the energy in hydrogen, there are two more versions of scenarios first one B2 and C2 investigating the chance of reducing the price of imported electricity from the grid, trying to maximize the import of the cheap electricity to meet the demand. The second versions are B4 and C4; these assume usage of renewable energy primarily for hydrogen production, utilizing cheap electricity import from the grid. Scenarios have different energy demand based on slightly different charging schemes for the cars and the amount of energy needed. The construction of the scenarios is based on developing the hourly data sets for the consumption that is further compared with the renewable energy supply. The resulting balance on a monthly, daily, and hourly basis is used to describe the scenarios. For further evaluation of the scenarios, the intraday balance is used to simulate the needed import of electricity from the grid to balance the system. For scenario A, a referral scenario A0 is based on fully importing the electricity from the grid without own renewable energy production. The first versions of scenarios A1, B1, C1 are based on the balance between importing and exporting the electricity without using the battery storage. In the hydrogen-based scenarios, the export is assumed to be used for the production of hydrogen. The versions A2, B3, and C3 are based on incorporating the battery storage of different capacities into the system. The battery storage is simulated with the help of an MS Excel spreadsheet.

The comparison of the scenarios is based on financial data of the different versions of the scenarios and the balance between import-export (hydrogen production). The investment in renewable energy is not included in evaluating the scenarios because it is considered to be alike among the scenarios.

5.2. Data and Data collection

5.2.1. Demand data

Demand consists of the demand for the charging of the cars and the demand for the terminal's building. The demand for cars is upon the yearly produced kilometers for different cars and routes per the year 2019. Furthermore, on the calculated expected energy consumption of 5 kWh per/10 km for the smaller cars and 15 kWh for the heavy vehicles. Those data are provided by Posten. After accessing the average daily demand for the different cars, these are further divided into different categories based on expected battery capacity. Different charging profiles for the different groups of cars are constructed, assuming the slow charging of 6.6 kW per hour for light vehicles, and fast charging of 50 kW per hour for the heavy vehicles. The demand for the terminal is based on monthly consumption over the year 2019 provided by the Tafjord kraft. Daily and weekly, and monthly demand profiles are constructed on the data from the graph of electricity consumption during the period between 10.8.2020 until 7.2.2021. Those data are also provided by Tafjord kraft.

Each of the demands was developed into the data sets of the hourly demand over the whole year. These sets were later combined based on the type of scenario.

5.2.2. Supply data

Supply data consists of solar PV energy and wind power.

PV production

PV power production data are based on the project from Integrate renewables AS provided for the Digerneset business park. The project is done with the help of the PVsyst program. Based on the monthly and hourly potential production, the set of the potential supply from the PV power was constructed.

Wind power

Wind power production is based on the qualitative self-assessment of the available wind resources in the area based on the Global Wind Atlas web page that is freely accessible. Based on this assessment and on the energy supply deficit, market research of the most suitable wind turbine capacity was concluded, and the potential yearly yield of the wind power was assumed.

For the hourly variation of the wind production data, the pattern from the energyPLAN for the onshore wind in Denmark was used. Based on this and the yearly production yield, wind production was modeled. This dataset was further used for the assumptions on monthly and daily potential production.

Data for the electricity price are imported from the Elspot as prices for the year 2020 for the Møre and Romsdal county (Molde).

5.3. Limitations of the study

This thesis has several limitations and assumptions that are important to refer to.

Demand

When constructing the demand, the referral year 2019 was used, having 303 that the cars will be operated. This will be slightly different for other years regarding the number of Sundays and public holidays, affecting the hourly balance between supply and demand.

Another assumption is that all the cars in the terminal are utilized six days per week.

Demand for the terminal also includes the 14 already electrified cars.

The consumption of the cars is based on the Posten calculation 5 kWh per 10 km for the light vehicles and 15 kWh for the heavy vehicles. Consumption of 8 kg of hydrogen per 100 km is used to calculate the demand for FCV.

Supply

Solar and wind power production have intermittent characteristics. The production data are based on the optimal conditions. Hence the real production patterns may be different in real life.

In the case of the PV solar production there was assumed that the whole production from all buildings will be used for the coverage of the Posten demand.

Data for wind power and the hourly variation pattern is based on the data from Denmark; Norwegian may be slightly different.

Hydrogen

Data for hydrogen production are based on the data from the Danish Energy Agency catalog. A production rate of 20 kg of hydrogen from 1 MWh (AEC) is used. The investment cost used for the AEC technology is 15 660 NOK/kgH2/day of maximal output and 570 000 NOK for 1 MWh of hydrogen storage (DEA, 2020).

Battery storage

The cost of battery storage used is 10 420 000 NOK/MWh (DEA, 2020).

For the battery storage in the scenarios, the roundtrip efficiency is 98 percent assuming the direct current (DC) charging and discharging, and 95 percent for alternating current (AC). The losses were not deducted from the results. Therefore, the actual results will be lower.

6. Data presentation and analysis

In this section, data will be presented on the basis of demand and supply for the energy system. Those will be later combined and composed into different scenarios. These scenarios will be later analyzed with the help of financial data.

6.1. Demand

The data related to the energy demand are divided into two main categories: the electricity consumption of the building of the terminal and the amount of energy needed for charging of the electrified vehicle fleet.

6.1.1. Consumption of the terminal

Data about the consumption of the terminal are based on the data provided by the Digerneset and Posten Norge and Tafjord kraft (Figure 12). The terminal is operating six days a week, from Monday to Saturday. As a base for the evaluation of the consumption pattern is the electricity consumption during the period between 10.8.2020 until 7.2.2021 was used. In those data, the charging of already electrified cars is included.

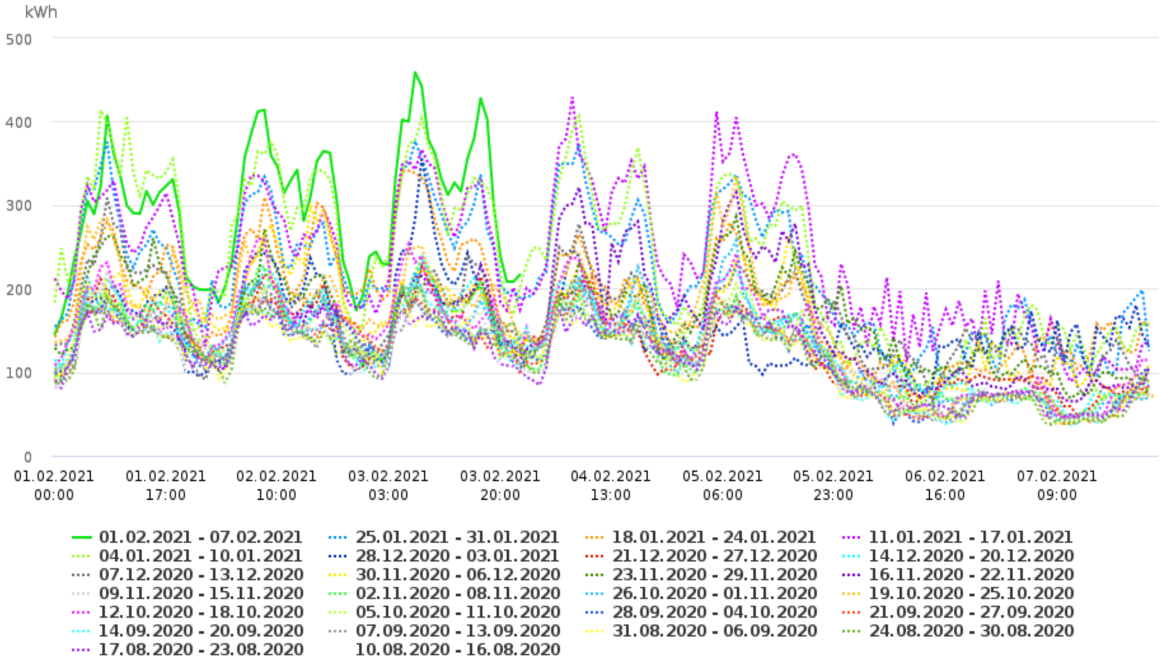

Figure 12: Weekly consumption of the terminal in the period from 10.8. 2020 -7.2.2021 (Tafjord kraft)

This consumption diagram shows the high monthly and weekly variation during the years with much higher consumption during the cold months. The weekday variation is relatively stable, with high demand during the weekdays and low during weekends.

Based on this diagram, the weekly pattern of the consumption with the actual consumption between the minimal and maximal curves was built.

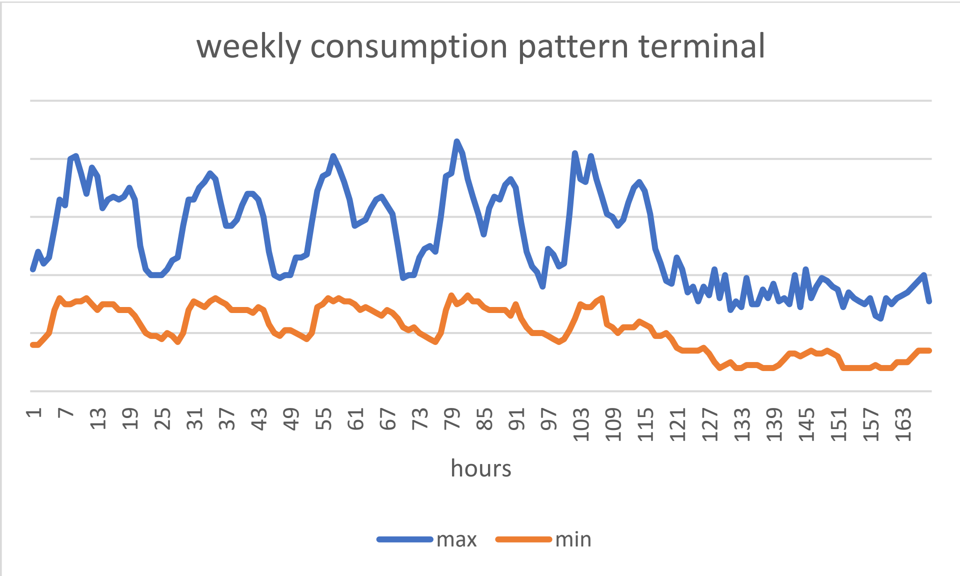

Figure 13: weekly consumption pattern of the terminal

For further analyses, the maximal consumption profile is used in order to capture the possible variation during the day and hours consumption. Based on this, the average daily profile for the weekdays is visualized in Figure 14.

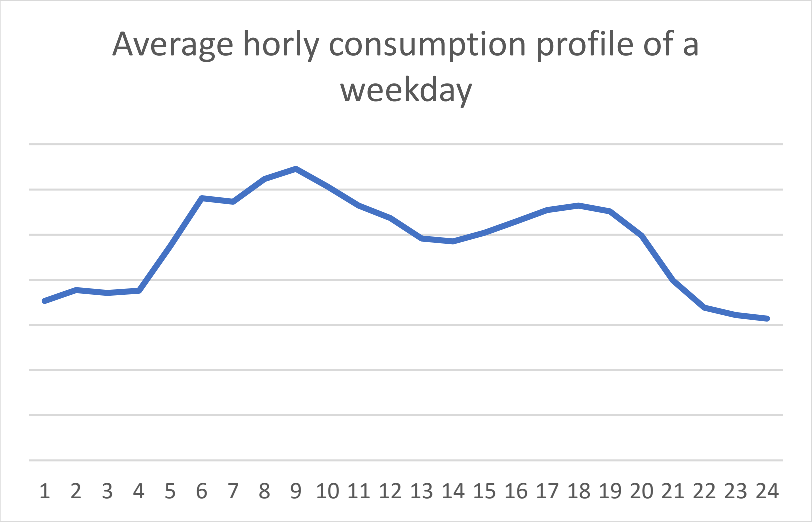

Figure 14: Average consumption profile for weekdays

The daily consumption profile shows two main demand peaks at 6 to 11 am and 5 to 8 pm. This opens the window of 9 hours for the night charging of the additional electric vehicles. Furthermore, the possibility for additional charging during the day in the period between 12 and 4 pm, if needed. Based on this pattern and the actual consumption, the hourly consumption of the referral year 2019 was modelled as a basis for further evaluation. The year 2019 had 303 days when the terminal was in operation.

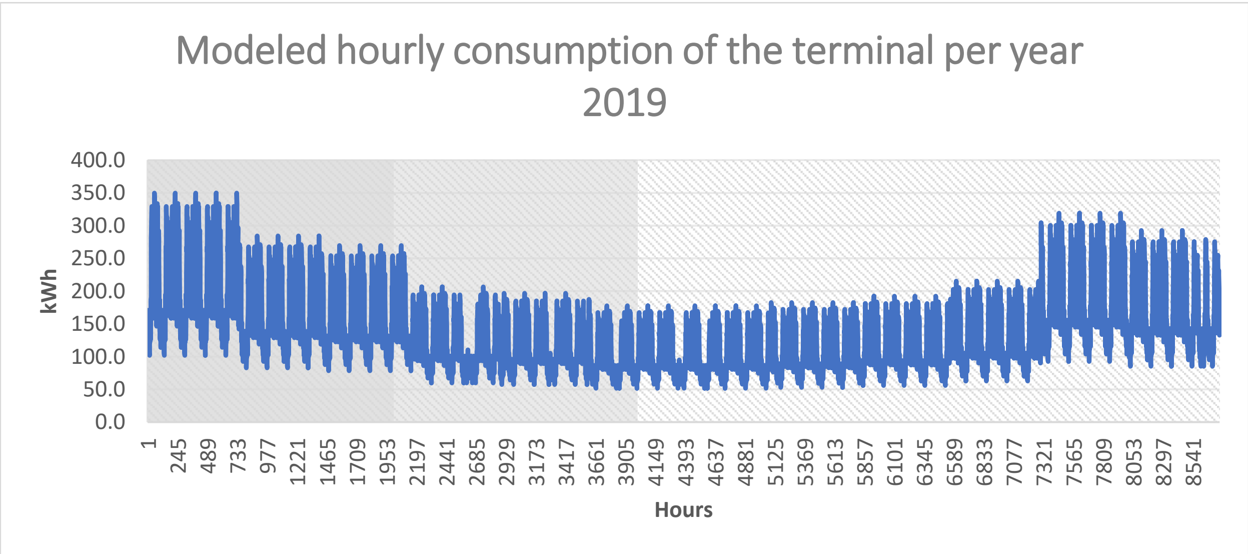

Figure 15: Modeled hourly consumption of the terminal per year 2019

Table 1: Consumption of the terminal in 2019

Month	January	February	March	April	May	June	July	August	September	October	November	December	Sum year
MWh	157.7	116.0	119.8	86.4	85.8	74.5	77.4	82.5	83.6	98.6	138.6	126.3	1247.1

6.1.2. Produced kilometers and analysis of the daily energy demand for cars

The car fleet consists of 14 already electrified cars (Renault Kangoo Express), the group of other light vehicles consists of 33 delivery cars and vans, and heavy vehicles consist of 29 trucks. Based on the average energy demand per day, the battery capacity category was assigned to the diverse cars in Table 2 and Table 3.

Table 2: Demand for the charging for light vehicles based on the produced kilometers and the battery capacity

Car	Route	km/year	km/day	kWh/day	Battery capacity (kWh)	Difference (kWh)	Daily demand for charging (kWh)	
							over night	additional
UF69189	Ålesund 2	16695	55.1	27.55	33	5.45	27.55	
BT24835	Ålesund 2	15939	52.6	26.3	33	6.7	26.3	
UF71497	Ålesund 1	18753	61.9	30.95	33	2.05	30.95	
UF71498	Ålesund 1	18109	59.7	29.85	33	3.15	29.85	
UF71502	Ålesund 1	18607	61.4	30.7	33	2.3	30.7	
UF71504	Ålesund 1	18068	59.6	29.8	33	3.2	29.8	
UF69194	Digernes	23912	78.9	39.45	33	-6.45	33	6.45
UF71495	Digernes	23820	78.6	39.3	33	-6.3	33	6.3
UF71496	Digernes	23541	77.7	38.85	33	-5.85	33	5.85
UF71874	Sykkylven	18693	61.7	30.85	33	2.15	30.85	
UF71876	Digernes	23593	77.9	38.95	33	-5.95	33	5.95
UF71884	Valldal	28337	93.5	46.75	33	-13.75	33	13.75
UF73089	Digernes	19280	63.6	31.8	33	1.2	31.8	
UF73090	Digernes	24371	80.4	40.2	33	-7.2	33	7.2
UF73110	Sykkylven	17499	57.7	28.85	33	4.15	28.85	
UN36389	Digernes	16889	55.7	27.85	33	5.15	27.85	
UF83731	Digernes	22212	73.3	36.65	33	-3.65	33	3.65
UF85477	Digernes	25000	82.5	41.25	33	-8.25	33	8.25
BT34490	Sykkylven	20600	68	34	33	-1	33	1
BT24777	Digernes	16410	54.1	27.05	33	5.95	27.05	
UF71507	Ålesund 2	30363	100.2	50.1	52.5	2.4	50.1	
UF71883	Ålesund 2	15763	52	26	35	9	26	
UF72736	Ålesund 1	34577	114.1	57.05	52.5	-4.55	52.5	4.55
UF70171	Ålesund 1	21320	70.4	35.2	35	-0.2	35	0.2
UF72856	Valldal	24665	81.4	40.7	35	-5.7	35	5.7
UF70172	Digernes	24742	81.6	40.8	35	-5.8	35	5.8
UF70184	Digernes	28516	94.1	47.05	52.5	5.45	47.05	
UF78443	Digernes	45029	148.6	74.3	52.5	-21.8	52.5	21.8
UF71877	Sykkylven	14051	46.4	23.2	35	11.8	23.2	
UF84562	Digernes	19442	64.2	32.1	35	2.9	32.1	
VH81979	Ålesund 2	20860	68.8	34.4	35	0.6	34.4	
UF81569	Breivika	22000	72.6	36.3	35	-1.3	35	1.3
XR 67651	BPX	30000	99	49.5	52.5	3	49.5	
Sum		741654	2447	1224		-21	1125.9	97.75

Table 3: Demand for the charging for heavy vehicles based on the produced kilometers and battery capacity

Car	Route	km/year	km/day	kWh/day	Battery capacity (kWh)	Difference (kWh)	Daily demand for charging (kWh)	
							over night	additional
UF 84470	vanylven	65000	214,5	321.75	300	-21.75	300	21.75
UF 62537	molde/stryn	60000	198	297	300	3	297	
UF 66967	selje	60000	198	297	300	3	297	
UF 72459	07/spjelkavik BP	30000	99	148.5	200	51.5	148.5	
UF 73498	ålesund/nordøyane	40000	132	198	200	2	198	
UF 73702	ulstein	31000	102.3	153.45	200	46.55	153.45	
UF 74485	ørsta	40000	132	198	200	2	198	
UF75706	sykkylven	26000	85.8	128.7	200	71.3	128.7	
UF75711	stryn	70000	231	346.5	300	-46.5	300	46.5
UF 76514	Hareid/ vigra	58000	191.4	287.1	300	12.9	287.1	
UF 76515	stranda/spjelkavik	35000	115.5	173.25	200	26.75	173.25	
UF 76516	moa	17400	57.4	86.1	200	113.9	86.1	
UF 77583	07/ytrebydel/sentru	25000	82.5	123.75	200	76.25	123.75	
UF 77568	Ålesund sentrum	25000	82.5	123.75	200	76.25	123.75	
UF 79177	molde/vigra	55000	181.5	272.25	300	27.75	272.25	
UF 79722	07/moa	30000	99	148.5	200	51.5	148.5	
UF 79723	valldal	40000	132	198	200	2	198	
UF 79724	ringnes	20000	66	99	200	101	99	
CV79935	sula/sentrum	25000	82.5	123.75	200	76.25	123.75	
uf44004	Ørsta	50000	165	247.5	300	52.5	247.5	
uf81899	Volda	50000	165	247.5	300	52.5	247.5	
uf82902	Hareid	44000	145.2	217.8	300	82.2	217.8	
uf84999	Hareid	42000	138.6	207.9	300	92.1	207.9	
uf66140	Stranda	49000	161.7	242.55	300	57.45	242.55	
uf75378	Ålesund	25000	82.5	123.75	200	76.25	123.75	
uf75379	Ålesund	22500	74.2	111.3	200	88.7	111.3	
uf75380	Brattvåg	23500	77.5	116.25	200	83.75	116.25	
uf75381		27000	89.1	133.65	200	66.35	133.65	
uf37715	Stranda	20000	66	99	200	101	99	
Sum		1105400	3433	5472		1428	5403.3	68.25

Based on the produced kilometers per day and the market research of the available electric vehicles. These have been divided into four categories based on the type of vehicle and the battery's capacity. Based on the available electric vehicles on the market, the light vehicles have been divided into delivery cars with a battery capacity of 33 kWh, category I. Other groups are vans with the capacity of the battery 35 (IIa category) and 52,5 kWh (IIb category), and the heavy-duty vehicles with 200 (IIIa category) and 300 kWh battery (IIIb category). The daily demand for categories I and II is 1 224 kWh (Table 2). The daily demand for category III is 5

472 kWh (Table 3). And The monthly demand for charging of different categories is summarized in Table 4.

Table 4: Monthly demand (MWh) for charging different categories of cars

car category	January	February	March	April	May	June	July	August	September	October	November	December	Sum year
I, IIa,b	31.8	29.4	31.9	28.1	29.4	29.4	33.0	33.1	30.6	33.1	31.8	28.2	369.8
IIIa	60.7	56.1	61.3	53.2	56.1	56.7	62.5	63.1	58.4	63.1	60.7	53.7	705.6
IIIb	78.3	72.3	80.8	66.8	72.3	74.8	78.8	81.3	75.5	81.3	78.3	69.3	909.9

6.2. Sources of the renewable energy for Digerneset - Energy supply

6.2.1. Solar PV production

The data for the potential solar PV power production is based on the simulation for Digerneset business park. The project was done with the PVsyst program version 6.67. The simulated production is based on the installation of 7 748 FU275P solar PV modules on five roofs in the business park (Figure 16).

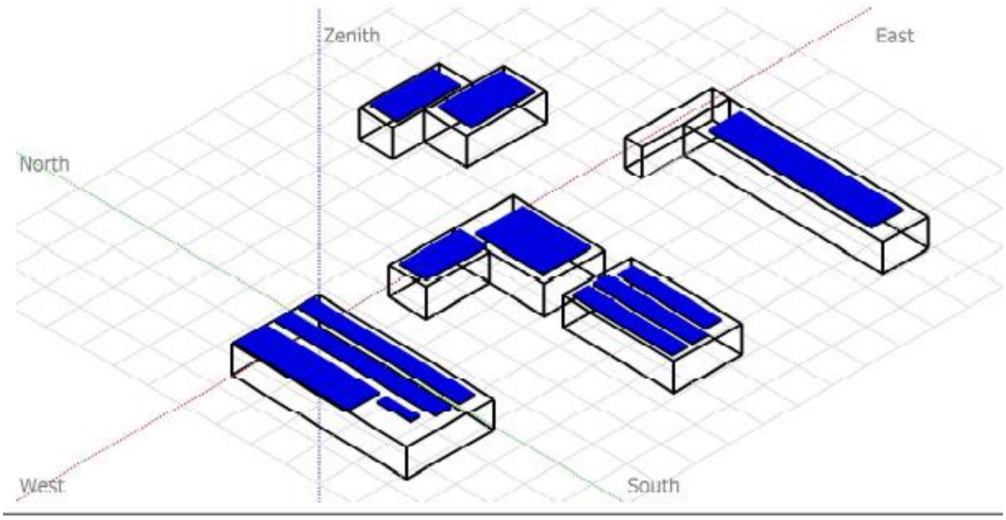

Figure 16: Placement and orientation of the PV field (PVsyst)

The installed capacity can under optimal conditions produce around 1 395 MWh, with the performance ratio of 87,43 percent. The variation in the production is following the length of the daylight and the levels of solar irradiation. The expected production is low during winter months, and peaking in June, May and July (Figure 17 and Table 5).

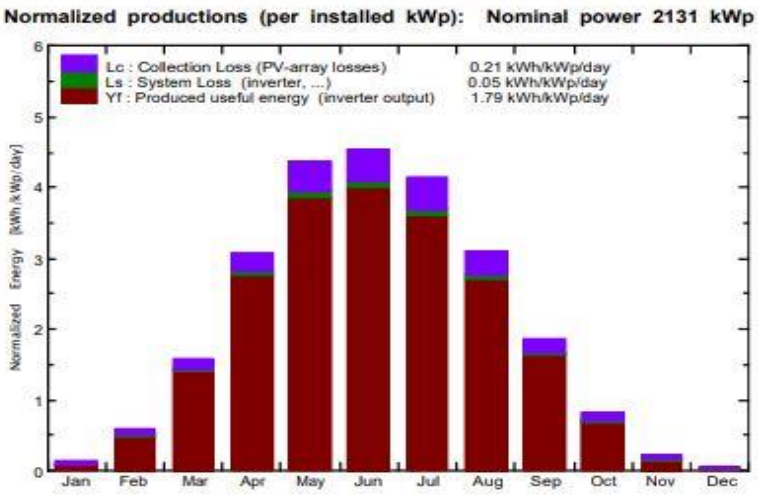

Figure 17: Normalized production per installed kWp (PVsyst)

Table 5: Potential monthly electricity production of the PV (PVsyst)

Month	January	February	March	April	May	June	July	August	September	October	November	December	Sum year
MWh	5.8	29.1	93	176.2	255.8	256.2	238.5	178.9	103.9	45.4	9.8	2.5	1395.1

The monthly data were further used to simulate the potential hourly solar production that will be used for the further analysis.

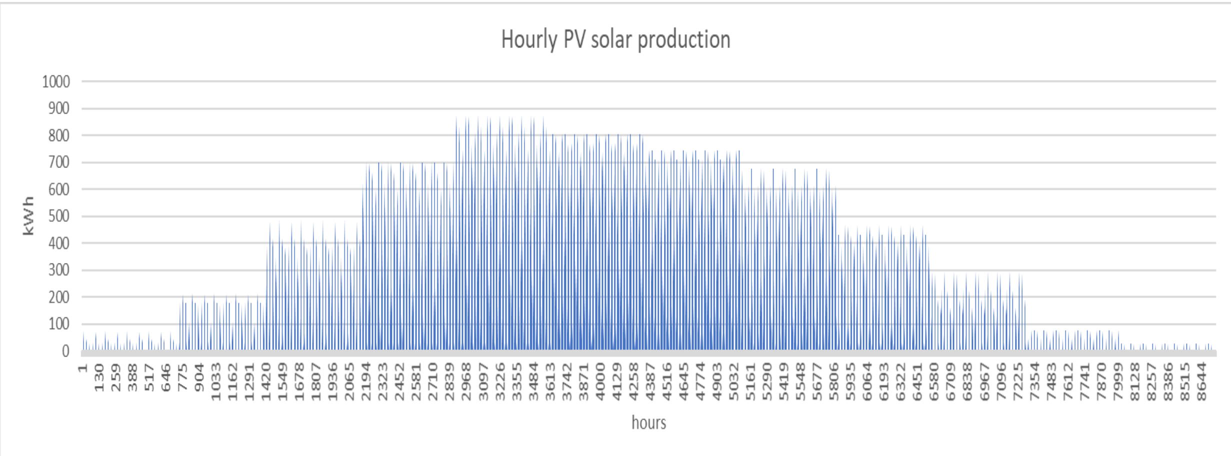

Figure 18: Hourly PV solar production per year

Based on the comparison of the potential solar production (supply) and the demand. The system is lacking around 1 887 MWh of electricity per year to cover the whole demand (Table 6). At the same time, there is a huge overproduction during the summer months that should be stored in some form to be utilized during winter months. Therefore, in an attempt to supply the rest of the energy needed, wind power production is further investigated.

Table 6: The balance between demand and supply

Demand kWh		Supply kWh	Balance kWh
terminal	cars	solar PV	
1248311	2034569	1395807	-1887073

6.2.2. Wind production

The Global wind atlas has been used to investigate the potential for wind power generation in the areas surrounding Digerneset. When investigating the potential, aside from the business park area A1, three other areas in relative proximity have been identified (Figure 19).

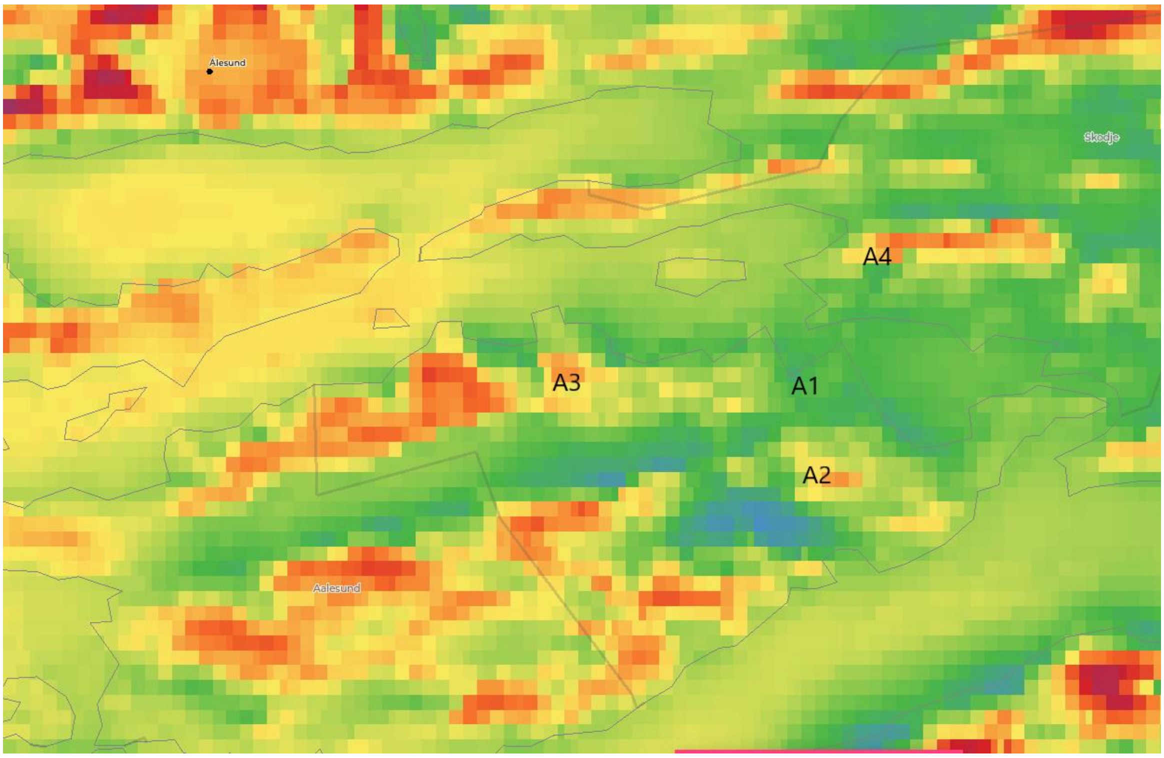

Figure 19 Average wind speed in the region (Global wind atlas)

Based on the average wind speed (Table 7), the business park area (A1) has a too low potential for wind power production. The rest of the areas show more potential. Area A2 that is closest to the business park is in the natural reservation Ørnakken. Area A4 has the highest wind speed.

However, there are other challenges; it is in close proximity to relatively densely populated area, may meet high resistance. Further, it is across the sea connected with the road. Area A3 has a relatively high wind speed, and the population surrounding it is minor.

Table 7: Average wind speed in different height in studied areas

	Average wind speed (m/s)		
	10m	**50m**	**100m**
A1	2.42	4.06	5.03
A2	5.32	6.08	6.66
A3	4.74	6.17	6.81
A4	6.07	6.83	7.37

For the purpose of the evaluation of the possible wind power production, area A3 seems to be the most suitable. Based on the E53 wind turbine data and the average wind speed of 6.17 m/s in the height of 50 meters, the 800kW turbine can produce approximately 2 100 MWh per year (Figure 20). Thus, presenting the possible overproduction of 213 MWh of electricity per year.

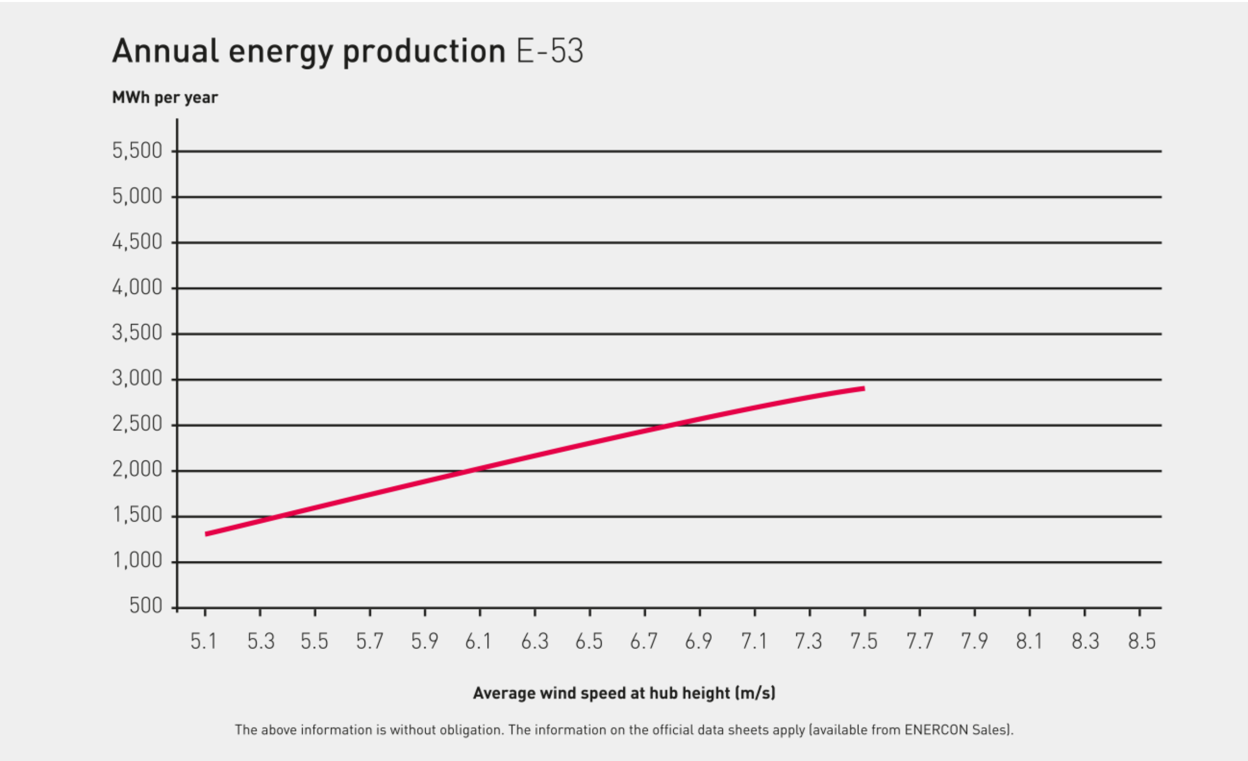

Figure 20: Annual energy production for 800 kW E53 wind turbine(enercon.de)

Based on the total yearly electricity production, the hourly pattern for wind power has been modeled with the help of the energyPLAN and the data for the onshore wind pattern in Denmark that are part of its` database. Figure 21 and the monthly electricity production in

Table 8 show high production from October to January that can compensate for the lower production from the PV field in these months. At the same time, it increases the overproduction of electricity in May and June.

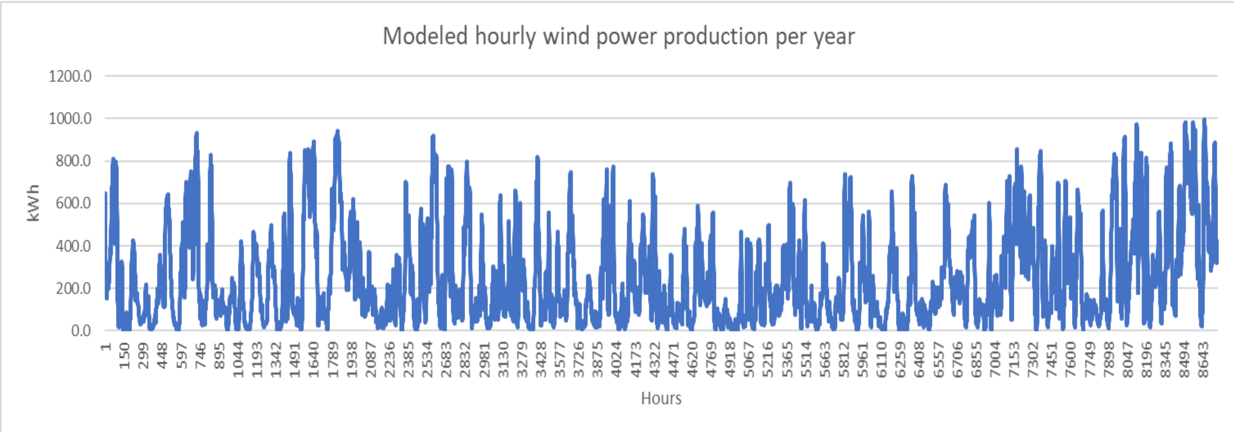

Figure 21: Modelled hourly production of the wind power

Table 8: Wind power production

Month	January	February	March	April	May	June	July	August	September	October	November	December	Sum year
MWh	196.0	115.3	245.4	191.7	133.6	163.8	103.4	134.6	129.8	215.8	189.0	344.5	2162.9

6.2.3. Electricity price analysis

Another source of renewable energy is the electricity from the grid. In 2019 94 percent of the electricity produced in Norway was coming from renewable sources (NVE 2020). Based on the intra-hour balance of the demand and own renewable electricity production, the system needs to rely on importing the electricity from the grid as a balancing power for the variability in the wind and solar production.

Based on the available data from Elspot for the Møre and Romsdal county (Molde), the price variation during the year 2020 was visualized through the graph in Figure 22 and in the Table 9. The price is high during the autumn and winter months and lower during the summer months. Further, the electricity is cheaper during the night, which can be utilized for night charging.

There also exists the possibility to import and utilize the cheaper electricity during the summer months and nights.

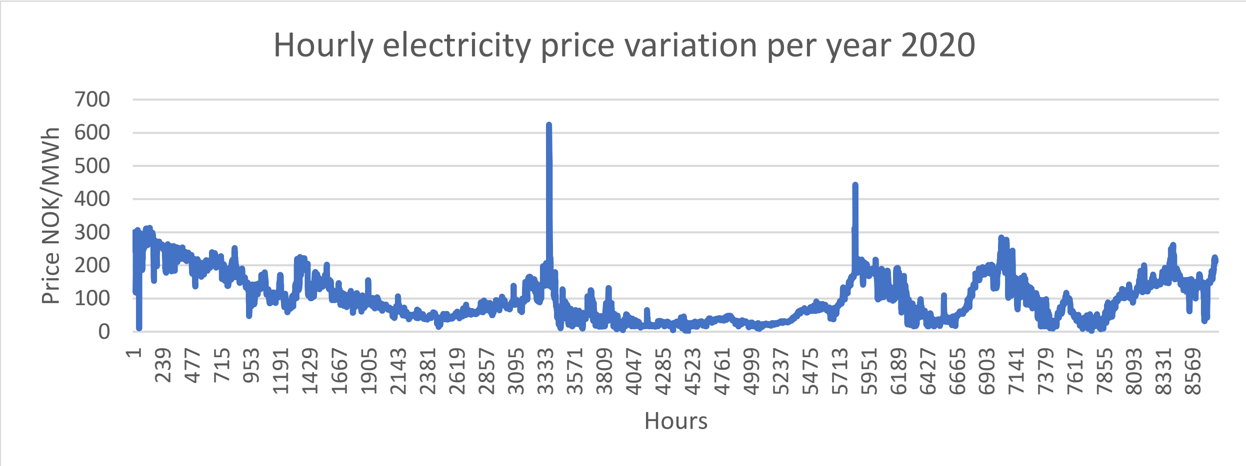

Figure 22: Hourly electricity price variation during the year 2020

Table 9: Average monthly electricity price compared to average electricity price between 6pm and 5am

Month	**Average electricity price NOK/MWh**		**Difference**
	per day	**6pm-5am**	
January	232.93	222.68	10.25
February	139.99	133.44	6.54
March	102.24	99.04	3.20
April	52.45	51.49	0.96
May	97.54	90.83	6.70
June	34.00	29.11	4.89
July	27.11	26.18	0.93
August	61.18	59.27	1.91
September	113.17	105.92	7.25
October	129.16	123.21	5.95
November	55.93	52.32	3.62
December	146.43	144.31	2.12

6.3. Scenarios

For the purpose of further analysis, different scenarios were created.

The charging of the vehicles is assumed to be conductive plug-in via cable with the slow charging of 6.6 kW for the light duty vehicles and fast charging 50 kW for the heavy-duty vehicles. The charging of the vehicles is happening overnight when they are not on duty, also presenting an opportunity to utilize the cheaper electricity from the grid when needed. The charging period for the scenarios is assumed to start at 6 pm for the light-duty vehicles and 8 pm for the heavy vehicles. To balance and reduce the potential load for the grid and to increase flexibility, the cars have been spread over the period of charging. For the same reasons, the 50kW charging for heavy-duty vehicles is being used as a base for the scenarios.

In the hydrogen-based scenarios, the average potential production of 20 kg of hydrogen per 1 MWh for the alkaline electrolysis (DEA, 2020) was used as a basis for the evaluation of the potential production. During AEC electrolysis, there is a heat loss of 21.4 percent of the energy input (DEA, 2020), where 3 percent are unrecoverable, and 18,4 can be recovered for central heating. This presents further opportunities to reduce the consumption of the buildings in the business park.

Table 10: Daily demand for charging of category I and II vehicles with hourly distribution

Charging (kWh)	Hours							
	1	2	3	4	5	6	7	8
Night	217.8	217.8	217.8	214.17	162.29	42.31	33	20.53
Extra (during day)	73.15	15.45	7.15	2				

Table 11: Daily demand for charging of category IIIa vehicles with hourly distribution

Charging (kWh)	Hours							
	1	2	3	4	5	6	7	8
Night	350	398	350	649	434.5	155	0	0
Extra (during day)								

Table 12: Daily demand for charging of category IIIb vehicles with hourly distribution

Charging (kWh)	Hours							
	1	2	3	4	5	6	7	8
Night	550	550	550	550	463.5	250	0	0
Extra (during day)	68.25							

6.3.1. Scenario A

Scenario A works with the assumption that all the cars will be electrified. Therefore, the yearly demand for the charging of these cars will be 369.8 MWh for the groups I, IIa and b, and 705.6 MWh for group IIIa, with 909.9 MWh for the group IIIb, that all together with the demand of the terminal (it is 1 247.1 MWh) makes the total demand on the basis of monthly data 3 232.4 MWh (Table 13).

Table 13: Monthly demand for scenario A

Month	**Demand (MWh)**				
	terminal	**I, II ab**	**IIIa**	**IIIb**	**Total**
January	157.7	31.8	60.7	78.3	328.6
February	116.0	29.4	56.1	72.3	273.7
March	119.8	31.9	61.3	80.8	293.8
April	86.4	28.1	53.2	66.8	234.4
May	85.8	29.4	56.1	72.3	243.5
June	74.5	29.4	56.7	74.8	235.4
July	77.4	33.0	62.5	78.8	251.7
August	82.5	33.1	63.1	81.3	260.0
September	83.6	30.6	58.4	75.5	248.0
October	98.6	33.1	63.1	81.3	276.1
November	138.6	31.8	60.7	78.3	309.5
December	126.3	28.2	53.7	69.3	277.5
Sum	1247.1	369.8	705.6	909.9	3232.4

In order to utilize the lower electricity price, together with the route schedules, the charging overnight between 6 pm and 5 am has been assumed as the best. However, there is also a need for extra charging (during the day) between 12 and 4 pm for some of the cars (Table 14 and Figure 23). Because of the high demand during the charging and to reduce demand peaks in relation to the consumption pattern of the terminal, the charging schedule was divided from 6 pm for groups I and II, and from 8 pm for category III. The charging of the category III was further divided between the hours, trying to hold demand during the charging as low and stable as possible (Table 14). Even though the charging was placed into the hours with lower demand of the terminal's building, the total demand is close to one MWh during the charging (Figure 23).

Table 14: Hourly demand for charging - scenario A

Charging (kWh)	Hours										
	18-19	19-20	20-21	21-22	22-23	23-24	0-1	1-2	2-3	3-4	4-5
Night	217.8	217.8	767.8	764.17	712.3	742.3	696.5	720.53	750	725	236.5
Extra (during day)	12-13	13-14	14-15	15-16							
	141.4	15.45	7.15	2							

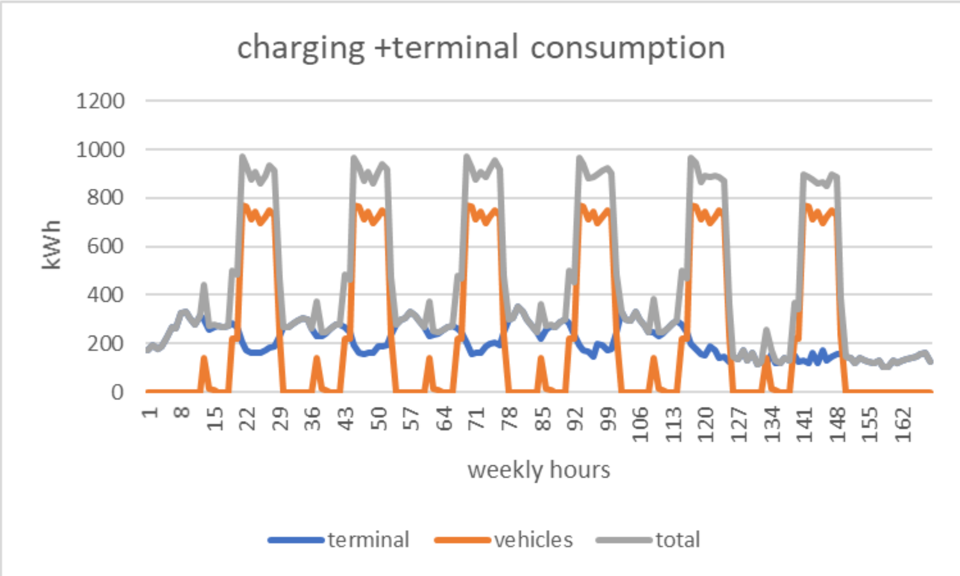

Figure 23: Weekly charging profile with the terminal consumption - scenario A

Comparing the monthly demand with the supply provided by the renewable production will show the high variation during the year, with high overproduction during the summer months with the top of 184 MWh in June and a negative balance during the autumn and winter months with the exception of December, where the wind power production is expected to be high. The total monthly balance seems to be 325.6 MWh in plus (Table 15). Because of the seasonal variation, there is a need for a significant energy transfer between the summer and winter months.

Table 15: Difference between supply and demand based on a monthly balance– scenario A

Month	Demand (MWh)					Supply (MWh)			Difference (MWh)
	terminal	I, II ab	IIIa	IIIb	Total	PV	wind	Total	
January	157.7	31.8	60.7	78.3	328.6	5.8	196.0	201.8	-126.9
February	116.0	29.4	56.1	72.3	273.7	29.1	115.3	144.4	-129.4
March	119.8	31.9	61.3	80.8	293.8	93	245.4	338.4	44.5
April	86.4	28.1	53.2	66.8	234.4	176.2	191.7	367.9	133.4
May	85.8	29.4	56.1	72.3	243.5	255.8	133.6	389.4	145.9
June	74.5	29.4	56.7	74.8	235.4	256.2	163.8	420.0	184.6
July	77.4	33.0	62.5	78.8	251.7	238.5	103.4	341.9	90.2
August	82.5	33.1	63.1	81.3	260.0	178.9	134.6	313.5	53.6
September	83.6	30.6	58.4	75.5	248.0	103.9	129.8	233.7	-14.3
October	98.6	33.1	63.1	81.3	276.1	45.4	215.8	261.2	-14.8
November	138.6	31.8	60.7	78.3	309.5	9.8	189.0	198.8	-110.7
December	126.3	28.2	53.7	69.3	277.5	2.5	344.5	347.0	69.5
Sum	1247.1	369.8	705.6	909.9	3232.4	1395.1	2162.9	3558.0	325.6

On the closer look the intra-day and intra-hour balances are showing the similar seasonal variation (Figure 24, Table 16).

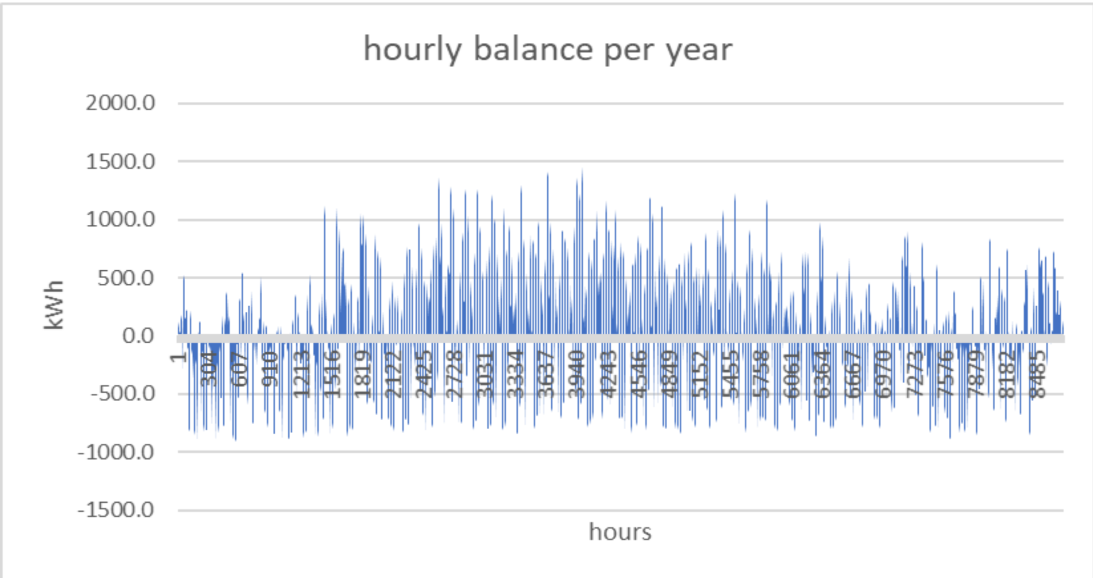

Figure 24: Hourly demand/supply balance Scenario A

The intra-day balances were used for closer evaluation of the data related to the need to import/ export energy into the energy system based on the renewable energy (RE) supply with no storage involved and compared it further with the system that would import the electricity directly from the grid without RE.

The version of this scenario without RE (version A0) covers the yearly demand of 3 232.4 MWh by the import from the grid, which is around 333 360 NOK. In comparison, the version of this scenario with RE (A1) is importing 751.7 MWh per year of electricity from the grid with the price of 98 376 NOK. The relatively higher price is due to the high import during January and February when the electricity price is highest. At the same time, this version of scenario A exports 1 035.5 MWh of electricity. Based on the Norwegian regulation, the sale of more than 100 kWh is not allowed unless the company is registered as an energy production company. Therefore, other buildings at the business park can utilize this electricity in the case they will be integrated into the smart microgrid.

Table 16: Scenario AO and A1 electricity import/export based on intraday balance

Month	**Average electricity price**	**Total import from grid without RE (A0)**		**Import from the grid with RE (A1)**		**Export with RE (A1)**	
	NOK/MWh	**MWh**	**NOK**	**MWh**	**NOK**	**MWh**	**NOK**
January	232.93	328.6	76551.54	154.7	36045.65	24.2	5632.6
February	139.99	273.7	38320.51	145.1	20311.04	12.2	1710.6
March	102.24	293.8	30038.81	68.2	6976.605	109.1	11155.2
April	52.45	234.4	12295.64	15.2	796.8319	145.4	7625.6
May	97.54	243.5	23754.14	0.1	9.023248	142.5	13894.3
June	34.00	235.4	8002.103	1.1	38.55404	183.5	6238.6
July	27.11	251.7	6824.372	9.6	260.1038	95.9	2598.4
August	61.18	260.0	15905.29	24.1	1475.56	73.8	4516.8
September	113.17	248.0	28071.1	77.0	8717.63	59.3	6712.4
October	129.16	276.1	35655.64	64.7	8353.824	46.0	5936.6
November	55.93	309.5	17312.77	140.2	7839.976	25.8	1442.5
December	146.43	277.5	40628.91	51.6	7551.891	117.8	17255.9
Sum		3232.4	333360.8	751.7	98376.69	1035.5	84719.4

In order to balance the variation, reduce the demand peaks and reduce overall export and import, the incorporation of energy storage with the capacity of 1, 2.5, and 5 MWh was simulated based on the intra-day balance. This version is called A2 (Table 17).

Table 17: Scenario A2 import/ export with energy storage of different capacity

Month	Storage MWh											
	1		1		2.5		2.5		5		5	
	Import from the grid		Export		Import from the grid		Export		Import from the grid		Export	
	MWh	NOK	MWh	NOK	MWh	NOK	MWh	NOK	MWh	NOK	MWh	NOK
January	152.2	35457.55	20.7	4811.6	149.2	22715.49	16.2	2459.466	144.2	21954.37	8.7	1317.786
February	142.1	19891.08	10.2	1430.6	137.6	19551.03	7.2	1025.841	130.3	18517.32	2.4	347.3661
March	64.2	6567.653	105.1	10746.2	58.2	3741.166	99.1	6366.646	50.4	3234.837	91.2	5860.316
April	13.0	680.3447	142.2	7456.7	10.0	129.3639	137.7	1786.012	6.8	88.39987	132.0	1712.618
May	0.0	0	142.4	13885.3	0.0	0	142.4	0	0.0	0	142.4	0
June	0.0	0	182.4	6200.0	0.0	0	182.4	0	0.0	0	182.4	0
July	5.2	140.6229	91.4	2479.0	2.7	14.18574	89.0	461.6584	0.2	1.216988	86.5	448.6896
August	19.3	1178.461	69.0	4219.7	13.3	255.4266	63.0	1212.847	6.3	122.2817	56.1	1079.702
September	72.6	8212.971	54.9	6216.9	66.6	4831.361	49.2	3567.995	56.6	4105.637	41.7	3023.703
October	59.7	7710.465	40.9	5282.7	53.2	3175.264	34.2	2041.305	47.3	2821.249	25.8	1538.044
November	134.9	7543.463	21.5	1201.9	128.9	17383.22	17.0	2291.106	120.0	16178.12	10.6	1423.192
December	46.2	6767.899	111.5	16325.4	40.0	1850.819	103.8	4798.342	30.3	1400.196	91.6	4232.16
Sum	709.3	94150.5	992.1	80256.0	659.7	73647.3	941.0	26011.2	592.4	68423.6	871.2	20983.6

The energy storage of low capacity on an intraday basis seems to have a higher effect in the months with higher variation between production and consumption when the storage with a fast response can regulate the demand/supply balance. Hence, decrease the need for the import/export of electricity. The results show that the adding of battery (or flywheel) storage of capacity 1 MWh for balancing will reduce the electricity import by approximately 42 MWh (5.6 percent) per year compared to the version without battery reducing the export by approximately 43 MWh (4.15 percent) per year. However, because of the high imports from the grid during the months with high electricity prices (January and February), the price of the import will be reduced just by 4.3 percent (4 226 NOK). The battery storage of 2.5MWh will reduce the import by 92 MWh (12.2 percent) per year, reducing the price by 25.1 percent (around 24 729 NOK) and at the same time reducing export by 94.5 MWh (9.13 percent). The storage capacity of 5 MWh will decrease the import by 159.3 MWh (21.2 percent) per year, reducing the price by 30.45 percent (29 953 NOK). The export reduction is by 164.3 MWh (15.87 percent). However, the price of battery storage is 10 420 000 NOK per MWh (DEA,2020). Therefore, the battery storages with higher capacities are too costly.

6.3.2. Scenario B

This scenario is based on the possibility of replacing the heavy trucks with the highest demand (IIIb) with FCV, while the rest will be of the vehicles will be BEV. The number of kilometers per day for category IIIb is 1 775, 4. This multiplied by the average consumption of hydrogen of 8 kg per 100 km (DEA, 2020) constitutes the base for the assumed demand of hydrogen and the electricity for its production (Table 18).

Table 18: Monthly demand for hydrogen - scenario B

Month	workdays	km/day	Demand	
			H2 (kg)	MWh
January	26	1775.4	3692.8	184.6
February	24	1775.4	3408.8	170.4
March	26	1775.4	3692.8	184.6
April	26	1775.4	3692.8	184.6
May	24	1775.4	3408.8	170.4
June	24	1775.4	3408.8	170.4
July	27	1775.4	3834.9	191.7
August	27	1775.4	3834.9	191.7
September	25	1775.4	3550.8	177.5
October	27	1775.4	3834.9	191.7
November	26	1775.4	3692.8	184.6
December	24	1775.4	3408.8	170.4

While the direct demand for charging of EVs will be reduced. Incorporating the hydrogen into the system will increase the yearly demand for electricity by 1 263.3 MWh compared to scenario A. The monthly electricity demand is presented in Table 19.

Table 19: Monthly demand for scenario B

Month	**Demand (MWh)**				
	terminal	**I, II ab**	**IIIa**	**IIIb**	**Total**
January	157.7	31.8	60.7	184.6	435.0
February	116.0	29.4	56.1	170.4	371.9
March	119.8	31.9	61.3	184.6	397.6
April	86.4	28.1	53.2	184.6	352.3
May	85.8	29.4	56.1	170.4	341.7
June	74.5	29.4	56.7	170.4	331.0
July	77.4	33.0	62.5	191.7	364.6
August	82.5	33.1	63.1	191.7	370.4
September	83.6	30.6	58.4	177.5	350.1
October	98.6	33.1	63.1	191.7	386.5
November	138.6	31.8	60.7	184.6	415.8
December	126.3	28.2	53.7	170.4	378.6
Sum	1247.1	369.8	705.6	2173.1	4495.6

The reduced demand for charging will allow to reduce the charging time of the EVs of the other categories while also later start for charging in order to utilize the lower electricity price. There is also the need for extra charging during the day, although almost halved in comparison to the previous scenario.

Table 20: Hourly demand for charging - scenario B

Charging (kWh)	Hours										
	18-19	19-20	20-21	21-22	22-23	23-24	0-1	1-2	2-3	3-4	4-5
Night	0	0	217.8	217.8	567.8	612.17	512.3	692.3	467.5	175.53	0
Extra (during day)	12-13	13-14	14-15	15-16							
	73.15	15.45	7.15	2							

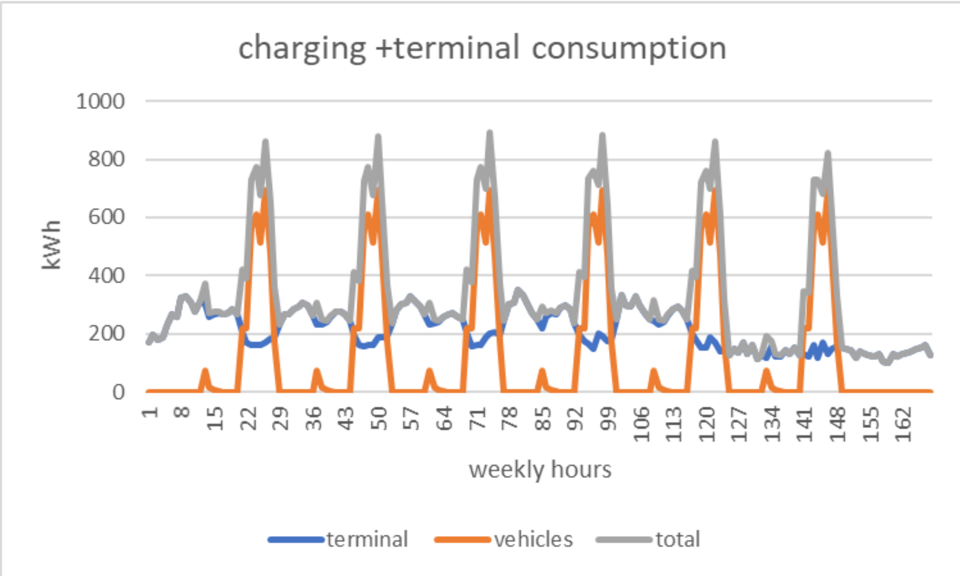

Figure 25: Weekly charging profile with the terminal consumption - scenario B

A comparison of monthly balances in Table 21 shows that the overproduction will not be sufficient to produce enough hydrogen to cover the amount needed for the hydrogen cars. Based on this, the system is lacking 937.6 MWh per year.

Table 21: Difference between supply and demand based on a monthly balance– scenario B

Month	Demand (MWh)					Supply (MWh)			Difference (MWh)
	terminal	I, II ab	IIIa	IIIb	Total	PV	wind	Total	
January	157.7	31.8	60.7	184.6	435.0	5.8	196.0	201.8	-233.2
February	116.0	29.4	56.1	170.4	371.9	29.1	115.3	144.4	-227.5
March	119.8	31.9	61.3	184.6	397.6	93	245.4	338.4	-59.3
April	86.4	28.1	53.2	184.6	352.3	176.2	191.7	367.9	15.6
May	85.8	29.4	56.1	170.4	341.7	255.8	133.6	389.4	47.7
June	74.5	29.4	56.7	170.4	331.0	256.2	163.8	420.0	89.0
July	77.4	33.0	62.5	191.7	364.6	238.5	103.4	341.9	-22.7
August	82.5	33.1	63.1	191.7	370.4	178.9	134.6	313.5	-56.9
September	83.6	30.6	58.4	177.5	350.1	103.9	129.8	233.7	-116.4
October	98.6	33.1	63.1	191.7	386.5	45.4	215.8	261.2	-125.2
November	138.6	31.8	60.7	184.6	415.8	9.8	189.0	198.8	-217.0
December	126.3	28.2	53.7	170.4	378.6	2.5	344.5	347.0	-31.6
Sum	1247.1	369.8	705.6	2173.1	4495.6	1395.1	2162.9	3558.0	-937.6

The hourly balance between RE production and demand in Figure 26 shows an increased number of days with electricity overproduction over the whole year. This is assumed to be utilized to produce the hydrogen needed.

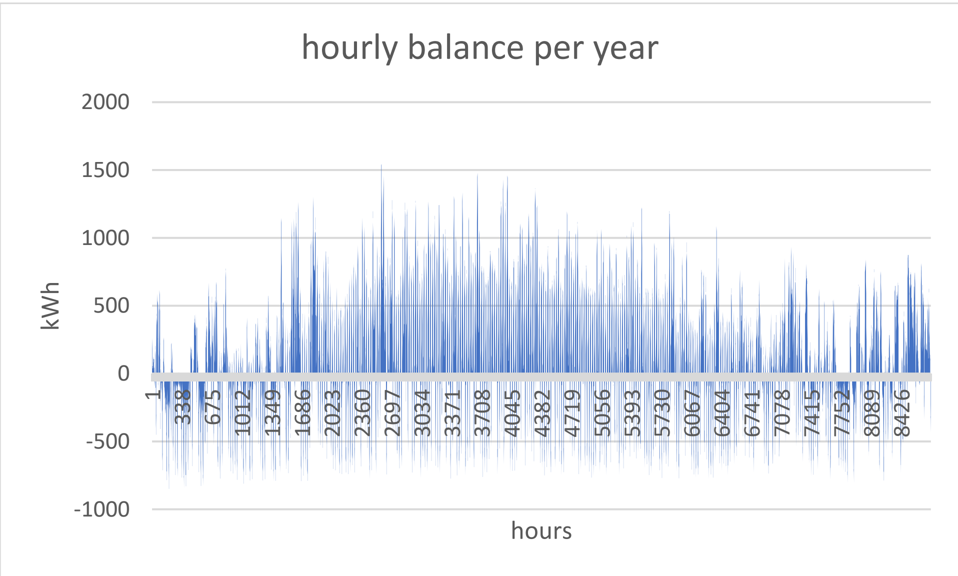

Figure 26: Hourly demand/supply balance Scenario A

The intraday balances are showing the need to import the electricity from the grid. The results show that the system will produce 31 876.8 kg of hydrogen per year, and it will need to import extra 709.3 MWh from the grid to do so. At the same time, there is a deficiency of 634.1 MWh to cover the hydrogen production of extra 11 585 kg hydrogen from the total of 43 461.8 kg. Hence the total demand for extra electricity will be 1 343.4 MWh in this version of the scenario. The difference of 634.1 MWh can be covered by an increase in the capacity for wind production or by the import of electricity from grid. This import presents a possibility to utilize cheaper electricity from the grid during the months with low electricity price (Table 22). The version of this scenario with importing over the whole year without consideration for the price got name B1, and the version with the adjusted import based on cheaper electricity was named B2. The results for B2 show that the price can be in optimal conditions can be reduced by nearly two-thirds when storing it in the form of hydrogen for further use in FCVs, in comparison to the imminent import from the grid.

Table 22: Scenario B1 based on intraday balance

Month	Demand		Import from the		Export /production		Difference	
	MWh	H2(kg)	MWh	NOK	MWh	H2(kg)	MWh	H2(kg)
January	184.6	3692.8	99.0	23048.8	50.4	1007.7	-134.3	-2685.2
February	170.4	3408.8	78.3	10962.0	21.1	422.5	-149.3	-2986.3
March	184.6	3692.8	25.3	2582.0	150.6	3012.2	-34.0	-680.6
April	184.6	3692.8	0.0	0.0	200.3	4005.2	15.6	312.3
May	170.4	3408.8	0.0	0.0	218.1	4361.0	47.6	952.3
June	170.4	3408.8	0.0	0.0	260.5	5210.9	90.1	1802.1
July	191.7	3834.9	0.0	0.0	168.9	3378.5	-22.8	-456.3
August	191.7	3834.9	0.6	38.6	135.5	2709.8	-56.3	-1125.0
September	177.5	3550.8	24.6	2787.0	85.8	1715.1	-91.8	-1835.7
October	191.7	3834.9	24.5	3161.1	90.9	1818.2	-100.8	-2016.6
November	184.6	3692.8	77.8	4351.1	45.4	908.3	-139.2	-2784.6
December	170.4	3408.8	27.6	4035.8	111.5	3327.4	-58.9	-81.4
Sum	2173.1	43461.8	709.3	50966.4	1539.0	31876.8	-634.1	-11585.0

Table 23: Scenario B2, with electricity import price reduction

Month	Average El. price(NOK/MWh)	Import from the grid		Difference/extra demand		Extra import		Extra import with cheaper electricity	
		MWh	NOK	MWh	H2(kg)	MWh	NOK	MWh	NOK
January	232.9	99.0	23048.8	-134.3	-2685.2	134.3	31282.5	0.0	0.0
February	140.0	78.3	10962.0	-149.3	-2986.3	149.3	20900.0	0.0	0.0
March	102.2	25.3	2582.0	-34.0	-680.6	34.0	3476.1	0.0	0.0
April	52.4	0.0	0.0	15.6	312.3	-15.6	-818.2	99.0	5192.1
May	97.5	0.0	0.0	47.6	952.3	-47.6	-4642.7	54.8	5344.9
June	34.0	0.0	0.0	90.1	1802.1	-90.1	-3063.2	40.0	1359.9
July	27.1	0.0	0.0	-22.8	-456.3	22.8	618.1	130.0	3524.0
August	61.2	0.6	38.6	-56.3	-1125.0	56.3	3444.6	56.3	3444.6
September	113.2	24.6	2787.0	-91.8	-1835.7	91.8	10388.9	0.0	0.0
October	129.2	24.5	3161.1	-100.8	-2016.6	100.8	13019.1	0.0	0.0
November	55.9	77.8	4351.1	-139.2	-2784.6	139.2	7786.0	254.0	14207.3
December	146.4	27.6	4035.8	-58.9	-81.4	58.9	8624.6	0.0	0.0
Sum		709.3	50966.4	-634.1	-11585.0	634.1	91015.8	634.1	33072.9

Version B3 investigates the effect of the storage on this system; the three storage capacities were simulated as in scenario A. The results show that the 1 MWh storage can help to utilize more of the energy, halving the base import from the grid and increasing the potential hydrogen production of the system by 640 kg (22.8MWh) per year. However, the whole system is still lacking 611 MWh in order to cover the extra demand for hydrogen production. The results from the simulation show that the storages with higher capacity are further reducing the import, but much less than the 1 MWh version. At the same time, they reduce the potential hydrogen production.

Table 24: Scenario B3 import/ export with energy storage of different capacity

Month	Storage MWh																	
	1		1		1		2.5		2.5		2.5		5		5		5	
	Import		Export /production		Difference		Import		Export /production		Difference		Import		Export /Production		Difference	
	MWh	NOK	MWh	H2 (kg)	MWh	H2(kg)	MWh	NOK	MWh	H2(kg)	MWh	H2(kg)	MWh	NOK	MWh	H2(kg)	MWh	H2(kg)
January	95.9	22330.7	46.3	926.0	-138.3	-2766.8	92.8	21606.7	41.7	833.8	-142.9	-2859.0	87.8	20442.1	34.2	683.8	-150.5	-3009.0
February	74.3	10402.1	17.5	349.5	-153.0	-3059.3	68.5	9595.1	13.2	264.3	-157.2	-3144.5	61.0	8545.2	8.2	164.3	-162.2	-3244.5
March	21.6	2209.0	146.7	2934.3	-37.9	-758.5	17.1	1748.9	142.2	2844.3	-42.4	-848.5	9.6	982.1	134.7	2694.3	-49.9	-998.5
April	0.0	0.0	200.2	4003.0	15.5	310.2	0.0	0.0	198.7	3973.1	14.0	280.3	0.0	0.0	196.2	3923.1	11.5	230.3
May	0.0	0.0	218.1	4361.0	47.6	952.2	0.0	0.0	218.1	4361.0	47.6	952.2	0.0	0.0	218.1	4361.0	47.6	952.2
June	0.0	0.0	260.5	5210.8	90.1	1802.0	0.0	0.0	260.5	5210.8	90.1	1802.0	0.0	0.0	260.5	5210.8	90.1	1802.0
July	0.0	0.0	168.9	3378.5	-22.8	-456.4	0.0	0.0	168.9	3378.5	-22.8	-456.4	0.0	0.0	168.9	3378.5	-22.8	-456.4
August	0.0	0.0	134.9	2697.2	-56.9	-1137.7	0.0	0.0	134.9	2697.2	-56.9	-1137.7	0.0	0.0	134.9	2697.2	-56.9	-1137.7
September	20.6	2334.4	81.8	1635.0	-95.8	-1915.8	14.6	1655.3	75.8	1515.1	-101.8	-2035.7	7.1	806.3	68.3	1365.0	-109.3	-2185.8
October	20.2	2605.1	86.6	1732.1	-105.1	-2102.8	14.8	1907.6	81.2	1624.1	-110.5	-2210.8	9.8	1261.8	87.0	1739.1	-104.8	-2095.8
November	70.8	3959.6	39.4	788.3	-145.2	-2904.5	61.6	3444.5	31.7	633.4	-153.0	-3059.4	52.3	2925.5	11.6	232.9	-173.0	-3460.0
December	23.2	3398.2	161.0	3220.3	-9.4	-188.5	17.2	2519.7	153.6	3071.0	-16.9	-337.8	7.2	1055.4	143.6	2871.0	-26.9	-537.8
Sum	326.6	47239.0	1561.8	31236.0	-611.3	-12225.8	286.6	42477.8	1520.3	30406.6	-652.8	-13055.2	234.8	36018.4	1466.0	29321.0	-707.0	-14140.8

The last version of this scenario - B4, is based on the usage of renewable energy primarily for hydrogen production, with the excess energy used for covering the other electricity demand. The rest of the demand is covered by the electricity from the grid. This version counts on minimal hydrogen production during the months with high demand and high electricity price, producing hydrogen during Sundays and public holidays when there is an excess of the RE in the system. This version is based on the capacity of hydrogen production of 344 MWh per month. However, this capacity will be fully utilized just for four months per year. Reducing the electricity import during the months with a high price, and at the same time maximize the import during the months with a lower price based on the renewable production balance. This will result in covering the hydrogen production from self-produced RE from 100 percent and importing 937.6 MWh from the grid (during the months with lower price in Table 25), for the total price of 62 107 NOK.

Table 25: Scenario B4

Month	RE produced el. (MWh)	H2(MWh)		RE for el. cars (MWh)	Demand terminal+el. cars (MWh)	El. price(NOK/MWh)	El. Import	
		demand	production				MWh	NOK
January	201.8	184.6	10.0	191.8	250.3	232.93	58.6	13639.4
February	144.4	170.4	10.8	133.6	201.4	139.99	67.9	9503.7
March	338.4	184.6	125.4	213.0	213.0	102.24	0.0	0.0
April	367.9	184.6	344.0	23.9	167.6	52.45	143.8	7539.7
May	389.4	170.4	218.2	171.2	171.2	97.54	0.0	0.0
June	420.0	170.4	344.1	75.9	160.6	34.00	84.7	2878.5
July	341.9	191.7	341.9	0.0	172.9	27.11	172.9	4686.0
August	313.5	191.7	313.5	0.0	178.6	61.18	178.6	10927.9
September	233.7	177.5	61.1	172.6	172.6	113.17	0.0	0.0
October	261.2	191.7	66.5	194.7	194.7	129.16	0.0	0.0
November	198.8	184.6	198.8	0.0	231.2	55.93	231.2	12931.8
December	347.0	170.4	138.8	208.2	208.2	146.43	0.0	0.0
Sum	3558.0	2173.1	2173.1	1384.9	2322.5		937.6	62107.0

6.3.3 Scenario C

This scenario follows the same logic as scenario B, with the difference of replacing all of the vehicles of category III with FCVs. Categories I and II will be replaced with BEV. The number of produced kilometers per category III is 3 433 per day. The monthly hydrogen demand is presented in Table 26.

Table 26: Monthly demand for hydrogen - scenario C

Month	workdays	km/day	Demand	
			H2 (kg)	MWh
January	26	3433	7140.6	357.0
February	24	3433	6591.4	329.6
March	26	3433	7140.6	357.0
April	26	3433	7140.6	357.0
May	24	3433	6591.4	329.6
June	24	3433	6591.4	329.6
July	27	3433	7415.3	370.8
August	27	3433	7415.3	370.8
September	25	3433	6866.0	343.3
October	27	3433	7415.3	370.8
November	26	3433	7140.6	357.0
December	24	3433	6591.4	329.6

Adding this extra demand to the existing one will result in an increase of 2 586.5 MWh per year in comparison to scenario A (Table 27).

Table 27: Monthly demand for scenario C

Month	**Demand (MWh)**				
	terminal	**I, II ab**	**IIIa**	**IIIb**	**Total**
January	157.7	31.8	172.4	184.6	546.6
February	116.0	29.4	159.1	170.4	474.9
March	119.8	31.9	172.4	184.6	508.7
April	86.4	28.1	172.4	184.6	471.5
May	85.8	29.4	159.1	170.4	444.7
June	74.5	29.4	159.1	170.4	433.5
July	77.4	33.0	179.0	191.7	481.2
August	82.5	33.1	179.0	191.7	486.3
September	83.6	30.6	165.8	177.5	457.5
October	98.6	33.1	179.0	191.7	502.4
November	138.6	31.8	172.4	184.6	527.5
December	126.3	28.2	159.1	170.4	484.0
Sum	1247.1	369.8	2028.9	2173.1	5818.9

The charging of the BEV in this scenario is assumed to be between 8 pm and 4 am., with extra charging during the day in Table 28, with the weekly profile presented in Figure 27.

Table 28: Hourly demand for charging - scenario C

Charging (kWh)	Hours										
	18-19	19-20	20-21	21-22	22-23	23-24	0-1	1-2	2-3	3-4	4-5
Night	0	0	217.8	217.8	217.8	214.17	162.29	42.31	33	20.53	0
Extra (during day)	12-13	13-14	14-15	15-16							
	73.15	15.45	7.15	2							

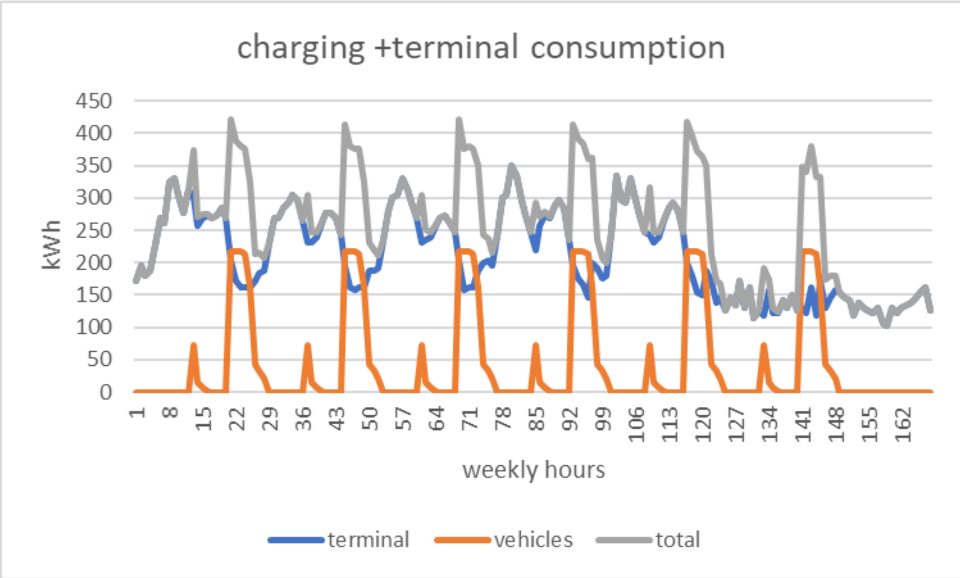

Figure 27: Weekly charging profile with the terminal consumption - scenario C

The supply/demand balance monthly basis shows a negative balance of 2 260.8 MWh per year (Table 29).

Table 29: Difference between supply and demand based on a monthly balance– scenario C

Month	**Demand (MWh)**					**Supply (MWh)**			**Difference (MWh)**
	terminal	**I, II ab**	**IIIa**	**IIIb**	**Total**	**PV**	**wind**	**Total**	
January	157.7	31.8	172.4	184.6	546.6	5.8	196.0	201.8	-344.8
February	116.0	29.4	159.1	170.4	474.9	29.1	115.3	144.4	-330.6
March	119.8	31.9	172.4	184.6	508.7	93	245.4	338.4	-170.3
April	86.4	28.1	172.4	184.6	471.5	176.2	191.7	367.9	-103.6
May	85.8	29.4	159.1	170.4	444.7	255.8	133.6	389.4	-55.3
June	74.5	29.4	159.1	170.4	433.5	256.2	163.8	420.0	-13.5
July	77.4	33.0	179.0	191.7	481.2	238.5	103.4	341.9	-139.2
August	82.5	33.1	179.0	191.7	486.3	178.9	134.6	313.5	-172.8
September	83.6	30.6	165.8	177.5	457.5	103.9	129.8	233.7	-223.8
October	98.6	33.1	179.0	191.7	502.4	45.4	215.8	261.2	-241.2
November	138.6	31.8	172.4	184.6	527.5	9.8	189.0	198.8	-328.6
December	126.3	28.2	159.1	170.4	484.0	2.5	344.5	347.0	-137.0
Sum	1247.1	369.8	2028.9	2173.1	5818.9	1395.1	2162.9	3558.0	-2260.8

The graph of the hourly energy balance (Figure 28) shows the overproduction during the majority of the year, with a more negative balance during the autumn and winter months.

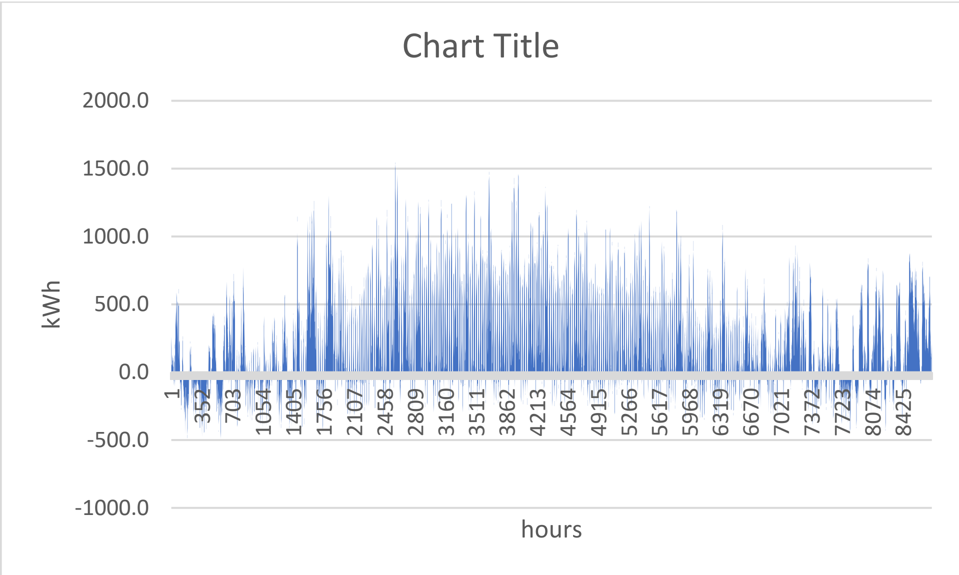

Figure 28: Hourly demand/supply balance Scenario C

The intraday balance in version C1 shows that the existing system can produce less than half of the demanded hydrogen. At the same time, it is importing 164.8 MWh per year from the electric grid. The whole system has a further need to import 2 095.4 MWh per year to cover the deficiency. The capacity of hydrogen production in this version of this scenario will be 371 MWh per month.

Table 30: Scenario C1 based on intraday balance

Month	Demand		Import grid		Export /production		Difference	
	MWh	H2(kg)	MWh	NOK	MWh	H2(kg)	MWh	H2(kg)
January	357.0	7140.6	63.0	14679.0	75.2	1504.0	-281.8	-5636.6
February	329.6	6591.4	37.5	5245.7	36.4	727.3	-293.2	-5864.0
March	357.0	7140.6	3.7	377.6	190.4	3807.7	-166.6	-3332.9
April	357.0	7140.6	0.0	0.0	253.4	5068.2	-103.6	-2072.5
May	329.6	6591.4	0.0	0.0	274.1	5482.6	-55.4	-1108.8
June	329.6	6591.4	0.0	0.0	317.2	6344.2	-12.4	-247.2
July	370.8	7415.3	0.0	0.0	231.4	4628.5	-139.3	-2786.8
August	370.8	7415.3	0.0	0.0	197.9	3958.9	-172.8	-3456.4
September	343.3	6866.0	2.4	271.6	121.9	2438.8	-221.4	-4427.2
October	370.8	7415.3	6.6	851.0	136.1	2722.2	-234.7	-4693.1
November	357.0	7140.6	37.6	2102.0	66.0	1319.1	-291.1	-5821.6
December	329.6	6591.4	14.0	2049.8	206.5	4130.9	-123.0	-2460.4
Sum	4202.0	84039.8	164.8	25576.7	2082.6	41652.5	-2095.4	-41907.5

The total amount of imported electricity in this scenario is 2 260.8 MWh per year at the price of 264 571 NOK per year. This can be possibly reduced by importing more during the months with cheaper electricity (version C2). The results for the hydrogen capacity production of 371 MWh per month show the possibility for price reduction of approximately 26 000 NOK per year on the extra import (Table 31).

Table 31: Scenario C2, with electricity import price reduction

Month	Average El. price(NOK /MWh)	Import from the grid		Difference/extra demand		Extra import		Extra import with cheaper electricity	
		MWh	NOK	MWh	H2(kg)	MWh	NOK	MWh	NOK
January	232.9	63.0	14679.0	-281.8	-5636.6	281.8	65647.2	100.0	23293.0
February	140.0	37.5	5245.7	-293.2	-5864.0	293.2	41044.1	333.0	46615.4
March	102.2	3.7	377.6	-166.6	-3332.9	166.6	17037.6	179.6	18362.0
April	52.4	0.0	0.0	-103.6	-2072.5	103.6	5434.6	116.6	6115.2
May	97.5	0.0	0.0	-55.4	-1108.8	55.4	5407.3	95.9	9350.7
June	34.0	0.0	0.0	-12.4	-247.2	12.4	420.2	52.8	1795.1
July	27.1	0.0	0.0	-139.3	-2786.8	139.3	3777.3	138.6	3756.8
August	61.2	0.0	0.0	-172.8	-3456.4	172.8	10573.6	172.0	10523.5
September	113.2	2.4	271.6	-221.4	-4427.2	221.4	25051.3	248.1	28077.2
October	129.2	6.6	851.0	-234.7	-4693.1	234.7	30307.2	233.9	30207.4
November	55.9	37.6	2102.0	-291.1	-5821.6	291.1	16281.2	304.0	17004.0
December	146.4	14.0	2049.8	-123.0	-2460.4	123.0	18013.7	121.0	17717.7
Sum		164.8	25576.7	-2095.4	-41907.5	2095.4	238995.3	2095.4	212818.1

Version C3 incorporates storage into this system. The three storage capacities were simulated as in the previous scenarios. Although the results show that the 1 MWh storage can help to utilize more of the energy, reducing the import from the grid, not affecting the potential hydrogen production because of the extremely high energy demand in this scenario. The results from the simulation show that the storages with higher capacity are further reducing the import, but much less than the 1 MWh version. At the same time, they reduce the potential hydrogen production, hence increasing the demand for an extra secondary import of electricity.

Table 32: Scenario C3 import/ export with energy storage of different capacity

Month	Storage MWh																	
	1		1		1		2.5		2.5		2.5		5		5		5	
	Import		Export /production		Difference		Import		Export /production		Difference		Import		Export /Production		Difference	
	MWh	NOK	MWh	H2 (kg)	MWh	H2(kg)	MWh	NOK	MWh	H2(kg)	MWh	H2(kg)	MWh	NOK	MWh	H2(kg)	MWh	H2(kg)
January	59.3	13823.7	70.5	1410.5	-286.5	-5730.1	56.2	13084.5	65.9	1317.1	-291.2	-5823.6	51.2	11919.8	58.4	1167.1	-298.7	-5973.6
February	34.3	4800.0	33.2	663.6	-296.4	-5927.8	27.5	3845.9	26.4	527.3	-303.2	-6064.0	19.1	2671.0	20.0	399.8	-309.6	-6191.6
March	1.7	173.1	188.4	3767.7	-168.6	-3372.9	0.0	0.0	186.7	3733.9	-170.3	-3406.8	0.0	0.0	184.7	3693.6	-172.4	-3447.1
April	0.0	0.0	253.4	5068.2	-103.6	-2072.5	0.0	0.0	253.4	5068.2	-103.6	-2072.5	0.0	0.0	253.4	5068.2	-103.6	-2072.5
May	0.0	0.0	274.1	5482.6	-55.4	-1108.8	0.0	0.0	274.1	5482.6	-55.4	-1108.8	0.0	0.0	274.1	5482.6	-55.4	-1108.8
June	0.0	0.0	317.2	6344.2	-12.4	-247.2	0.0	0.0	317.2	6344.2	-12.4	-247.2	0.0	0.0	317.2	6344.2	-12.4	-247.2
July	0.0	0.0	231.4	4628.5	-139.3	-2786.8	0.0	0.0	231.4	4628.5	-139.3	-2786.8	0.0	0.0	231.4	4628.5	-139.3	-2786.8
August	0.0	0.0	197.9	3958.9	-172.8	-3456.4	0.0	0.0	197.9	3958.9	-172.8	-3456.4	0.0	0.0	197.9	3958.9	-172.8	-3456.4
September	0.2	26.5	119.8	2395.4	-223.5	-4470.6	0.0	0.0	119.5	2390.8	-223.8	-4475.2	0.0	0.0	119.5	2390.8	-223.8	-4475.2
October	4.0	514.1	133.5	2670.1	-237.3	-4745.2	2.3	299.9	131.8	2636.9	-238.9	-4778.4	0.0	0.0	129.5	2590.5	-241.2	-4824.8
November	32.6	1822.4	61.0	1219.1	-296.1	-5921.6	26.6	1488.7	55.0	1099.7	-302.0	-6040.9	20.2	1129.1	48.6	971.2	-308.5	-6169.4
December	9.6	1412.3	202.2	4043.9	-127.4	-2547.5	3.7	543.0	196.3	3925.1	-133.3	-2666.2	0.0	0.0	192.5	3851.0	-137.0	-2740.4
Sum	141.8	22572.0	2082.6	41652.5	-2119.4	-42387.3	116.3	19261.9	2055.7	41113.1	-2146.3	-42926.8	90.4	15720.0	2027.3	40546.1	-2174.7	-43493.8

The last version of this scenario (version C4) is based on the usage of the produced renewable energy primarily for hydrogen production, as in the previous scenario with the excess energy used to cover the other electricity demand. The rest of the demand is covered by the import from the grid. The capacity of the hydrogen production here is 420 MWh input per month. The high energy demand of this scenario is giving less flexibility for potential reduction of the price through cheaper electricity purchase.

Table 33: Scenario C4

Month	RE produced el. (MWh)	H2(MWh)				Demand terminal+ el.cars (MWh)	El. price (NOK/ MWh)	El. Import	
		demand	production	difference	transfer			MWh	NOK
January	201.8	357.0	201.8	-155.2	155.2	189.6	232.9	189.6	44163.5
February	144.4	329.6	144.4	-185.2	23.2	145.4	140.0	307.3	43017.8
March	338.4	357.0	338.4	-18.6	0.0	151.7	102.2	170.3	17411.2
April	367.9	357.0	367.9	10.9	-10.9	114.5	52.4	114.5	6005.1
May	389.4	329.6	389.4	59.8	-59.8	115.2	97.5	115.2	11236.1
June	420.0	329.6	420.0	90.4	-90.4	103.9	34.0	103.9	3532.4
July	341.9	370.8	341.9	-28.9	0.0	110.4	27.1	139.3	3776.1
August	313.5	370.8	313.5	-57.3	0.0	115.5	61.2	172.8	10572.4
September	233.7	343.3	233.7	-109.6	0.0	114.2	113.2	223.8	25327.2
October	261.2	370.8	261.2	-109.6	0.0	131.6	129.2	241.2	31152.8
November	198.8	357.0	198.8	-158.2	0.0	170.4	55.9	328.6	18379.9
December	347.0	329.6	347.0	17.4	-17.4	154.4	146.4	154.4	22608.4
Sum	3558.0	4202.0	3558.0	-644.0	0.0	1616.9		2260.9	237183.0

6.3.4. Comparison of the scenarios

To compare the results, the price of the investment into the AEC technology was estimated based on the maximal output of hydrogen produced per day for the different scenarios (Table 34).

Table 34: Investment into the hydrogen for different scenarios, based on the maximal hydrogen production output per day

Scenario	Electrolysis	
	Max. output per month (kg/h2/day	Investment AEC(NOK)
B1	233	3654000
B2	260	4071600
B3	233	3654000
B4	229	3591360
C1	247	3862800
C2	247	3873240
C3	247	3873240
C4	247	3873240

In order to compare the scenarios, the results have been summarized in Table 35. In this comparison, there is no cost related to investment into the PV and wind power included because they are the same for all scenarios, with the exception of scenario A0, which is used as a referral one without the RE production. The results show that there is a need to import electricity from the grid in all scenarios. The implementation of the battery storage is increasing the system efficiency of the scenarios. However, the price for the battery storage is too high compared to the reduced cost for the import of electricity. The smaller battery systems can be utilized in order to balance the power system. From the hydrogen-based scenarios, the most efficient and least costly are scenarios B4 and C4. The B4 also creates more flexibility for utilization of the import of cheaper electricity during the months with low electricity price. The C4, because of the high demand, has this flexibility heavily reduced. Hence the expenses for import are much higher. The main expenses in these scenarios are related to hydrogen storage. Because of the relatively lower expenses concerning the high levels of energy stored over a longer period compared to battery storage, hydrogen storage seems to be a more suitable and cheaper option here.

Table 35: Comparison of different scenarios

Scenario	Supply	Demand		Difference	El. Import		El. Export		Export/import		Battery 1MWh (NOK)	Hydrogen (NOK)	
	RE	total	hydrogen		MWh	NOK	MWh	NOK	MWh	NOK		electrolysis	Storage /MWh
A0	0	3232	0	-3232	3232	333361	0	0	-3232	-333361	0	0	0
A1	3558	3232	0	326	752	98377	1035	84719	284	-13657	0	0	0
A2	3558	3232	0	326	709	94151	992	80256	283	-13894	10420000	0	0
B1	3558	4496	2173	-938	992	141984	0	0	-992	-141984	0	3654000	570000
B2	3558	4496	2173	-938	992	84038	0	0	-992	-84038	0	4071600	570000
B3	3558	4496	2173	-938	938	134254	0	0	-938	-134254	10420000	3654000	570000
B4	3558	4496	2173	-938	938	62107	0	0	-938	-62107	0	3591360	570000
C1	3558	5819	4202	-2261	2260	264572	0	0	-2260	-264572	0	3862800	570000
C2	3558	5819	4202	-2261	2260	238395	0	0	-2260	-238395	0	3873240	570000
C3	3558	5819	4202	-2261	2261	264806	0	0	-2261	-264806	10420000	3873240	570000
C4	3558	5819	4202	-2261	2261	237183	0	0	-2261	-237183	0	3873240	570000

The variation of solar PV power production has extreme highs during the day during the summer months, while the wind power production is higher during the night and autumn and winter months, but still relatively high during summer. This is resulting in high surplus of electricity in summer that needs to be utilized. Therefore, there is a need to store vast amounts of energy during the summer (scenario A) to utilize this during the months with lower RE production. Storing this electricity in the form of hydrogen that will be further utilized when needed presents an opportunity for further development of the energy systems based on renewable energy. Hydrogen production is costly, and a relatively significant part of it is lost during the conversion, but from the point of utilizing the intra-seasonal energy storage seems to be more suitable. At the same time, based on the literature, replacing the heavy trucks with the longest routes and heavy loads should present a better option than a battery-electric one.

7. Conclusion

The external pressure coming from the socio-technical landscape due to the Paris Agreement has aligned with the political landscape and created a window of opportunity for the transition to energy systems on renewable energy. This opens the possibility for new actors and niche technologies to enter the market to replace the incumbent fossil-fuel-based regime. As a result, renewable technology has gained momentum and started to flourish. Consequentially the prices have significantly decreased, and that has further accelerated the deployment of RE. However, renewable technology is still facing challenges regarding the high investment price and incorporation into the existing systems. The main issue with wind and solar power is the seasonal variation and intermittency of the production, creating a need for energy storage and the balancing power from the grid in an energy system based on continuous consumption. The energy storage systems are expensive, and therefore having usually limited capacity. Hydrogen presents a unique opportunity when combined with renewable energy. Hydrogen, being still in the niche position on the market, is facing regulatory, economic, and technological challenges in order to access it. The high price of hydrogen production and storage and the lack of a network of hydrogen filling stations are hindering its further deployment. Although with higher RE penetration of the market and the localized energy production with a surplus of renewable electricity should stimulate the green hydrogen technology deployment. In the meantime, to be market competitive, hydrogen-based projects have to rely on right policy support, and on financial support from ENOVA.

The transport sector in Norway has a vast potential for reduction of carbon emission reduction. As a part of their green strategy, the logistics companies are working on the decarbonization of their business models using renewable energy as a source of clean energy.

In order to answer the main research question of: *How to make the Post/Bring terminal in Digerneset more sustainable with the help of available renewable energy resources.* The supporting research questions will be answered first.

Question nr.1.: What is the energy demand for the terminal and transportation?

The demand for the building of the terminal is 1 247.1 MWh per year for all scenarios, with total demand for transportation being 1 984.9 MWh in scenario A. Constituting the total demand of 3 232 MWh. The total demand is 4 496 MWh for scenario B and 5 819 MWh for scenario C.

The higher demand in these scenarios is because of the hydrogen production, which stands for the increase of 2 173 MWh for scenario B and 4 202 MWh for scenario C.

Table 36: Monthly demand for the different scenarios

Scenario	Demand (MWh)				
	terminal	I, II ab	IIIa	IIIb	Total
A	1247.1	369.8	705.6	909.9	3232.4
B	1247.1	369.8	705.6	2173.1	4495.6
C	1247.1	369.8	2028.9	2173.1	5818.9

Question nr.2.: What is the potential of the available renewable energy sources in meeting this demand?

The yearly solar PV power production of 1 395.1 MWh will not be sufficient to meet the demand standalone. Further, the highest production during the day and the summer months does not correspond with demand for the vehicle's charging. Thus, as a complementary power supply, wind power was added to the system. The potential supply from the wind power is 2 162.9 MWh per year. However, because of the intermittency of this renewable production, the additional import of the electricity from the grid is needed both as a balancing power in scenario A and to meet the extra demand for the production of hydrogen in scenarios B and C (Table 37).

Table 37: Electricity import per scenario

Scenario	El. Import (MWh)
A1	752
A2	709
B1	992
B2	992
B3	938
B4	938
C1	2260
C2	2260
C3	2261
C4	2261

In scenario A, there is also needed to export 1 032 MWh of energy. The sale of more than 100 kWh is not allowed unless the company is registered as an energy production company which means large-scale export is not desirable. In the case of Digerneset it can be assumed that the export can be utilized in other business park buildings. The hydrogen production also presents an opportunity to recover and store part of the energy used for the electrolysis in the form of heat. This can be used to reduce consumption for the heating of the terminal or other buildings during the cold months.

Question nr. 3: What type of scenario is more suitable and profitable?

For scenario A, the scenario with the simulated battery of 1 MWh (A2) utilizes more of the energy from the renewable production, reducing the import from the grid. However, the price of the battery system of 1 MWh capacity is 10 420 000 NOK. Therefore, this version of scenario A seems to be less profitable than A1. The result shows that the incorporation of the battery system will increase the efficiency of the energy system. The battery of a smaller capacity can be added to the system to reduce the cost.

For scenario B, the best and more profitable seems to be version B4, which utilizes primarily renewable energy for hydrogen production, using the rest of this energy to charge the cars. This version utilizes the low electricity price during the year in order to minimize the price of the imported electricity. That all with a lower capacity of the AEC is hence reducing the price of the whole system. The main expenses related to this scenario are related to hydrogen storage.

For scenario C, it is also similar to scenario B. Version C4, using primarily the renewable production for the hydrogen, seems to be the most profitable for this scenario. Because of the high demand, the amount of imported electricity is much higher. That also with the limited capacity of the hydrogen production gives less flexibility in relation to importing the cheaper electricity during the year.

Answering the main research question:

In the light of transforming the transport into a sustainable direction, different technologies can be utilized. Incorporating renewable energy from PV and wind into the energy system creates challenges related to the alignment of the production with consumption. The modeled system overproduces energy during the summer, while the highest demand is during the winter months. The modeled system is further overproducing energy on the yearly balance in the fully electric scenario but underproduces in the case of hydrogen-based scenarios. On the intraday and hourly balance base, there is a need to import energy from the grid to meet the demand in all scenarios. The need for storing surplus energy during the day, between days, and between seasons is heavily increasing the price of the whole system. The storage is improving the efficiency of the system and utilize more of the produced energy. At the same time, it can reduce the extra demand peaks during the charging of vehicles, reducing the cost. The lower prices of the electricity from the grid during the night and summer months present a possibility to reduce the expenses related to electricity import.

Although the FCVs are seen to be more suitable for the longer distances with the heavy freight, the scenarios including hydrogen are further increasing the energy demand, so there is a need for a higher import of the electricity from the grid. There is a significantly higher investment in electrolysis. Because of the disproportion between production and consumption, there is a need for long-term storage of a high capacity to transfer and utilize the produced electricity. Hydrogen is a more suitable and cheaper solution for this, although there is a relatively high energy loss during the production. However, storing the higher amount of energy in the battery is nearly 20 times more costly than storing it in the form of hydrogen. There is also a possibility of utilizing the excessive heat from the electrolysis, thus reducing the expenses related to heating of the buildings. Although the price of storage technology for both batteries and hydrogen is expected to decrease in the future, they will still be connected to high investment and need, therefore policy support and subsidies so they will become competitive.

The results of this thesis cannot be used for generalization, and future more quantitative research is needed. The consumption and financial data are used as an instrument for comparing the scenarios, showing certain trends, but there is a need for further research to investigate the feasibility of energy systems based on renewable energy.

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