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Industrial Electrical Engineering and Automation

EV charging approaches in remote regions

Analysis of capacity, cost and logistics

Juan Ordóñez Marín
Farhaan Ahamed

Division of Industrial Electrical Engineering and Automation
Faculty of Engineering, Lund University

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by

Farhaan Ahamed

(farhaan.ahamed@gmail.com)

&

Juan Ordóñez Marín

(juanor99@gmail.com)

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Supervisor: Fran Márquez
Assistant Supervisors: Lars Palm & Benjamin Berg
Examiner: Mats Alaküla

Preface

The Master thesis has been submitted to fulfil the requirements of the Mechanical Engineering Program. The work has been carried out together with Farhaan Ahamed, who has also submitted the thesis, with LUTMDN/TMHP-23/5532-SE and ISSN 0282-1990, to fulfil the requirements of the Master Program in Sustainable Energy Engineering.

Abstract

With countries across the world finding pathways to counter CO_2 emissions, sustainable mobility has become a critical topic for leaders, policymakers, and industries. The development of Battery Electric Vehicles (BEV's) is seen as an important and effective way through which reliance on fossil fuels and thereby related CO_2 emissions can be reduced. Statistics show that the number EV's on the roads are expected to increase at a very high rate. However, the lack of access to charging stations could prove to be an obstacle for the growth of the EV market and the charging infrastructure must develop simultaneously along with the growth of EV's. Power grids would need to undergo a major overhaul to support the charging infrastructure, in particular infrastructure for fast charging and this process could take many years. The aim of this research is to look at solutions which can be implemented in a short period of time by operating with either a weak grid connection or without any grid support. After carrying out an extensive literature review, this paper investigates the feasibility of charging batteries or generating hydrogen from energy parks in remote locations and using electric trucks for transportation of the same to the charging station. The results show that using ESS packs is more favorable over hydrogen when the distance between the energy park and the station is less while hydrogen performs better when both the overall energy demand and the distance between the energy park and the station is higher. Further on, the sensitivity analysis for both solutions shows that varying certain parameters could help in making the ESS or Hydrogen system more feasible even during unfavorable conditions. With results showing a good scope for both the systems and recent implementation of weak grid ESS powered stations, further analysis can be undertaken to see if these systems work effectively in other industries like the telecom industry.

Acknowledgement

This thesis has been undertaken in partnership with BayWa r.e. We would like to express our gratitude for the opportunity provided by the company, and specifically Benjamin Berg, for placing their trust in us and for their unwavering support throughout these past months.

We are grateful to our supervisors Dr Fran Marquez and Dr Lars Palm for having provided their continuous support throughout the course of the project, especially during points where we felt that our progress was being halted. The experience you all brought in from your respective domains helped us to learn new concepts while also motivated us to perform better. In addition, we thank Lund University and BayWa r.e. who provided us with the necessary workspaces to execute our project work. We are grateful to Dr Mats Alaküla for providing critical feedback when examining our paper.

Lastly, we are greatly appreciative of our respective families and friends who have provided emotional support and played a motivational role in helping us perform well.

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Equations – Nomenclature

Symbol	Representation	Unit
BEV	Battery Electric Vehicle	[-]
SOC	State of Charge	[%]
E_{car}	Energy needed per car charge	[kWh]
E_{day}	Total energy needed per day	[kWh]
N_{cars}	Number of cars per charging station	[-]
$\eta_{battery}$	Battery efficiency	[%]
$\eta_{charger}$	Charger efficiency	[%]
$E_{batteries}$	Energy needed for batteries	[kWh]
E_{pack}	Energy available in each battery pack	[kWh]
$N_{batteries}$	Number of batteries needed	[-]
E_{wind}	Energy required from the wind park	[kWh]
P_{wind}	Power required from the wind park	[kW]
T_{charge}	Time to charge a set of batteries	[h]
$E_{wind\ loss}$	Energy losses from wind park to batteries	[kWh]
$P_{wind\ loss}$	Power losses from wind park to batteries	[kW]
GTW	Gross train weight of a truck	[kg]
P_{kWh}	Price per kWh for ESS	[$/kWh]
$B_{capacity}$	Battery capacity	[kWh]
$CAPEX$	Capital Expenditure	[€]
$OPEX$	Operating expense	[€]
$Cost_{pack}$	Cost per battery pack	[€]
$E_{consumption}$	Energy needed in the wind park	[kWh/day]
$E_{electrolyzer}$	Energy needed in the electrolyzer	[kWh/day]
$E_{compressor}$	Energy needed in the compressor	[kWh/day]
$E_{charging}$	Energy needed for charging trucks	[kWh/day]
$E_{W.Farm}$	Daily energy needed from the wind park	[MWh/day]
$\eta_{W.FarmLosses}$	Losses from wind park to electrolyzer	[%]
$Elec_{consumption}$	Electrolyzer consumption	[kWh/kg$_{H2}$]
LHV_{H2}	Low Heating Value of Hydrogen	[kWh/kg$_{H2}$]
$\eta_{electrolyzer,\ electrical}$	Electrical efficiency of the electrolyzer	[%]
$Elec_{losses}$	Losses in the electrolyzer	[kWh/day]
$H_{2,\ production}$	Daily production of hydrogen needed	[kg/day]
$Elec_{consumption}$	Compressor consumption	[kWh/kg$_{H2}$]
$n_{working\ hours}$	Number of working hours of the compressor	[hours/day]
$Comp_{losses}$	Losses in the compressor	[kWh/day]
$\eta_{compressor,\ electrical}$	Electrical efficiency of the compressor	[%]
$Distance_{run}$	Distance to be covered by the truck per run	[km/run]
$N_{fuel\ cell(s)}$	Number of fuel cells needed in the process	[-]
$E_{fuel\ cell}$	Energy obtained in the fuel cell per run	[kWh/run]
$\eta_{fuel\ cell,\ electrical}$	Electrical efficiency of the fuel cell	[%]
$Fuel\ Cell_{losses}$	Losses in the fuel cell(s)	[kWh/day]

$N_{chargers}$	Number of chargers needed	[-]
$FCEV$	Fuel Cell Electric vehicle	[-]
$PLDV$	Passenger long distance vehicle	[-]
ESS	Energy Storage Solution	[-]
η_{panel}	Panel efficiency	[%]

Table of Content

1. Introduction

1.1 Background

As the Nordic countries stand out for their successful implementation of renewable energy, electric vehicles can be utilized to their complete potential to ensure carbon neutrality during the operation of a vehicle. Norway, which boasts the highest EV ownership per capita has leveraged from a right set of policy instruments which steered the country's population towards purchasing electric vehicles. These include heavy purchase taxes on polluting vehicles in addition to the Value added tax (VAT) which in turn helped the government to incentivize the purchase and usage of EV's. Some of the incentives include cheaper parking fares, lower toll fares and the ability to use bus and taxi lanes on some of the country's roads. Moreover, motorists have been exempted from paying any purchase tax or VAT until the start of this year where about 25% VAT was added to vehicles that have a selling price of more than 500000 NOK [1].

While policy instruments have helped in expediting the process towards electrification in Norway, the government does acknowledge that a more robust fast-charging network needs to be in place for ensuring that motorists can undertake long distance trips without major disruptions during their journeys. As of 2022, there are about 5600 fast charging points installed throughout the country and there is a roadmap in place to increase this number in the coming years [2]. Hence, electrification of vehicles in the coming decades would also mean that a complete overhaul of infrastructure as many fueling stations would need to either have or be replaced completely by charging stations.

Sweden, Norway's Scandinavian neighbor is trailing in the race towards electrification with the EU parliament aiming towards selling 100% zero emission vehicles by 2030 [3]. Energiforsk, a Stockholm based research firm carried out a scenario-wise forecasting for the growth of EV's in Sweden. During the study, it found that the lack of charging infrastructure development could be one of the biggest obstacles towards achieving 100% electrification by 2030. This can further be attributed to the time required for obtaining land permits and increasing the access to grid capacity. The grid capacity does pose a challenge as the incorporation of renewable energy would require major upgrades in the grid system. Grid upgrades generally require a large amount of time for permits and installation.

In addition, the rapid electrification of the automotive industry would result in higher peak loads, beyond the available capacity in certain areas of the grid supply [4]. As a result, drivers would need to take cognizance of this fact and charge their vehicles during times where the loads are not very high, and this would be recommended in areas where the grid is not very strong. Hence, this would result in a situation where people travelling through or living in areas with either zero or weak grid/low voltage connections would refrain from purchasing an electric vehicle thereby dampening the Swedish prospects of achieving 100% electrification by 2030.

To consider fast-charging options in areas with weak or no grid connections, alternative solutions need to be devised and while some contemporary solutions already exist, the idea is to investigate nascent solutions that can potentially be implemented on a large scale. These solutions would involve the usage of batteries or fuel cell systems that obtain their power from solar/wind parks present in Sweden. As a result, a robust supply chain plan needs to be considered in order to transport the batteries/hydrogen from the wind/solar farm to the charging station.

1.2 Objective

The goal of this thesis is to explore the economic feasibility of different solutions for off/weak grid EV charging stations in different scenarios. Common to all scenarios is the fact that the electricity used for EV charging is produced in large renewable energy parks, and then transported to the charging stations as required. Both portable battery modules and hydrogen are considered as energy carriers. For each scenario, the capital investment as well as the operational costs, including the supply chain processes are calculated. The following key research questions will be answered through this paper:

1. Which are the important parameters to consider in a business case to determine the level of profitability of different solutions?
2. How can we build synergies between off/weak-grid charging station and renewable energy parks that exist in Sweden?

In addition, several sub level research questions are answered in this paper. They include:

1. How can we supply the batteries or the renewable fuel (in case of fuel cells) from the production facility to the designated charging stations?
2. How could these solutions contribute to the development of the renewable EV market and as well as wind and solar power production?

1.3 Method

The method is to develop parametrized models of the necessary processes to supply energy to EVs in remote areas with no grid or with a weak grid connection using either portable batteries or hydrogen. These models are later used in a parametric study in order to answer the research questions listed before. All models in this thesis have been created in MS Excel.

1.4 Delimitations

The solution model carried out and which will be explained below, has been used as a means for the subsequent obtaining of results and analysis of different situations, this being the main objective of the elaboration of this thesis. Therefore, a simple solution model has been elaborated and always focused on giving priority to the simulation of different scenarios. A series of assumptions and the use of values obtained through the company have been made to facilitate its execution.

The process analyzed is something that could be implemented years ahead and with potential profitability in the future. Nowadays, it is very unlikely to find technologies in the market that meet all the requirements in each of the phases. This is another reason why in different aspects it has been necessary to resort to certain assumptions and, as previously mentioned, always keeping in mind the real target of the elaboration of this work, the analysis and discussion of different situations.

As different scenarios with emerging technologies are explored, the pricing information is obtained mostly from information available in literature while some information is advised by BayWa r.e. based on their experience. The energy transfer and conversion process have been modeled through their efficiencies which is deemed sufficiently accurate for the purpose of this study. To simplify the process, only one ESS system is considered for the battery solution and this system stood out for its modularity and energy density.

Härnosand municipality has been considered as a sample remote location as a suggestion from BayWa r.e.

In the supply chain aspect of the solution, it is assumed that the number of trucks transporting energy (stored in portable batteries or hydrogen tanks) between the production site and the charging station does not exceed three in all scenarios.

2. Theory

2.1 Energy Market

2.1.1 Energy Mix

There are several factors that will have a direct impact on and shape the global energy mix in the years to come. Despite the increasing commitment of governments and businesses to decarbonization, energy markets are experiencing extreme volatility due to geopolitical tensions and a rebound in demand, leading to significant price fluctuations. The situation is exacerbated by the uncertainty surrounding supply security and affordability, triggered by the conflict in Ukraine and other factors. Furthermore, global energy demand and emissions have risen by 5% in 2021 [5], nearly reaching pre-COVID levels, following the COVID-19 rebound. Despite these challenges, the fact that 64 countries, accounting for 89% of global CO_2 emissions, have pledged to achieve net-zero emissions and that financial institutions and private sector enterprises are stepping up their decarbonization efforts is encouraging, especially in the context of COP26.

In the future, the energy mix is expected to shift towards power, synfuels and hydrogen. By 2050, electricity and the mentioned alternative fuels are predicted to make up 50% of the energy mix [5]. The demand for electricity is expected to triple by 2050 due to increased electrification in different sectors and the rise of decarbonized hydrogen and fuel markets. Renewable energy sources like solar and wind power are expected to contribute 80-90% of the global energy mix by 2050 with solar and wind power generation growing by five and eight times respectively [5]. In addition, there could be a significant increase in hydrogen demand from new sectors, reaching 350-600 million metric tons per annum by 2050 compared to approximately 80 million metric tons per annum today. The demand for sustainable fuels is also expected to increase and reach 8-22% of all liquid fuels by 2050.

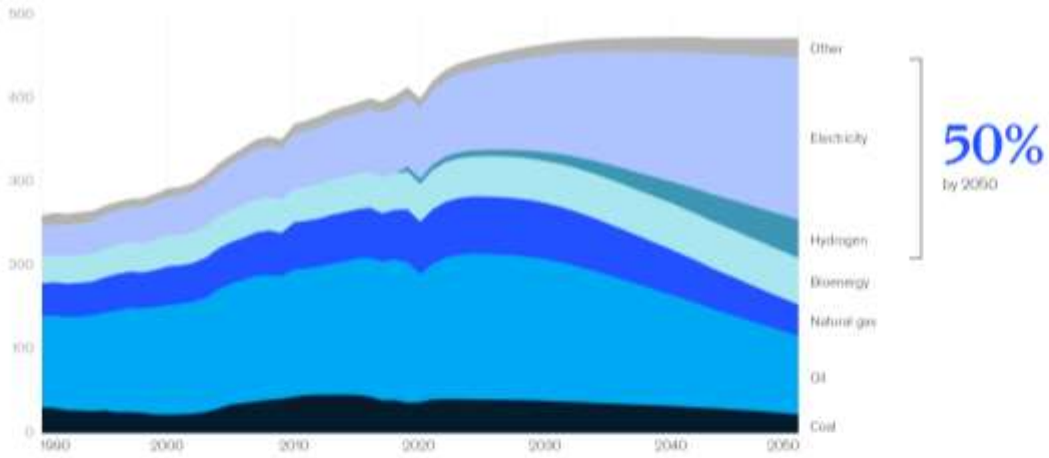


Figure 1. Final energy consumption per fuel, million TJ [5]

The demand for oil is projected to reach its peak between 2024 and 2027, driven by the increasing uptake of electric vehicles, while coal demand is expected to continue its downward trend. Gas demand is projected to grow by 10-20% until 2035, after which it may face larger uncertainties due to its interplay with hydrogen [5]. To decarbonize heavy industries where fossil fuels play a significant role, CCUS (Carbon Capture, Usage and Storage) will need to capture two to four Gt of CO_2 by 2050. The ongoing conflict in Ukraine has led to price spikes as consumers balance supply security and affordability.

Global warming is projected to reach 1.7°C by 2100, even if all countries with net-zero commitments deliver on their aspirations. To keep the 1.5° pathway in sight, the global energy system may need to accelerate its transformation significantly, shifting away from fossil fuels towards efficiency, electrification, and new fuels, quicker than even the announced net-zero commitments. Investments in the energy sector are expected to increase by over 4% annually and will be focused more on non-fossil fuel and decarbonization technologies. However, the returns on these investments are still uncertain [5].

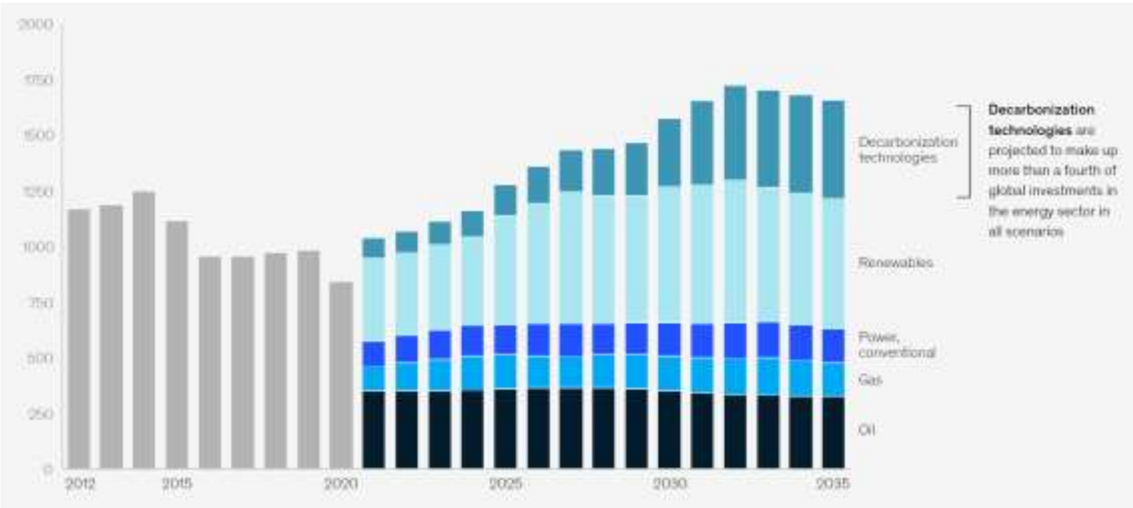


Figure 2. Global energy investments, $ billion [5]

Regarding the current situation in Sweden, The Swedish Energy Agency, entrusted with the responsibility of Energy Statistics, provides a comprehensive overview of the energy system in Sweden, comprising the supply, transformation, distribution, and consumption of energy. Renewable energy sources, such as hydro, wind, solar, and biofuels, constitute the predominant domestic energy sources utilized in Sweden. However, the country also relies on imports of nuclear fuels, biofuels, and fossil fuels, including oil and natural gas. The Swedish energy system may be categorized into two distinct areas - the supply and consumption of energy - representing energy generation, distribution, and consumption, respectively.

The energy system operates in a state of equilibrium, where the total energy input remains equivalent to the energy consumed, factoring in any associated losses. The Swedish energy system has remained relatively consistent since the mid-1980s, with an annual energy supply hovering between 550 to 600 TWh [6].

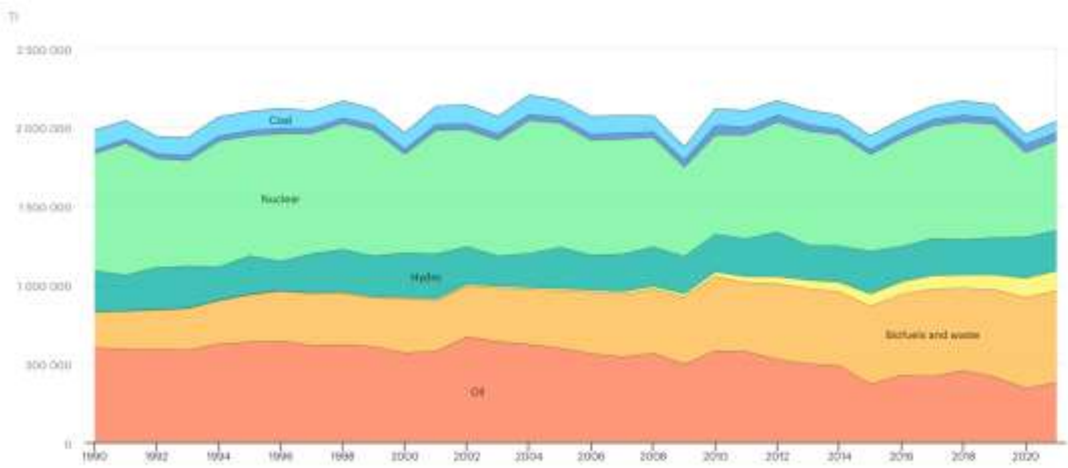


Figure 3. Total energy supply (TES) by source, Sweden 1990-2021 [7]

If we pay attention to the data obtained in the year 2021, the total consumption by source was a total of 605 TWh. The data show that Sweden is one of the countries with the highest share of energy from low-carbon sources, defined as the sum of nuclear and renewable sources, with approximately 88.5%. Of the total share, renewable energy accounts for 65% approximately. These usually include hydropower, solar, wind, geothermal, biomass and wave and tidal energy. At present, fossil fuels (combination of coal, oil and gas) represent 28.07% and it is important to mention that 50 years ago the percentage was 75%, nuclear energy consumption represents 21.01% of the total in 2021 [8].

Sweden is at the forefront of decarbonization efforts and has set ambitious goals to reduce greenhouse gas emissions by 59% by 2030 compared to levels in 2005. Furthermore, Sweden aims to achieve a carbon-neutral economy by 2045 [7]. As a pioneer in the field, Sweden implemented the first carbon pricing system in the world and currently boasts the highest carbon price globally. This effective pricing system has been instrumental in driving decarbonization efforts in the country.

2.1.2 Power grids in Sweden

The grid system in Sweden can be divided into three segments based on the level of voltage the system is capable of transmitting. The regional and national grids are capable of transmitting voltages of 130 kV and 220-400 kV respectively while the local grids transmit smaller voltages that do not exceed 20 kV [4]. The operators of these systems too can vary based on the type of grids. While national grids are operated by public authorities, regional grids are operated by companies like Vattenfall Eldistrubution and local grids are operated by municipal authorities. From a stability perspective, these grids are extremely stable with 99.98 % of electricity requested by the customers being supplied [9].

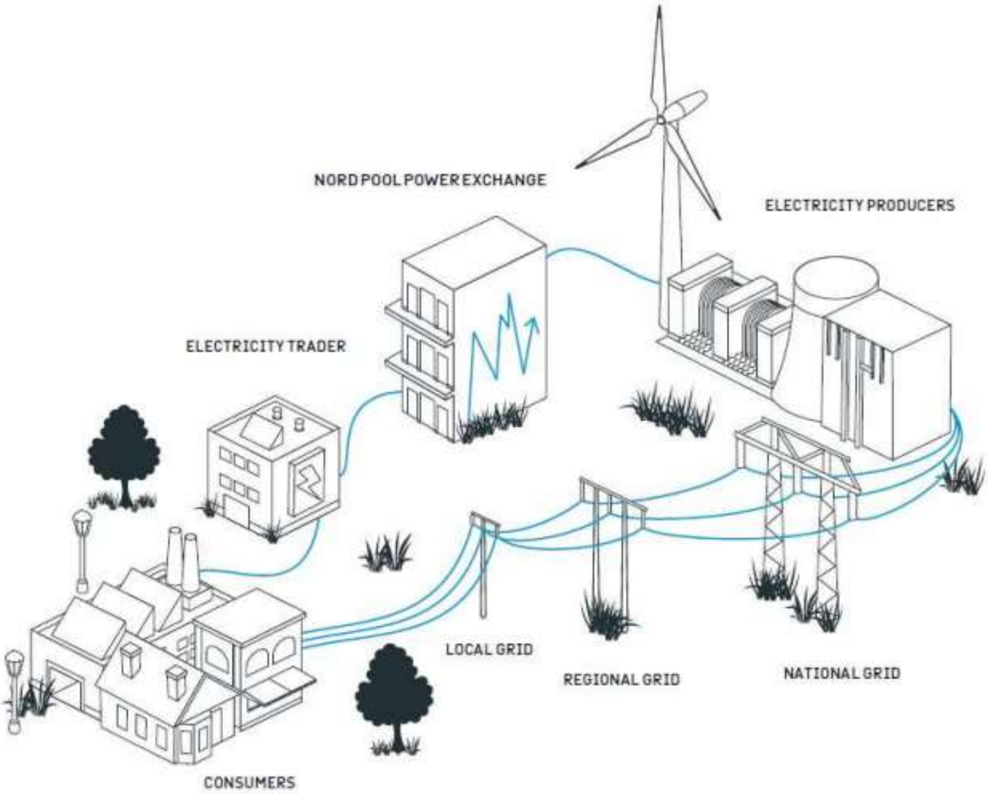


Figure 4. Illustration of Sweden's power grid market [9]

With the rapid increase in the implementation of renewable energy, it is expected that grid upgrades will be required at all segments to facilitate this transition [9]. Furthermore, the electrification of vehicles and the expansion of charging infrastructure would also require installations of new power lines and an overhaul of the power infrastructure. To add on to this, the electrification would result in higher peak loads, beyond the available capacity in certain areas of the grid supply and vehicle owners would need to take cognizance of this fact and charge their vehicles during times where the loads are not very high, and this will be recommended in areas where the grid is not very strong [4].

Sector	Today's electricity use 2013 [TWh]	Estimated electricity use beyond 2030 [TWh]
Households and services	71	65-85
Industry (including data centres)	51	50-60
Transportation	3	10-16
Other electricity use	4	3-4
Total electricity use excluding grid losses	129	128-165
Total electricity use including grid loses	139	140-180

Table 1. Projected energy use in Sweden [4]

Grid upgrades can be a complex process from a time perspective. A simple local grid requires an upgradation time of up to two years while regional and national grids take much longer with such upgrades requiring between 10-15 years [10]. This timeframe will dampen the prospects of expediting the expansion of charging infrastructure especially in areas where the grid is weak or totally absent. Hence, the upgrading time coupled with higher peak demands plays a motivational role in considering off/weak grid charging solutions as these solutions are easier to implement thereby providing a viable alternative platform for fast charging vehicles.

2.2 Projected growth EVs

2.2.1 BEVs

With EV's becoming more affordable, incentives being provided by governments of countries, increase in choice of vehicles and commitment towards sustainability and net-zero emissions are major factors that will drive the growth of the EV industry in the coming decades. This shift towards electric vehicles is being spearheaded by China with 13.8 million or more than 50 % of the worlds EV's being found in this country. Successful implementation of incentives, which include support in purchasing, easy registration process coupled with more accessible charging infrastructure has helped the country to become a world leader in EV's. Hence, China has already exceeded its 2025 target of 20% sales in what it calls New Energy Vehicles (NEVs) as more than 29% of the vehicles sold in 2022 were EV's [11].

When segmenting EV's between Battery Electric Vehicles (BEV) and Plug-In Hybrids (PHEV), the growth levels of BEV's are projected to be much higher than PHEV's. Furthermore, more than 70% of the EV's found in today's roads are BEV's thereby making them a dominant upcoming technology in the coming years. Europe is one exceptional area where PHEV's still form significant numbers with close to 44% of all EV's being PHEV's but these numbers are expected to plunge in the coming decade as automakers concentrate more firmly on BEV'S [11].

Despite seeing a contraction in total car sales during the year 2022, EV sales in Europe increased by 15% when compared against the previous fiscal year. This growth was primarily steered by the rise in sales of BEV's, which went up by 30% relative to the previous year while the sales of PHEV's went down by 3%. While the growth rates for EV's in Europe went down when compared to the exceptional growth rates that averaged around 40% between 2017-2019 and 65% in 2021, this region will continue in contributing to the increase in the number of EV's as stronger emission targets under the "Fit for 55" package will help in improving the prospects for such vehicles. The Scandinavian countries of Norway and Sweden lead in selling EV's with more than 88% and 54% of the vehicles respectively sold in the country being electric and these figures were distantly followed by the Netherlands, Germany, the UK and France whose sales shares were between 20-30 % [11].

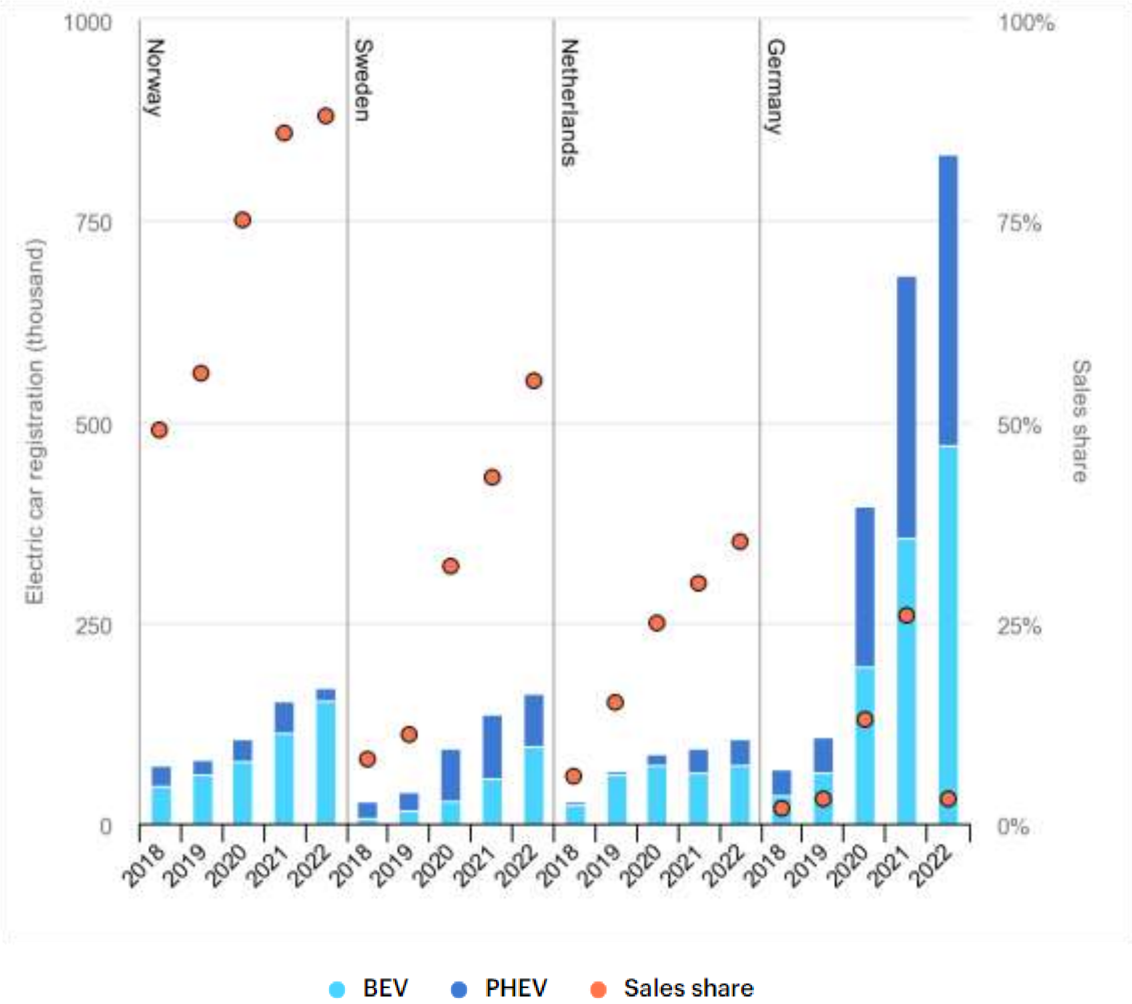


Figure 5. New Electric car registrations in selected European countries [11]

Sweden, currently has around 204,000 BEV's and 241,000 PHEV's as of Q1 2023, with the former seeing a rise by 85% in just over a year's time [12].In the coming decade, it is expected that BEV's in the country will outnumber the number of PHEV's. Energiforsk, carried out a scenario analysis to project the growth of EV's in Sweden and found that under a high scenario, it is expected that the national government targets will be met with and that every new car sold in the country by 2023 will be electric if incentivization on the usage of electric vehicles and popular local manufacturers like Volvo continue to develop and promote EV's thereby helping towards achieving a price parity with respect to ICE powered vehicles . If the measures are implemented successfully, It is projected that around 3 million (2.5 million BEV's and 0.5 million PHEV's) EV's will be found throughout the country by 2030, accounting for almost half of all vehicles present [13].

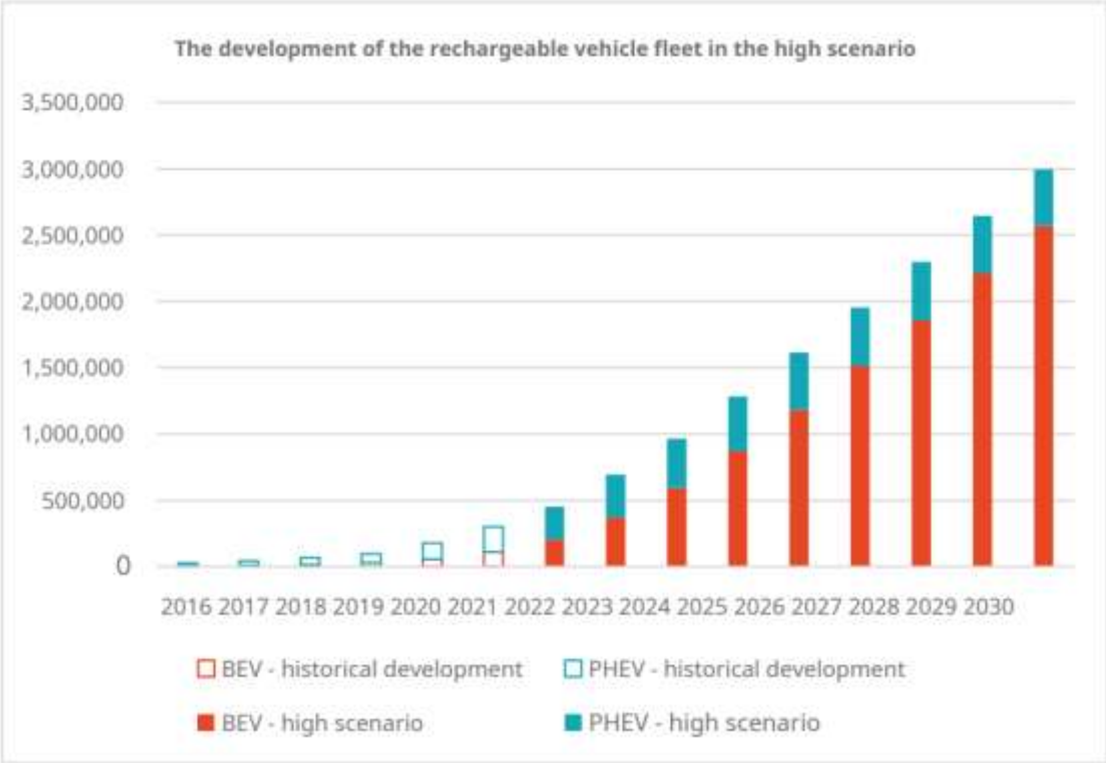


Figure 6. Projected number of EV's in Sweden under a high scenario [13]

This report has, however, found potential roadblocks that could dampen the country's prospects towards achieving its national targets by 2030 [13]. Firstly, it is vital for the government to continue incentivizing potential customers as this will play a pivotal role in motivating people towards purchasing EV's. However, due to a rapid increase in EV purchases, the government ran out of their 2022 incentive budget during the start of the year itself. As a result, the government plans on reducing the incentives from 70K SEK to 50K SEK for BEV's and from 20K to 10K SEK for PHEV'S during fiscal year 2023 in addition to adding ceiling caps for supporting the purchase of expensive EV's [13]. It is to be seen whether a reduction in incentives would have an impact on the EV sales in the coming years.

Another key topic of concern, which centers around the topic of this paper is the lack of access to charging infrastructure. According to a nationwide survey carried out by LeasePlan in 2021, 34% of the respondents were skeptical of purchasing an electric vehicle due to lack of adequate charging infrastructure available in the country [3]. Moreover, the company also found that, Sweden still struggles with adequate charging infrastructure and more development needs to be undertaken. According to the "Fit for 55" package stipulated by the European Union (EU), access to charging infrastructure is vital and having charging stations every 60 kms should be in the road map for all member states. While fast charging can help in expediting the EV ownership process, majority of the people living in Sweden still prefer to charge their vehicles at home and not having access to charging points was one of the biggest obstacles for purchasing an EV in 2021.

From an overall perspective, the growth prospects for BEV's throughout Sweden and the world seem to be promising and it is vital for international agencies, local governments, and communities to promote the usage of EV's to ensure greater levels of carbon neutrality and provide an effective pathway towards net-zero emissions in the automotive sector. If all stakeholders work in close cooperation, the projected number of EV's is expected to be around 240-250 million on a worldwide scale with BEV's accounting for almost 75% of the projected EV figures. The projection of PHEV's may not be as promising as BEV's but more than 50 million PHEV's are expected to be found on the roads by 2030, up from the current 11.6 million figure [11]. While BEV's will be the preferred choice among car manufacturers for promoting sustainable mobility, fuel cell technology has also been a topic of interest among auto makers and hence it will be interesting to see how the growth of such vehicles is projected in the coming decade.

2.2.2 FCEVs

Proposed as an alternative to BEV's, Fuel Cell Electric Vehicles (FCEV's) have been a topic of research and discussion over the past decade with Toyota leading the R&D work that is taking place for PLDV's [14]. This technology uses hydrogen to generate electricity rather than relying on battery charging for powering the vehicles. Currently, there are just 25 thousand FCEV's found throughout the world and most recognized FCEV, the Toyota Mirai costs about 50000 USD with the company also providing 15000 USD or approximately six years of free hydrogen supply [15]. The momentum for FCEV's has not picked up when compared to BEV's and there could be reasons attributed to this.

While charging EV's does remain an issue, the world has been working to enhance and find solutions for charging electric vehicles. However, the same level of importance has not been given to setting up hydrogen stations with just over 730 charging stations being found throughout the world by the end of 2021 [16]. This will play a pivotal role in discouraging people from purchasing FCEVs as PLDV's in the years to come if infrastructural overhauls are not undertaken.

Lack of variety in vehicles and high capital expenditure could possibly be another roadblock towards considering FCEV's. Unlike BEV's, which come in a wide range of segments and prices which start even as low as 25K USD, the options for FCEV's remain limited and prices do not start from below 50K USD. The heavy price tag can be attributed to the costs involved in developing fuel cells as they require the usage of expensive metals like Platinum and Iridium which tend to be used as catalysts in fuel cells [17]. Unless further development is undertaken, price parity is achieved and auto makers consider FCEVs as a potential prospect to enhance sustainable mobility, FCEV's are not expected to gain momentum in the coming decade. As a result, the growth rates are expected to be much lesser for FCEV's as PLDV's than BEV's with the projected number of vehicles expected to fall between 750k – 900 k vehicles by 2030 [18]. More than 60% of the FCEV's found today are in either South Korea or the USA with another 17% being found in Japan. Hence, it can be said that FCEV's do not have the global appeal that is seen in BEV's and this trend is expected to continue in the coming decade [16]. The scenario for fuel cell powered heavy vehicles is expected to differ since compressed hydrogen has a high energy density thereby providing high amounts of energy for the volume of hydrogen fueled in. However, this technology in heavy vehicles is expected to come into commercial production only during the second half of this decade [19].

2.3 Charging infrastructure in Sweden

One of the foremost components of the global energy transformation aimed at reducing atmospheric emissions is the electrification of transportation. Moreover, studies have proven that as time passes, the cost of electric vehicles will decrease while simultaneously exhibiting greater efficiency than their traditionally fuel-powered counterparts. As we move towards widespread electrification of transportation, it is crucial to consider the potential challenges that may arise in the coming years [20]. One key factor that will play a determining role in this transformation is battery technology. The battery not only dictates the range and charging time of the vehicle, but also has a significant impact on the overall lifespan and reliability of the vehicle. As such, continued advancements in battery technology will be critical to overcoming the challenges and unlocking the full potential of electrification [21].

The acceleration of the adoption of electric vehicles depends on the growth of charging infrastructure, which is crucial for their widespread use. Despite some cities and regions starting to invest in charging infrastructure, it is clear that there is still a long way to go. Ensuring that charging stations are available and easily accessible should be a top priority to promote the success of the electrification of transportation. By providing drivers with access to charging stations, they will feel more confident in making the switch to electric vehicles, which will help drive the demand and market growth for electric cars.

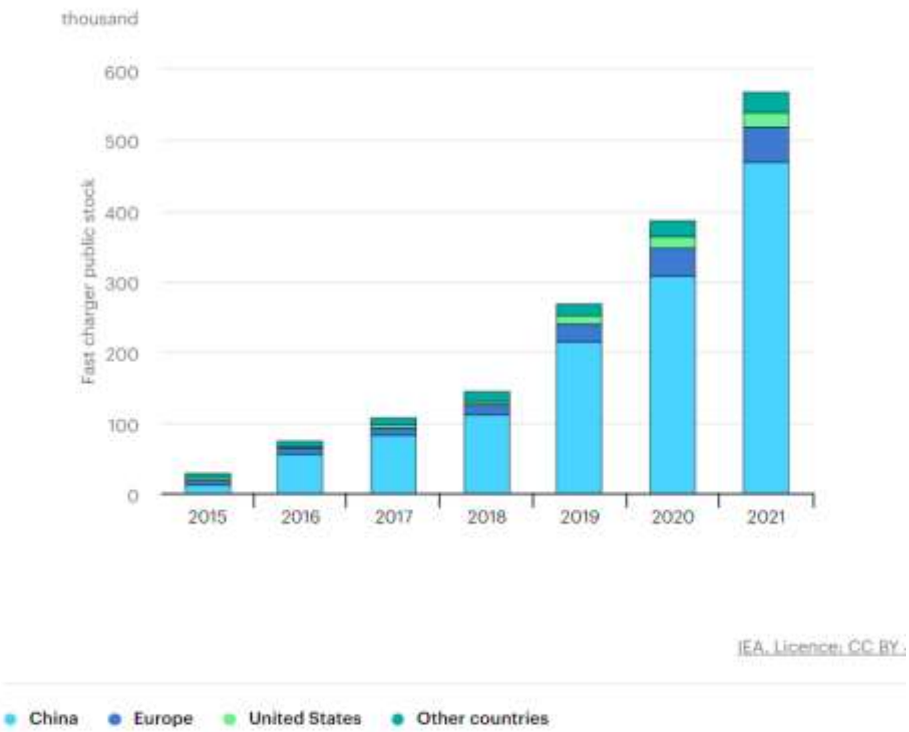


Figure 7. Fast publicly available chargers evolution, 2015-2021 [22]

Sweden was one of the first countries to establish a net-zero emissions target, which is why it comes as no surprise that Sweden ranks 8th in Forbes Advisor's evaluation of countries that are most suitable for EV drivers [23]. As anticipated, the evolution of charging infrastructure in recent years has been remarkable. To be more precise, charging stations are distributed across Sweden, but some areas have a higher concentration of them. For instance, Stockholm is one of the top 10 European capitals with the highest EV charging density, having 16 EV charging bays per square kilometer and a total of 3865 chargers throughout the city. In the western coast, Västra Götaland has 3153 charging stations, and in the south, Skåne has 2133. In contrast, Gotland, Blekinge, and Kronoberg have significantly fewer chargers, with only 170, 176, and 191 respectively. From 2017 to 2022, the number of charging points in the country has increased from 2,000 to almost 20,000, according to [24]. According to the latest data, there are a total of 3,186 public charging stations and 20,189 charging points, with 2,312 of those offering fast charging. Overall, there has been a 40% increase in the past 12 months. Therefore, according to the news that has been published, the ambition to decarbonize transport may be affected by the shortage of power capacity for new charging stations in Swedish cities [25].

Despite the abundance of recharging points in the country, it is important to note that not all charging stations are of the same type. The primary differentiation lies between alternating current (AC) and direct current (DC) chargers. AC charging currently dominates most charging stations, while DC charging is typically found near major highways or in public charging stations where quick charging times are essential. It is worth noting that the electrical current from the grid is always AC, and the difference between AC and DC charging refers to where the AC-to-DC converter is located, either inside or outside the vehicle [26]. Unlike AC chargers, the power conversion takes place inside the charger, which means they can deliver power directly to the car's battery without the need for the power conversion taking place in the vehicle. As a result, DC chargers are larger, faster, and represent an exciting breakthrough for EVs. The most common chargers today are usually 22kW AC chargers.

2.4 Battery technology

2.4.1 Introduction to battery systems

In many parts of the world, storage systems have been utilized to prevent power shortages in developing countries or to provide additional support during periods of grid overloading. These storage systems have primarily been powered by fossil fuels like Diesel and Gasoline and operated themselves based on thermodynamic principles. As the world works collectively towards adopting climate change agreements and sustainability measures, there has been emphasis to consider alternative measures like biofuels, fuel cells or even batteries that can function effectively as a substitute for the already present diesel generators.

In this section, battery systems will be analyzed as the emphasis is to investigate the potential of using battery systems as a viable power source for off/weak grid chargers. Battery systems are systems which convert chemical energy into electrical energy. They tend to have high levels of efficacy and their lifetime depends on a variety of factors that will be discussed further.

2.4.2 Types of battery systems

There are various types of battery systems that exist in the market and the overall performance could vary based on the type of battery chemistry.

Lead Acid batteries: These are the most affordable and popular battery systems that are available in the market. They have a low energy density of 25-35 kWh/kg [27] and have drawbacks which include environmental concerns. The recycling process of lead acid batteries has been questioned by environmental agencies of countries like China and Malaysia as the lead from the used batteries is disposed of into rivers and other water bodies which would enhance groundwater and crop contamination. Moreover, lead pollution caused from these batteries could even be higher than that pollution caused by fossil fuels like gasoline [28].

Nickel Based batteries: Nickel-Cadmium batteries work well under extreme situations but contain toxic materials and have high maintenance costs in addition to having a memory effect. Nickel-Zinc batteries are environmentally friendly but have a short cycle life. Nickel-Metal Hydride batteries enjoyed some popularity during the start of the millennium but lost popularity as they come with their own set of disadvantages which include a high self-discharge rate [28].

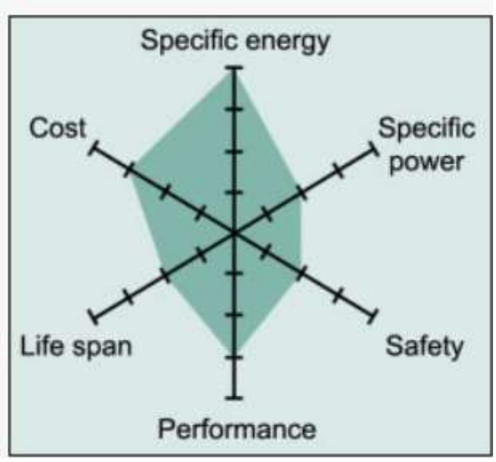
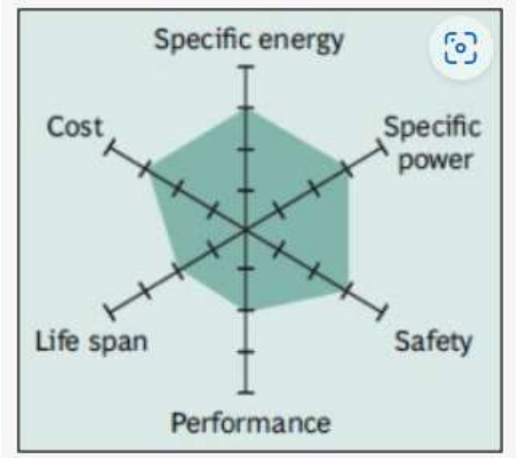
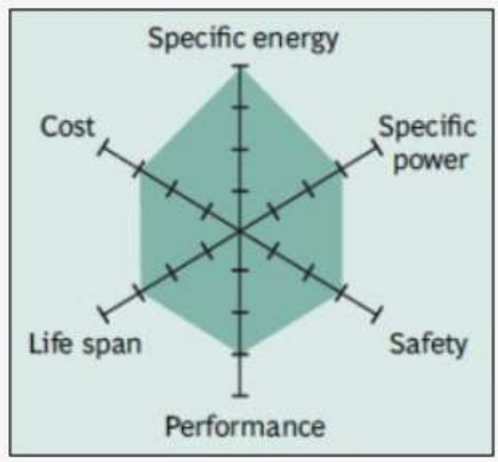
Lithium-Ion Batteries: Seen as the best technology available, Lithium-Ion battery systems will be considered when analyzing the battery solution model. These batteries are environmentally friendly as they do not contain poisonous metals like lead and mercury. Moreover, these batteries are immune from memory effect, but the overall production process of these batteries is relatively costlier. Lithium-Ion batteries can be segmented based on the active material that will signify the main characteristics of the battery.

1. Lithium Cobalt Oxide (LCO): This battery system has a layered structure cathode consisting of cobalt oxide and an anode made of graphite. During discharge, the lithium ions move from the anode to the cathode while moving in the opposite

direction as the battery is being charged. These batteries stand out for their high specific energy which makes them an ideal choice for laptops, mobile phones and cameras. However, they come with their own set of drawbacks which include short life span, low thermal stability, and limited load capabilities. The battery system should not be charged beyond their C-rate. The short life cycle is attributed to the solid electrolyte interface (SEI) thickening on the anode and lithium plating while charging at low temperatures and even fast charging [29].

2. Lithium Manganese Oxide (LMO): With the cathode material containing manganese oxide, the three-dimensional spinel structure eases the lithium-ion flow of the electrode thereby enhancing current handling, thermal stability and safety while lowering resistance. However, the cycle life is lowered down. Design flexibility of these batteries enables engineers to maximize desired parameters which include maximum load current (specific power), life span or high capacity. Power tools, medical instruments and even electric vehicles are applications where LMO batteries are utilized. In electric vehicles specifically, LMO batteries are blended with Nickel Manganese Cobalt Oxide (NMC) to enhance the specific energy and improve life span thereby bringing out the best of each other [29].
3. Lithium Nickel Manganese Cobalt Oxide (NMC): Considered as one of the most successful battery systems, the combination of Nickel which stands out for its high specific energy with Manganese which can form a spinel structure to lower resistance can help in bring out the best of these two metals. NMC batteries can be used as energy or power cells and common applications include power tools and different types of electric powertrains and energy storage systems. The reasoning behind the naming of this battery system is attributed to the elemental combination of the cathode which consists of 1/3 Nickel, 1/3 Manganese and 1/3 Cobalt. Due to the high costs and limited supply of Cobalt, manufacturers are lowering the cobalt content which in turn will have a negative impact on the overall performance of the battery system [29].

4. Lithium Iron Phosphate (LFP): The potential of using Phosphate as the cathode material in Lithium batteries was discovered about 26 years ago by researchers in Texas, USA. These batteries are recognized for their long cycle life, high current rating, thermal stability and enhanced safety features. Common applications include starter batteries for cars where Lead-Acid batteries used to be the preferred system in the past. A major drawback to this battery system is its high self-discharge rate which results in balancing issues with respect to aging [29].
5. Lithium Titanate (LTO): In these battery systems, the anode which generally consists of graphite is replaced by lithium titanate and has a spinel structure. These batteries can be fast charged and capable of delivering a high discharge current of 10C. Furthermore, these batteries can be operated efficiently at very low temperatures and can deliver 80% of their capacity at -30^{o} C. Common applications include electric power trains and solar powered streetlights [29].

Lithium Cobalt Oxide (LCO)	
Lithium Manganese Oxide (LMO)	
Lithium Nickel Manganese Cobalt Oxide (NMC)	

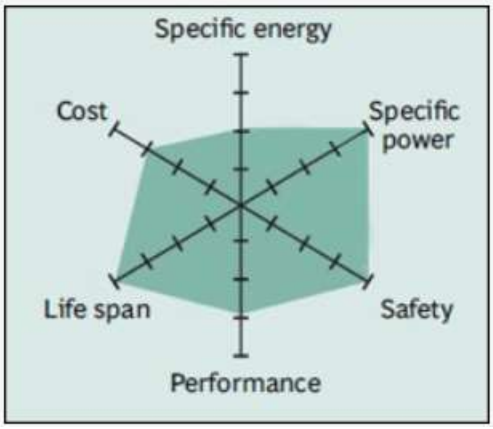
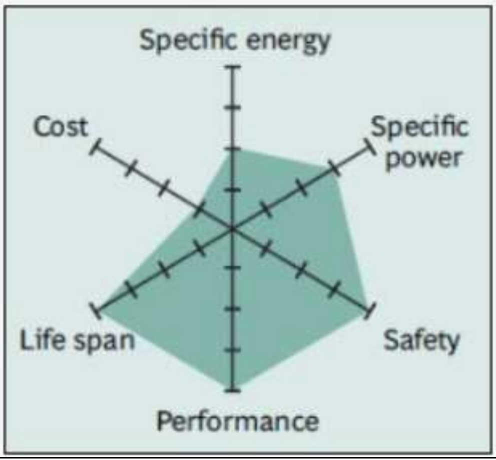
Lithium Iron Phosphate (LFP)	
Lithium Titanate (LTO)	

Table 2. Characteristics of Lithium – Ion batteries [29]

2.4.3 Thermal Runaway

A topic of concern with these batteries has been the thermal runaway effect which if initiated could potentially result in catastrophic fires and hence a protection circuit will be required to maintain a safe operation [28]. This phenomenon occurs when the cell temperature has reached a juncture where the temperature moving forward will continue to rise by itself since oxygen is created which provides fuel to the fire [30]. The entire phenomenon can be divided into five stages based on the temperature of the battery cells.

At stage 1 when the battery cell temperature is around 80^o C, the Solid Electrolyte Interphase (SEI) layer present in the anode decomposes due to the reaction between lithium and the solvents found in the electrolyte and this reaction is exothermic in nature. As the battery temperature reaches between 100-120^o C, the stage 2 of thermal runaway commences with the electrolyte breaking down in an exothermic reaction which results in the release of various gases including Carbon Monoxide (CO), Carbon Dioxide (CO_2) and Methane (CH_4). With the temperature continuing to rise around 120-130^o C, the separator starts to melt at stage 3 enabling the cathode and anode to contact each other and cause an internal short circuit generating more heat. At stage 4, the cell temperature is around 130-150^o C, the cathode breaks down in an exothermic reaction which generates oxygen and as a result, the cell starts to catch flame up and burn. This exothermic reaction is extremely strong in nature and breaks down the active material of the cathode thereby causing the cell to fail and temperatures to rise further to almost 180^{o}C. When temperatures of around 180° C is achieved, it can be said that thermal runaway has been achieved and the reaction becomes self-sustaining until all the fuel has been utilized completely [30].

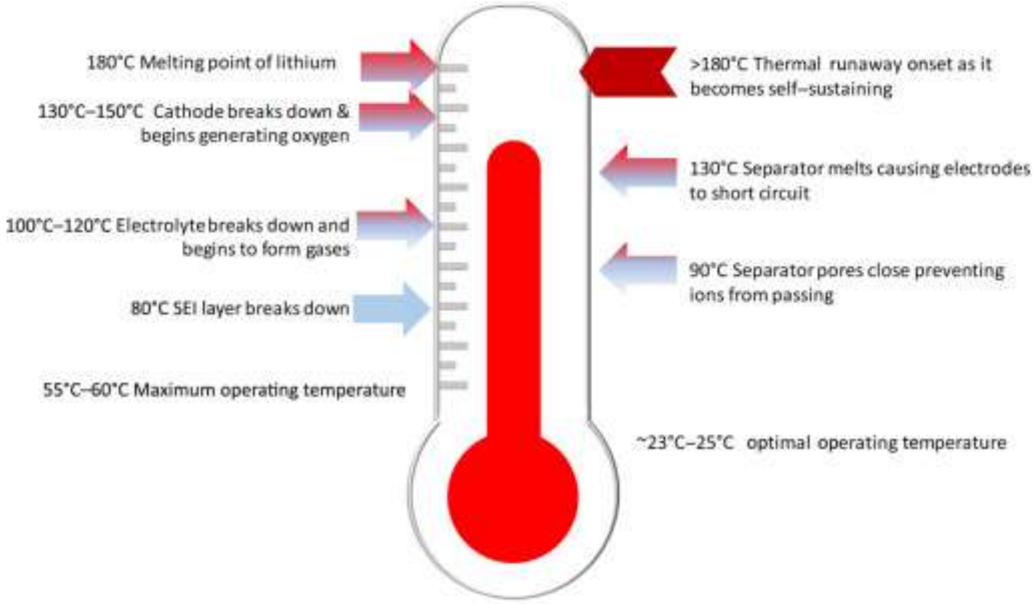


Figure 8. Different stages during thermal runaway [29]

2.4.4. Environmental concerns and ageing

In general, many environmentalists still have concerns with regards to the development of battery systems as an alternative to fossil fuels. The extraction of metals like Nickel and Cobalt from countries like Congo have been a topic of concern since the legal system in such countries is flawed and children could be exploited into labor [31]. In addition, the extraction of Lithium requires a large amount of water. To put into perspective, mining one metric ton of Lithium requires around 500,000 gallons of water [32].

While preparing the solution model, ageing was a critical criterion that had to be considered during the operational aspect of the battery. Ageing in batteries can be divided into two categories.

1. Calendar Ageing: This ageing is associated with keeping a battery under rest conditions and is caused due to the formation and growth of SEI layer on the anode [33]. Electric cars for most of their time remain idle and hence calendar ageing is considered as a critical factor for battery degradation. In the battery solution for charging vehicles, this ageing factor is considered as a critical factor for the Energy Storage System (ESS) since the batteries do not remain idle.

2. Cycle Ageing: This ageing is associated with the depth to which a battery is discharged and caused by lithium plating on the anode. Cycle ageing can be exacerbated by high C-rates and low temperatures [33]. Due to the continuous charging and operational aspects of the ESS system, it was vital to consider factors that would enhance cycle ageing. To reduce battery degradation caused by cycle ageing, manufacturers recommend certain levels of SOC that can maximize the

operation of the battery. Northvolt, whose ESS was used for the battery solution recommended the ideal SOC for operating their systems to be between 20 and 80 %. This range would ensure that the system lasts for a period of around 10 years. Furthermore, the rate at which the battery is charged or discharged, known as the C-rate had to be analyzed when considering the battery solution as this could play a role on the battery degradation due to cycle ageing. To put into perspective, a battery of 1Ah will provide its full capacity in one hour at a C-rate of 1 and the same battery if discharged at a C-rate of 2, will provide its full capacity in half an hour. To reduce the rate at which the battery is getting discharged, the concept is to always have two ESS packs operating in parallel and letting them discharge simultaneously which would lower down the C-rate rather than letting each battery operate at a time and discharge at a higher C-rate.

EV manufacturers have also taken cycle ageing as an important factor for the operation of a vehicle and hence worked with battery engineers to prevent batteries from reaching 100% SOC. This is achieved by slowing down the C-rate after the battery reaches 80% SOC while charging. Hence, it is observed that the charging speed lowers down after the capacity of the battery has exceeded 80% as seen in the charging curves of most vehicles as the ions in the battery need to be stabilized and the battery moves to slow charging after that [34].

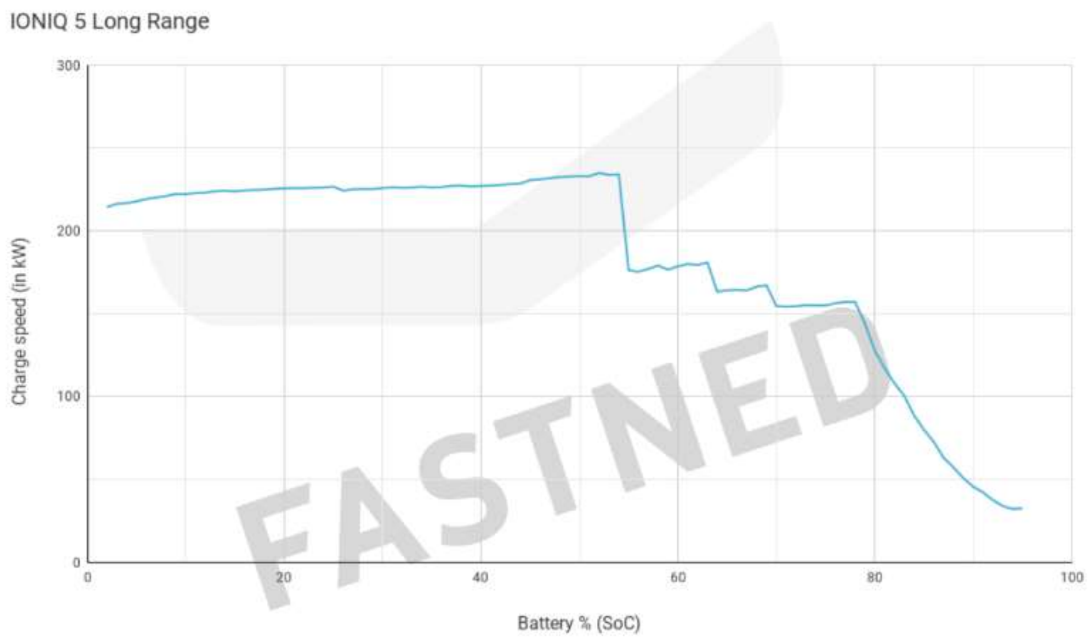


Figure 9. Charging curve of a sample BEV [35]

2.4.5 Costs

Every technology during its premature stage tends to have high costs whether it was mobile phones, computers or even ICE powered cars. Upon the maturity of technology, price parity is generally achieved, and commodities tend to become more affordable to the public. BEV’s too, when launched onto the market, have come at a high purchase cost and the batteries have contributed significantly to the overall cost of a vehicle. However, advanced R&D into batteries, usage of low-cost chemistries like LFP, manufacturing and supply chain improvements and capacity expansion have helped the prices of EV batteries to come down from 732 USD/kWh in 2013 to 151 USD/kWh in 2022. In fact, 2022 can be considered as an outlier since the price/kWh went up by around 7% when compared against the previous year due to an increase in demand for raw materials and components which was caused mostly due to geopolitical events. Nevertheless, these prices should start reducing from 2024 onwards with an increase in lithium extraction and the projection is to see a price of 100 USD/kWh by 2026 [36].

These low prices generally come into play when considering mass production and may not hold true for the price of an ESS system which is not produced in bulk. The National Renewable Energy Laboratory (NREL) based in Colorado, USA documented a report based on the findings of various publishers and projected the cost reduction of battery storage systems in the coming decade. These cost projections have been divided into high, mid and low scenario and in the upcoming analysis, it was agreed that the mid scenario would be the best-case estimate when taking into account the storage costs. These estimates show that a storage system is expected to cost around 240 USD/kWh in the year 2026 and this price has to be taken into account for the battery solution [37].

2.5 Hydrogen

2.5.1 Introduction

Hydrogen has the potential to be a game-changer in the pursuit of a more sustainable and secure energy future. Clean hydrogen is currently receiving strong support from governments and businesses worldwide, with a growing number of policies and projects dedicated to its development [38]. It is a versatile and abundant alternative fuel that can be produced from various domestic resources, including water and organic matter. Although the market for hydrogen as a transportation fuel is still developing, the government and industry are working towards making hydrogen production and distribution cleaner, more economical, and safer for widespread use in fuel cell electric vehicles (FCEVs) [39].

In May 2022, the European Commission released the Repower EU plan as a complement to the EU hydrogen strategy. This plan aims to raise the European aspirations for renewable hydrogen as a significant energy carrier, in order to reduce dependence on fossil fuel imports from Russia [40]. More specifically, these new suggestions are part of the "Fit for 55 package", a series of proposals that have been put forward to revise and update EU legislation and implement new initiatives, with the objective of aligning EU policies with the climate goals that were agreed upon by the Council and the European Parliament [41].

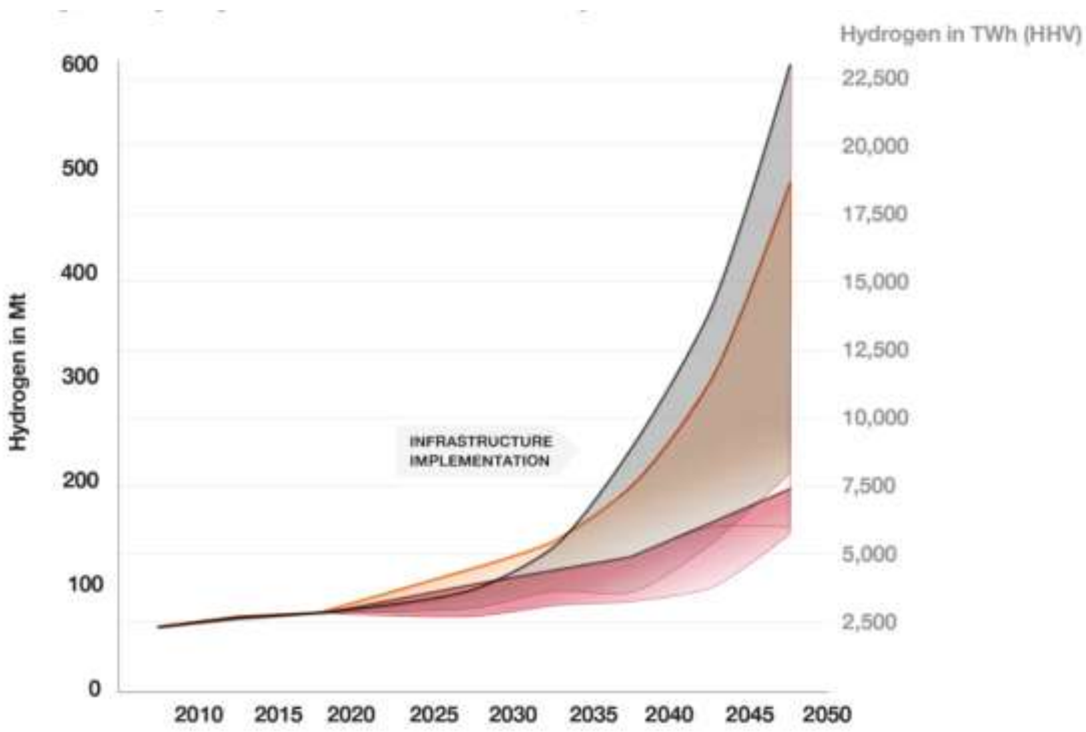


Figure 10. Range of Hydrogen Demand Assessment by 2050 [42]

2.5.2 Green hydrogen

Green hydrogen is produced by electricity from solar, wind or hydro plants, without emitting any pollutants into the atmosphere. Green hydrogen is not the only type of hydrogen that exists and far from it, depending on the method used for its production and consequently its polluting emissions, hydrogen is called with one color or another.

If we pay attention to the most important and most used today, the ones that are noteworthy to mention are grey, blue, turquoise, purple, yellow and green. At present, the most abundant type of hydrogen is classified as grey hydrogen, which is obtained through steam reforming of natural gas or coal gasification, but lacks carbon capture, utilization, and storage (CCUS) technology. Hydrogen that is generated through steam methane reforming with the aid of CCUS technology, utilizing natural gas or biomass, is referred to as blue hydrogen [43].

Turquoise hydrogen is produced through a process called methane pyrolysis, which yields hydrogen and solid carbon. Its eco-friendliness depends on using renewable energy to power the process and either storing or reusing the carbon. Turquoise hydrogen has potential as a low-emission hydrogen source in the future [44]. Lastly, and being the least common today, purple hydrogen is obtained by electrolysis through an atomic current and a form of green hydrogen made through electrolysis that is powered by solar energy is called yellow hydrogen.

The object of study and the type of this gas that should grow in the coming years and be able to overcome the challenges ahead is green hydrogen.

It is important to mention that, for the production and implementation of green hydrogen to be real, there are still many years to go, since the first thing that is needed is a significant increase of the installed renewable energy capacity. Today's electricity systems must be decarbonized in order to accelerate the electrification of the energy sector and thus take advantage of renewable energy at a low cost [45]. For all this, initial regulations and incentives must be put in place. Not only do you have to increase the capacity of the electrolyzers, but you have to have enough renewable energy. So, the most important is renewable electricity and subsidies, considering also investments from the private sector [46].

Green hydrogen has numerous benefits, including its 100% sustainability, ability to be stored in high-pressure containers, and versatility in its use as a source of electricity or synthetic fuels across commercial, industrial, and mobility applications. Also, low-carbon generation is becoming cost competitive as the years go by [47], which can help to increase investment in production. However, it also presents certain challenges and drawbacks. The production process demands a significant amount of energy, and the element itself is volatile and flammable, necessitating special safety measures [48] .

2.5.3 Hydrogen process

The methodology for producing green hydrogen and harnessing it to power electric vehicles involves a multi-step process. This process is comprehensively modeled in the present study. This report explains the approach that was taken to obtain all requisite information and subsequently presents the findings derived from this investigation. In chapters 3 and 4, it is explained how the results are achieved.

As previously mentioned, the process begins with an electrolyzer, which utilizes electricity to break apart water molecules and produce hydrogen and oxygen. As the primary aim of this solution is to generate hydrogen with zero emissions into the atmosphere, the electricity needed for this process would come from renewable sources.

This can be achieved by harnessing the energy generated by solar parks or, more specifically, from a wind park in the solution considered. The electricity from the wind power plant is fed into the electrolyzer, a device that utilizes a chemical process known as electrolysis to produce hydrogen. This process is capable of separating the hydrogen and oxygen molecules of water, thereby generating hydrogen as a byproduct [49].

Currently, there are various electrolyzers available in the market. The most widely used and commercially available electrolyzer is the conventional alkaline electrolysis system. This system involves immersing two electrodes in an alkaline electrolyte solution, which conducts OH- anions, while a diaphragm separates the electrodes [50]. Although it is the simplest and most economical system, it has low current densities, and thus requires batteries for energy storage.

Additionally, protonic exchange membrane electrolysis (PEM) utilizes ionized water, which is pure and requires less water compared to other hydrogen production methods such as gray or blue hydrogen. This method also generates highly pure hydrogen; however, it involves using noble metal-based materials, which are scarce and expensive.

Finally, there is solid-state electrolysis. Although not yet commercialized, it boasts nearly 100% efficiency, eliminates the need for noble metals, and can operate at high pressures. However, due to the high temperatures involved, durability of its components remains a challenge, and it may not meet the requirements of renewable energy systems.

After the hydrogen is produced, the process continues with compression. As with any gas, it must be compressed for subsequent use and distribution. In this case, the pipelines that exit the electrolyzer lead to the high-pressure compressor. Furthermore, the hydrogen compressor is also strategically located close to the wind turbine plant and the electrolyzer.

Two important factors must be taken into account that make a difference. The first pertains to the calorific power contained in hydrogen. The lower calorific value of hydrogen is 120 MJ/kg while the lower calorific value of gasoline is 44.3 MJ/kg [51], being this what makes it so attractive. In contrast, when it comes to density, at ambient pressure it is approximately 0.09 kg/m3, which is roughly 8000 times less compared to gasoline (which is about 720 kg/m3). This is why the compression of hydrogen is essential. Once compressed, the hydrogen is ready to be distributed or stored in high-pressure containers.

Once compressed, high-pressure hydrogen is introduced into containers and stored for distribution. However, these tanks must be specially prepared to withstand the high pressure and a large number of fatigue cycles due to the loading and unloading of the tank. The materials used must also be as resistant as possible to hydrogen embrittlement [52]. Safety problems that may arise from possible leaks or accidents must also be considered. In chapter 3, the tanks used for the solution and the working pressure of the hydrogen are specified.

The hydrogen tanks are placed on electric trucks (remembering that during the entire process no emissions are produced) and delivered to the charging stations where electricity is regenerated again using a fuel cell and provides the energy needed to charge electric vehicles.

At this point, several different scenarios are considered, varying both the number and distances between charging stations and the number of vehicles that will use those stations, resulting in different energy demand levels to be supplied. Numerous situations are explained with results are obtained in chapter 4 for further analysis and discussion.

A stationary hydrogen fuel cell stack is a device that produces electricity through a chemical reaction between hydrogen and oxygen [53]. Anode, cathode, and an electrolyte membrane make up the components of a fuel cell. The fuel cell's overall capacity is determined by the delivery of pure hydrogen into the anodic chamber and air or pure oxygen into the cathode chamber. As the gas travels through the electrolyte layer at the anode end of the cell, electrons become separated. It is probable that the layer is utilized to isolate electrons from hydrogen particles while still enabling them to pass through [54].

There are currently six different types of hydrogen fuel cells being utilized. These fuel cells have varying methods for converting gases into electricity and differ based on the type of electrolyte used [55]. Additionally, fuel cells are categorized as low, medium, or high temperature, depending on their operating temperature. The various fuel cell types are placed into the following categories:

Low temperature fuel cells, which include alkaline fuel cells, membrane fuel cells, and direct methanol fuel cells. Medium and high temperature fuel cells, which include phosphoric acid fuel cells, molten carbonate fuel cells, and solid oxide fuel cells.

The electricity generated by the fuel cell is utilized to supply chargers, enabling the charging of electric vehicles at charging stations. The number of chargers is dynamically modeled, taking into consideration the varying energy demands of different situations. Depending on the energy demand, a higher or lower number of chargers may be required at different demand points. The subsequent section outlines the type of chargers and the type of load they provide.

2.5.4 Process efficiency and limitations

The energy efficiency factor is a critical element in this process. At present, some stages of the process are not yet optimal, leading to energy loss throughout. The electrolyzer and fuel cell, in particular, are technologies with low efficiency levels that significantly impact the overall performance of the process. Improvements in the efficiency of these technologies will be essential to enhance the energy efficiency of the overall system.

Firstly, as previously mentioned, everything comes down to the heating value contained in hydrogen. It is the amount of energy that can be obtained by burning a certain amount of hydrogen [56]. Therefore, and since electrolysis is the first phase of the studied and analyzed project, the efficiency of the electrolyzer plays a key role. The lower its efficiency, the more electricity is needed to produce the same amount of hydrogen. Consequently, the need for a greater amount of electricity leads to increased costs and thus, the process loses significant profitability from the outset.

Over the years, optimism regarding the efficiency of electrolyzers has been on the rise. It has been announced for years that highly efficient electrolyzers capable of generating hydrogen with decreasing energy requirements for their production would exist today, but this has not yet come to fruition.

When considering electrolysis, it is important to consider that efficiency is often dependent on the size of the electrolyzer in terms of its capacity. Specifically, smaller electrolyzers tend to exhibit greater efficiency compared to their larger counterparts that operate at a larger scale.

One kilogram of hydrogen contains 39.4 kWh of energy, but its production with current commercial electrolyzers typically costs about 52.5 kWh. Energy efficiency ranges from 56% to 73% [57]. Despite the aforementioned optimism, electrolyzer efficiency levels could rise to around 76% by 2050, according to the International Renewable Energy Agency [58].

Efficiency of the compressor is yet another critical factor that affects both the operational costs and environmental impact of hydrogen compression, similar to any other compression process. However, the impact is more significant in the case of hydrogen due to its unique properties, particularly its low density, which requires compression at higher pressures, requiring more energy to reach these pressures. To put things into perspective, compressing hydrogen isothermally from ambient pressure to 1000 bar consumes 2.64 kWh/kg, while air compression for the same pressure requires only 0.19 kWh/kg [59].

As for the fuel cell, the energy efficiency values are similar to those of the electrolysis process. And it is similar in terms of the size of these technologies. For example, the company Bosch recently developed a hydrogen compatible fuel cell in which a total efficiency of more than 85% is recorded but, the current prototype machines have a target power of 10 kW of electrical supply [60]. Therefore, at our level, higher power fuel cells are needed to be able to provide higher electrical power at the charging stations and in this case, as of today, the efficiency decreases considerably.

Fuel cells have different applications depending on their power, which could be summarized as: domestic sector (1 - 5 kW), residential and commercial sector (10 - 50 kW) and industrial sector (250 kW - 1 MW) [61]. Given the existence of different types of fuel cells, there is a lot of variability in terms of electrical efficiency. Highlighting the most important ones, Low-Temperature Proton Exchange Membrane Fuel Cells (LT-PEMFCs) present an efficiency of 40%-60%, High-Temperature Proton Exchange Membrane Fuel Cells (HT-PEMFCs) 50%-60%, Phosphoric Acid Fuel Cells (PAFCs) between 36 and 45% and lastly Alkaline Fuel Cells (AFCs) 60%-70% [62].

In the case of the hydrogen solution, certain limitations have been established, whereby certain elements were not deemed the object of study, and certain assumptions are made. Priority is given to analyzing relevant values and drawing conclusions about the feasibility and profitability of the project, particularly in terms of the logistics of the entire process.

The model is created based on the value of the efficiencies in each phase of the process explained. Based on the literature review and conversations with the company, certain values are adopted as fixed values prior to simulation and obtaining results.

In the case of the electrolyzer and the fuel cell, energy efficiencies of 65% and 60%, respectively, are assumed. For the compressor, and in a joint decision with BayWa r.e., an efficiency of 95% is assumed, in which 5% is lost in calorific form when compressing the hydrogen.

The capacity of the mobile storage is 1000kg, with an actual maximum transport of 90%, due to the difference in pressures in the high-pressure tanks.

As explained in the model description, the electrolyzer, compressor and fuel cell capacities are dynamically adapted to the proposed demand in each situation. For the costs, the literature review sources used to obtain them are provided in Chapter 3.

Regarding the capacities, as explained in the description of the model, some minimum values are assumed, decided together with the company and based on the information found. In the case of the electrolyzer and fuel cell, both technologies adopt a minimum capacity of 0.25 MW while the compressor has a minimum of 10kg/h of hydrogen.

As last assumptions, containers and trucks responsible for transporting compressed hydrogen would be manually loaded and unloaded by workers, which simplified the process. On the charging stations site, the number of fuel cells required varies depending on the number of refueling stations, the capacity of the stations, and their efficiency in generating electricity by introducing compressed hydrogen.

Overall, the study placed a strong emphasis on analyzing the logistical aspects of the hydrogen solution and sought to determine its feasibility and profitability by drawing on various efficiency metrics and assumptions.

2.6 Available solutions today

2.6.1 Battery solutions

With solar and wind parks being weather dependent, battery storage systems are commonly used to store surplus energy and support the functioning of the parks during periods of energy deficit. Similarly, installing off grid charging stations that involve the usage of solar panels or small-scale wind turbines that are directly connected to the fast chargers and provide energy to incoming vehicles is an interesting area of research. These off-grid charging stations generally make use of battery storage systems which provide additional support during periods of high demand and store surplus energy that gets generated. A key example is the Tesla Superchargers installed in Las Vegas, which run completely off-grid with the support of solar panels and batteries that power 24 fast chargers and 15 slow chargers [63].

Figure 11. Off-grid charging station developed by Tesla [63]

The concept of using batteries solely for fast charging vehicles is premature and is yet to be implemented on a large scale. Porsche has used battery filled containers to fast charge vehicles in remote locations such as Levi in Finland where the temperatures may go down to -30^{o}C or even in racing circuits to fast charge electric sports cars. These containers have battery modules which when combined provide an energy of 2.1 MWh and vehicles like the Porsche Taycan can draw energy at the power of 320 kW using these containers [64]. Eon, a German energy firm has also developed a booster charging system which operates on batteries developed in cooperation with Volkswagen group providing a total capacity of 193.5 kWh. These batteries come in built with chargers which means that transporting just the batteries is not an option although the overall system size is compact and modular in nature 2.2 x 1.3 x 1.2 (H X W X D) [65].

Alfen, a Dutch energy company developed battery packs using BMW i3 batteries with each pack weighing 7500 kg and proving 422 kWh in a 10 ft container. These battery packs have been successfully implemented in Haringvliet energy park, located in the Netherlands and functions as an effective energy storage system [66]. While these batteries can be used for EV charging, the energy density (56.26 Wh/kg) may not be the best in the market. Northvolt, Sweden’s most promising battery manufacturer can tackle this challenge by providing an energy supply of 281 kWh in their Voltpack Mobile System with each battery pack weighing 3000 kg thereby providing a highly modular system with an energy density of 94 Wh/kg [67]. Furthermore, Northvolt and Scania recently collaborated to supply Voltpack Mobile systems for charging EV's in the ski resort town of Åre with the latter's electric trucks being used to transport the battery packs [68]. This example is very similar to the work that has been done in developing the battery solution and timing of implementing these systems in Åre also happens to coincide with the work that was undertaken as part of this thesis project. Hence, this example signifies that transporting batteries from one location to another for charging vehicles can be a potential solution for tackling the charging infrastructure challenges faced by the world in the coming decade. While no information was provided as to how the batteries are powered, it is assumed that the Voltpack batteries will be connected to a weak grid which will then charge the batteries during periods of low load or demand.

Figure 12 Weak grid charging station- Åre, Sweden

2.6.2 Hydrogen solutions

Today, there are companies that are in the process or have been able to move forward with projects in which the goal was to provide energy without coming from the conventional electricity grid and using hydrogen.

Despite being primarily utilized in industrial applications such as ammonia, refining, methanol, and steel production, the demand for hydrogen is rapidly surging. Regrettably, the majority of hydrogen production that caters to this demand relies on fossil fuels, leading to the emission of CO_2.

If we focus on the production of green hydrogen, the Spanish company Iberdrola put into operation the largest plant to date in 2022, with an electrolyzer of up to 20 MW of power. It is located in the town of Puertollano, Spain. The total investment is 150 million euros and the process carried out in this plant consists of using energy from a solar plant to generate hydrogen using electrolysis.

The application is for industrial use, more specifically, the green hydrogen produced in it will be used in the ammonia factory located in the locality. In this way, the company has achieved emission-free fertilizer production. Finally, with this project, more than 1,000 jobs have been generated and it is estimated that a total of 48,000 tons of CO_2 per year will be spared [69].

Figure 13. Iberdrola´s green hydrogen plant [69]

Focusing on solutions where hydrogen is used for electric vehicle charging, ABB & Avia developed in 2017 the world’s first mobile fast charging station for electric vehicles, whose energy source is CO_2-free produced hydrogen. This is a self-contained cube that is portable and sealed off. It houses all the necessary technology for the conversion of green hydrogen into electrical energy through a fuel cell [70]. The resulting electricity can be used for the rapid charging of electric vehicles using a converter and charging station. In its eventual commercial application, the system will have the capability to charge up to 150 kilowatts per vehicle.

A prime illustration of this is Gaussin's recent creation of a container equipped with compressed hydrogen and an integrated fuel cell. This advanced fuel cell technology generates electricity from hydrogen, enabling it to be a zero-emission alternative to diesel generators and serve as a backup power solution [71].

3. Model

3.1 Traffic data and demand generation

To analyze the number of vehicles that will stop in a particular charging station, two factors are needed. Firstly, since the solution model is developed for future use, it is vital to know the EV growth projections and secondly, it is also important to analyze the traffic flows at the selected location. Therefore, before analyzing this data, consensus had to be made regarding the location of analysis. The majority of the wind projects developed by BayWa r.e. in Sweden are located in the Southern part of the country. However, consensus was achieved that Northern Sweden is an interesting area to analyze since the population density is lower and there are roadside areas where the grid is either weak or completely absent.

Among the counties in Northern Sweden, BayWa r.e. operates a wind farm in Härnösand and this wind farm can be considered as the reference energy source where the batteries are charged, or the hydrogen gets produced [72]. Hence, the traffic patterns of this area were analyzed more closely with the support of Trafikverket, Sweden's state-run transport administration which keeps a record of traffic data in certain points. One of the selected points is located just on the outskirts of Utansjö as seen in the map below. The traffic data recorded was relatively recent, having been recorded during the first week of September 2022 [73]. Once the 24-hour data was obtained, it was important to use certain parameters to assume and filter out the BEV'S that stop in the charging station. The reference year chosen is 2026, since it falls just in the middle of the 2020's and realistic projections can still be made when compared to a year which falls at a later stage like 2028 or 2029.

Figure 14. Selected location point [73]

According to Power Circle [12], an organization which monitors the number of EV's in Sweden, there were around 150000 BEV's in Sweden during 2022 making close to 2.9% of the total light passenger vehicles present in the country. To translate these figures and project the numbers in 2026, the BEV growth estimates for 2026 under a high scenario are 1.2 million out of 5.5 million light passenger vehicles thereby making around close to 21% percent of the total cars present in the country [13]. To further estimate the number of vehicles that will stop at the charging station, it is assumed that only those vehicles with critically low batteries, i.e., with an SOC of 10% or less will stop at the charging station. In addition, since these fast chargers are in a remote location, it is assumed that only those vehicles undertaking long distance trips will stop by and charge as fast chargers tend to be more expensive, and people would prefer to charge at home slowly during other times in order to save energy costs.

Through a travel survey carried out by Trafik Analys [74], Sweden, it was observed that close to twenty percent of motorists in the country undertake leisure long distance trips. The number of vehicles having an SOC of 10% or less is taken as an assumption and in this analysis, it is assumed that twenty percent of the vehicles undertaking the long trip have an SOC of less than 10%.

By using the traffic data and the above information to estimate the number of EV's that stop to charge, the calculation shows that 50 cars will stop in the mentioned location each day in 2026 with the demand being the highest during the afternoon time and low after evening. In both the hydrogen and battery solutions, the analysis was done keeping the demand between 3-70 cars/day thereby ensuring that information is obtained for a wide range of demand scenarios.

According to the information provided by PowerCircle, the top 4 most popular BEV's in Sweden are the Tesla model 3, Kia E-Niro, Volkswagen ID4 and Volvo XC 40 P8. If the battery capacities of these 4 vehicles is averaged out, the number comes down to 68 kWh/vehicle [12]. It is assumed that when a vehicle comes to fast charge at a location, the driver will not charge beyond 90% SOC since the charging speed starts to reduce after the battery has attained an SOC of 80%. Hence, in the analysis for both solutions, it is considered that the BEV batteries will get charged between 10-90 % SOC thereby requiring 80% of their total capacity or approximately 55 kWh/vehicle (0.8 * 68 kWh/vehicle).

3.2 Battery Solution

3.2.1 Introduction

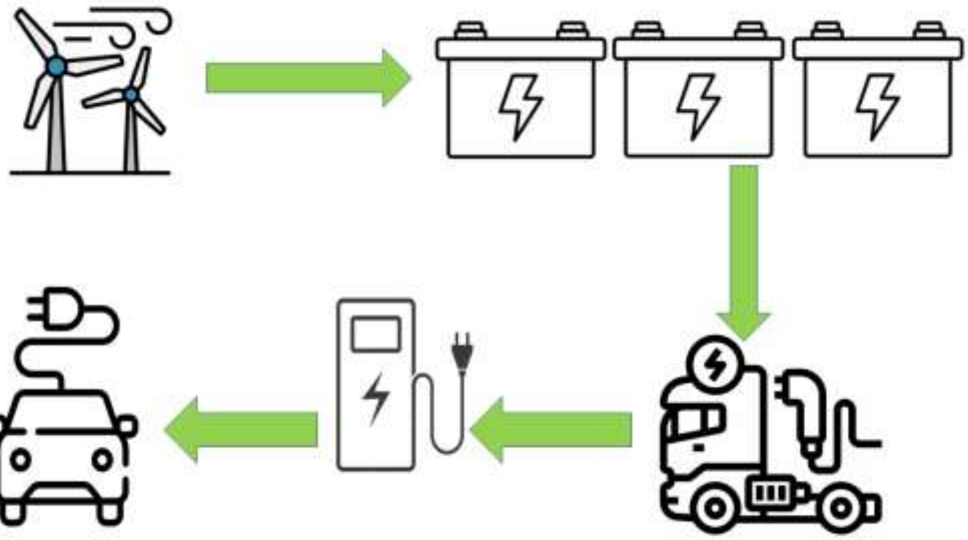


Figure 15. Battery solution schematic

With the information regarding battery systems having been provided in the previous chapter, the idea is to describe the solution in detail and the processes that were taken into consideration when designing the solution. From a bird's eye view, the battery solution is relatively simple with five elements that together make the solution model. These include:

1. The electric vehicles
2. The wind park
3. The energy storage system (Batteries)
4. The transportation system
5. The chargers

The sample wind farm considered in the solution can deliver an annual output of 54 GWh through its 6 turbines which have a total capacity of 16 MW. The batteries which will be charged through the wind farms would require energy converters to convert the AC voltage of wind farm into DC voltage before the energy is transferred into the battery. A typical AC-DC conversion has an efficiency of 92% [75] and this was considered when transferring the energy from the wind farm to the battery.

The battery system consists of Northvolt Voltpack Mobile battery packs and the number of packs supplied would depend on the demand generated from the charging station. These batteries are expected to last for a period of ten years if operated within the SOC limits of 20-80%, thereby allowing the user to capitalize about 60% of the total capacity in one charging cycle. Since the total capacity of each battery pack is 281 kWh [67], utilizing 60% would mean that the solution would consider 168.6 kWh as the available energy in each Voltpack mobile battery pack and size the battery pack requirements accordingly. The overall weight of each Voltpack Mobile battery system is 3000 kg.

Figure 16. Voltpack mobile [76]

For ensuring a high degree of carbon neutrality, it is vital to consider emission free supply chain processes. Hence, an electric truck is selected for modeling the solution, and it was considered to use a brand which is already available in the market today. Sweden's renowned heavy duty vehicle manufacturer, Scania, has now developed a heavy-duty electric truck which has a gross train weight (GTW) of 64 tons. This truck has batteries which provide 624 kWh of energy but only 75% or roughly 468 kWh is usable. The range of this truck can vary based on the load carried. For a GTW of 40 tons, this truck can provide a battery range of 350 kms while providing a range of 250 under full load conditions or when the GTW is 64 tons [77]**.** Like the ESS system, this solution considers that the longevity of the battery should be ensured and hence the truck will run between 75% to 25% SOC thereby consuming around 312 kWh per charge.

Through each delivery, the goal is to deliver as many batteries as possible in one run and hence while containers have standard dimensioning, the concept is to consider 40 ft long containers which can carry approximately 8 batteries. As a limitation, it is considered that the number of trucks procured will not exceed three thereby limiting the number of batteries delivered in one run to 24 (3 trucks x batteries/truck).

Upon arriving at the charging station, the batteries are connected to the chargers in parallel to ensure a lower discharge rate, keeping in mind the cycle ageing aspect of the stationary battery modules. In this solution, the idea is to fast charge a vehicle within a duration of half an hour. Considering that each vehicle will require around 55 kWh per charge, it would be reasonable to consider a 120 kW DC charger. In most BEV's, the charging speed is reduced automatically once the battery SOC has exceeded 80%.

3.2.2 Components

Electric vehicles (for demand generation)

$$Enter\ number\ of\ Vehicles\ stopping\ at\ station\ daily\ (N_{cars}) = User\ defined\ value \tag{1}$$

The user entered value in the excel sheet helps in determining the energy demand of the charging station daily. The average energy demand for charging a car is 55 kWh and hence,

$$Total\ energy\ needed\ daily\ (E_{day})in\ kWh = N_{cars}\ x\ E_{car} \tag{2}$$

Two efficiencies need to be considered before estimating the number of batteries required. The energy is transferred from the stationary battery modules to the charger and from the charger to the vehicle. In this solution the efficiency of the stationary battery is 95 % while the chargers have an efficiency of 97% [78]

$$\eta_{battery}\ x\ \eta_{charger} = 0.95\ x\ 0.97 = 0.9215 \tag{3}$$

The available energy in a battery pack is 60% of the total capacity (281 kWh). As the energy is transferred from the battery to the vehicle, there is an energy loss amounting to almost 8%. The energy in the battery pack after the battery and charger losses is calculated through equation 4 ,

$$E_{batteries}\ in\ kWh = 0.9215\ x\ Energy\ available\ in\ each\ battery\ pack\ (E_{pack})in\ kWh \tag{4}$$

Hence, the number of Northvolt Voltpack Mobile battery packs needed is estimated using the formula,

$$N_{batteries} = \frac{E_{day}}{E_{batteries}} \tag{5}$$

The number of batteries may not necessarily be an integer figure. In such instances, the estimated number of batteries is rounded down to a given number N if the number is between N and N.5. Hence the allowable pack capacity increases slightly above 60% of the total capacity, which is considered as an acceptable limit as increasing the allowable SOC by a small limit will not have a major effect on ageing. However, if the number is N.5 and above, the number of batteries is rounded to N+1.

Wind Farm

Energy which gets generated from the wind farm will need to undergo conversion from AC to DC and this process generally has an efficiency of around 92% [75]**.**As a result, more energy will be required from the wind farm to feed in the required energy into the battery.

$$E_{wind} \ in \ kWh = \frac{E_{battery}}{0.92} \tag{6}$$

The power required from the wind farm for charging these batteries is denoted by the formula and this would depend on the time it takes to charge a set of batteries (T_{charge}),

$$P_{wind} \ in \ kW = \frac{E_{wind}}{T_{charge}} \tag{7}$$

In this solution, the losses from the wind farm to the battery during the AC-DC conversion were considered as heat losses. The Power loss and Energy loss were calculated using the formulas,

$$E_{wind \ loss} = (1 - 0.92) \ x \ E_{wind} \tag{8}$$

$$P_{wind \ loss} = (1 - 0.92) \ x \ P_{wind} \tag{9}$$

Truck and Container Sizing

Transportation is a critical factor in the battery solution owing to the weight energy density of batteries. Northvolt Voltpack mobile comes with the following set of dimensions [67]

Battery pack information-Northvolt		
Length	2.000	m
Width	1.200	m
Height	1.600	m
Weight	3000.000	kg

Table 3. Voltpack Mobile dimensions

Since the goal was to transport as many batteries as possible in one round, a 40 ft long container is considered with the following specifications [79]:

	Container Information	
Type	40 ft high cube	
Interior Length	12.010	m
Interior Width	2.400	m
Interior Height	2.690	m
Container max Gross Weight	30480	kg
Max Payload Weight	26512	kg
Tare Weight	3968	kg

Table 4. 40 ft high cube container dimension

If we consider a volume limited scenario, the number of batteries that can be fitted into the container was calculated using the following formulas,

$$\text{Number of battery packs arranged lengthwise} = \frac{\text{Interior length of container}}{\text{Length of battery pack}} \tag{10}$$

$$\text{Number of allowable rows} = \frac{\text{Interior Height of container}}{\text{Height of battery pack}} \tag{11}$$

$$\text{Number of allowable batteries per row} = \frac{\text{Interior width of container}}{\text{Width of battery pack}} \tag{12}$$

From a volume limited perspective, around 12 batteries could be fitted into the container. However, the maximum payload weight of the container is around 26512 kg which limits the number of Voltpack mobile batteries to 8. Hence, each truck carries not more than 8 batteries.

The electric truck that carries the batteries or hydrogen is operated in a way to ensure that the SOC is around the 25% range before it gets charged. Linear interpolation was required to establish the mileages undertaken by the truck if the SOC range is between 75% and 25%. Since the total battery capacity of the electric truck is 624 kWh [77]. 75% and 25% of SOC would translate to 468 kWh and 156 kWh respectively. Operating the truck within this range would result in a consumption of 312 kWh per charge and the overall mileage would depend on the gross train weight which in turn is linked to the number of batteries carried by the truck in a run.

$$\begin{aligned}\text{Gross Train Weight } (GTW) \text{ in Kg} \\ &= \text{Kerb weight of Truck} \\ &+ (\text{Weight of pack} * \text{Number of battery packs}) \\ &+ \text{Tare weight of container}\end{aligned} \tag{13}$$

It is known that the truck required 468 kWh of energy for 250 Kms of driving when the GTW is 64 tons while providing 350 Kms of mileage for the same energy when the GTW is 40 tons [77]**.** Interpolating these numbers helped in determining the mileage when the consumption is 312 kWh and the GTW is known and the following results are calculated**.**

Reference sheet - Trucking			
Number of batteries	Total weight of truck	Mileage (25% to 75% SOC) in Kms	Energy consumed (kWh)
1	40488	232	312
2	43488	224	312
3	46488	215	312
4	49488	207	312
5	52488	199	312
6	55488	191	312
7	58488	182	312
8	61488	173	312

Table 5. Truck weight and mileage

The above information is vital to know when analyzing the scenarios as it helps in calculating factors like:

- Energy consumed/journey (kWh)
- Number of doable trips before recharging
- SOC before recharging
- Energy consumed/Km (kWh)
- Energy consumed/battery pack (kWh)

3.2.3 Costs

To measure profitability based on the scenarios, a cost analysis is carried out for the battery solution and considered the overall CAPEX and OPEX needed for the charging station.

The CAPEX investigates costs required for procuring the

1. Battery (ESS)
2. Chargers- Discussed in the common parameters section.

And the maintenance costs are estimated to obtain the OPEX costs for the same.

Battery (ESS):

The information pertaining to the price/kWh for ESS is provided in the theory. The following steps are taken for calculating the battery CAPEX and OPEX costs in €/$MWh_{delivered}$

$$\frac{Cost}{kWh}\ (P_{kWh}) = 240\,\frac{\$}{kWh}\,[37] \tag{14}$$

$$Battery\ Pack\ Capacity\ \left(B_{capacity}\right) = 281\ kWh \tag{15}$$

$$Cost\ of\ each\ battery\ pack\ \left(Cost_{pack}\right) in\ USD = P_{kWh}\ x\ B_{capacity} \tag{16}$$

The above figure is obtained in USD and is converted into Euros to obtain the result in €/$MWh_{delivered}$

$$Total\ CAPEX\ on\ batteries\ in\ Eur = N_{batteries}\ x\ Cost_{pack}\ in\ Eur \tag{17}$$

The battery lifetime will help in breaking down the total CAPEX into an annual amount which can further be broken down into a daily amount using the following formulas.

$$\frac{Cost}{year}_{batteries} = \frac{Total\ CAPEX\ on\ batteries\ in\ Eur}{Battery\ Lifetime} \tag{18}$$

$$\frac{Cost}{day}_{batteries} = \frac{\frac{Cost}{year}_{batteries}}{365\ days} \tag{19}$$

Since the daily energy demand is calculated based on the number of projected cars in the station, the Battery CAPEX/$MWh_{delivered}$ is then obtained through the formula.

$$\frac{Cost}{MWh_{delivered}}_{batteries} = \frac{\frac{Cost}{day}_{batteries}}{E_{car}/1000} \tag{20}$$

The demand was divided by 1000 since the values are in kWh and had to be converted to MWh.

To obtain the OPEX costs for the batteries, it is assumed that about 4% of the CAPEX will be spent on maintenance. Hence,

$$\frac{Cost}{year}_{battery\ maintainance} = \frac{Total\ CAPEX\ on\ batteries\ in\ Eur\ x\ 0.04}{Battery\ Lifetime} \tag{21}$$

$$\frac{Cost}{day}_{battery\ maintainance} = \frac{\frac{Cost}{year}_{battery\ maintainance}}{365\ days} \tag{22}$$

$$\frac{Cost}{MWh_{delivered}}_{battery\ maintainance} = \frac{\frac{Cost}{day}_{battery\ maintainance}}{E_{car}} \tag{23}$$

3.3 Hydrogen Solution

In this section, a description of the process of hydrogen production and reconversion into electricity is given. An explanation of the operation of each component that is part of the process considered relevant is provided below.

3.3.1 Overview

Each technology/phase that appears in it has its own purpose and works in a different way, with input and output values.

The technologies that appear are:

- BayWa r.e. Wind Farm
- Electrolyzer
- Compressor
- Transportation
- Fuel Cell
- Chargers

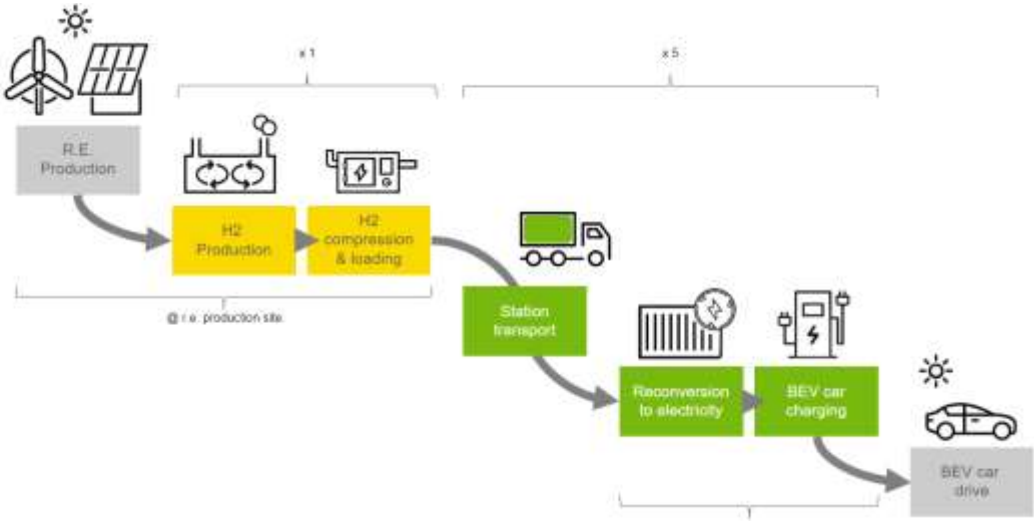


Figure 17. Energy flow process for the hydrogen solution

The heart of this process is the production of hydrogen and, ultimately, the energy contained in it that is used to charge electric vehicles. These are, therefore, the components necessary for the production of this gas and the generation of electricity using hydrogen as an energy vector. It is formed by the wind power plant, the electrolyzer, the compressor, the truck and distribution (transport) system, the fuel cell, and the chargers.

Electricity from the renewable energy plant is directed to the electrolyzer. Hydrogen is produced in the electrolyzer. This hydrogen is compressed and fed into high-pressure containers. They are then transported by truck to the demand points. At each point, compressed hydrogen is fed into the fuel cells. The electricity generated by the fuel cells is directed to electric vehicle chargers to supply the required demand.

The process is modeled from the end to the beginning. That is, depending on the demand of each situation, the energy required in each process is calculated on MS Excel. Although it is explained in chapter 4, the real input values given for the simulation are the total energy demand (the number of charging stations is implicit) and the distance at which the charging station(s) are located for both the logistics and costs of the transport phase.

3.3.2 Initial assumptions

In order to facilitate the description of the operation of each of the phases of this project, the assumptions that are previously made are explained here.

If hydrogen is used as an energy source for charging electric vehicles, the first decision to be taken is that, when this gas is transported, should always be attempted in large quantities. This has an explanation owing to its density [80]. Hydrogen in its gaseous state has a very low density compared to liquid hydrocarbons, so it requires a much larger tank to store the same amount of energy.

Therefore, as a first approach, it is decided that one of the fixed values is the amount of hydrogen that is transported per run. The frequency of trips varies according to the daily energy demand. By entering this demand as an input value, the trip frequency is generated automatically. Consequently, an analysis of the feasibility and profitability of the project is carried out, which allows the drawing of conclusions and their subsequent discussion.

At a later stage and after the analysis of different situations, the quantity of hydrogen transported per run will be changed, reducing the capacity but increasing the frequency of travel of the trucks to see the impact on the simulations and comparing the results with those obtained in the first instance.

Once the number of kilograms transported is known, the frequency of trips varies according to the daily energy demand. By entering this demand as an input value, the trip frequency is generated automatically.

3.3.3 Components

A short description of the components' purpose and functionality can be found in this section. All variables used are defined in the nomenclature.

Wind Plant

The wind farm supplies the whole process with electric power. This electric energy generated is supplied to three different process steps. First, to the electrolyzer for hydrogen production. Another fraction of the energy goes to the compressor, providing the necessary power to feed this phase and compress the gas produced. In addition, the electricity from the renewable energy plant is also used to charge the electric trucks responsible for transporting the high-pressure hydrogen containers. In this way, as previously mentioned, the energy source in any phase of the project is 100% green and true to the zero-emission goal.

The wind plant outputs the required energy ($E_{W.Farm}$) for the process, which is determined by the final energy demand in different situations. The required energy consumption is the sum of the energy needed in the electrolyzer, in the compressor and in the charging of the electric trucks.

$$E_{Consumption} = E_{electrolyzer} + E_{compressor} + E_{charging} \tag{24}$$

The consumption of these three technologies is defined in the next section. Other input values are considered. The efficiency of this wind plant ($\eta_{W.Farm,losses}$) includes the energy that is lost in this first process, transferring the electricity to the three technologies mentioned above. As in the battery process, losses of 8% are assumed when converting AC power to DC power to feed the above-mentioned technologies [81]. Therefore, once the necessary consumption of the process and the efficiency value are known, we obtain the real energy needed from the wind power plant.

$$E_{W.Farm} = \frac{E_{Consumption}}{\eta_{W.Farm,losses}} \tag{25}$$

Electrolyzer

Given the different types of electrolyzers mentioned in chapter 2, PEM type electrolyzers are considered for the solution. Without going into detail, it is considered that these electrolyzers have advantages such as low maintenance requirements and the purity of the hydrogen at the exit of the electrolysis process, reaching a value of 99.998% [82].

The electrolyzer takes energy as its input $E_{electrolyzer}$, is the electrical energy that comes from the wind power plant every day. It then outputs hydrogen gas $H_{2,\ electrolyzer}$. An electrical efficiency of the electrolyzer is assumed according to [83]. It is represented by $\eta_{electrolyzer,\ electrical}$ (65%). This value is used to obtain the actual energy required to produce one kilogram of hydrogen (kWh/kg).

It is considered relevant to use this section to explain the selection of the hydrogen heating value. The use of the LHV value is common practice in the hydrogen industry and in most hydrogen production estimates, so it is consistent with standard practice and allows easier comparison between different projects.

Therefore, given the low calorific value of hydrogen LHV_{H2} (33.3 kWh/kg) [56], the consumption of the electrolyzer is marked by:

$$Elec_{Consumption} = \frac{LHV_{H2}}{\eta_{electrolyzer,electrical}} \tag{26}$$

Therefore, the necessary energy to be introduced to the electrolyzer is given by the following equation:

$$E_{electrolyzer} = \dot{H}_{2\ production} * Elec_{Consumption} \tag{27}$$

To analyze the costs later, the capacity of the electrolyzer in operation must be determined. The calculation of its direct capacity is trivial.

$$Electrolyzer_{Direct\ Capacity} = \frac{E_{electrolyzer}}{24} \tag{28}$$

However, this value is not the one to be used later, since it is useful if the electrolyzer were in operation 24 hours a day, and not only that, it also increases the investment costs. Therefore, to calculate the real capacity of the electrolyzer, a load factor of 80% is applied (representing about 19/20 hours per day). This decision is made in conjunction with the study carried out by the company and is justified in the knowledge that the storage capacity and the logistical pattern allow the electrolyzer to be used flexibly. Therefore, a good balance is found between the capacity factor and avoiding too high electricity prices [84].

Therefore, the electrolyzer capacity is generated dynamically, following the equation below:

$$Electrolyzer_{Capacity} = \frac{Electrolyzer_{Direct\ Capacity}}{Load\ Factor} \tag{29}$$

The objective of this is to try to optimize the capacity of the electrolyzer by adjusting it to the necessary hydrogen demand. However, for this capacity, a minimum of 0.25 MW is maintained, in order to obtain capacity values comparable to those available on the market**.** The minimum value of the efficiencies plays an important role in the development of this model. Therefore, based on literature review in which different capabilities are found and above all, decided in conjunction with the company and given its more extensive knowledge of this type of technology, it was decided to use this value as a minimum. The initial investment varies depending on the capacity obtained.

Finally, it is important to consider the energy losses that occur in the electrolyzer. They are marked by the electrical efficiency previously mentioned. Therefore, the losses are determined by:

$$Elec_{Losses} = E_{electrolyzer} * (1 - \eta_{electrolyzer,electrical}) \tag{30}$$

The calculation of energy losses throughout the process are used to determine the total energy efficiency.

Compressor

The compressor takes as input value the energy coming from the wind power plant $E_{compressor}$. This value is generated automatically and is marked by the energy required for hydrogen compression. That is, the greater the number of kilograms of hydrogen produced and compressed per day, the greater its capacity and therefore its power consumption.

According to [59], 3 kWh are considered for each kilogram of hydrogen that is compressed. A conservative value is chosen again. As for the compressor outlet pressure, it is assumed to be 500 bar. Therefore, the consumption required by the compressor is marked by:

$$E_{compressor} = \dot{H}_{2\ production} * Comp_{consumption} \tag{31}$$

In this way, the capacity of the compressor is also adjusted to the demand and is marked by the number of kilograms of hydrogen it can compress per hour. The equation is as follows:

$$Compressor_{capacity} = \frac{\dot{H}_{2\ production}}{n_{working\ hours}} \tag{32}$$

For the number of operating hours of the compressor, it is important to mention that they will be the same as those in which the electrolyzer is in operation since there will not be an intermediate phase between the two. Therefore, the load factor considered before is also used in this phase.

As in the electrolyzer, a minimum capacity is established, and its value is 10 kg/h. No matter how much less capacity than that is needed, that value is used. It is a representative value for existing hydrogen compressors on the market [85]

In addition, the electrical efficiency of the compressor is considered. This represents the losses in the form of heat when consuming electricity to carry out the compression. In some cases, compressors can be close to 100% energy efficient, meaning that most of the electrical energy input is used to compress hydrogen and is not lost as heat. In other cases, compressors may have a lower energy efficiency, resulting in a higher amount of heat loss. In this case, 5% of energy losses are assumed to be introduced to the compressor. [86]

It is assumed that are no hydrogen leaks in the compression. The number of kilograms obtained in the electrolysis process remains constant after passing through the compression phase.

Lastly, the losses in the form of heat in the compression phase are marked by:

$$Comp_{Losses} = E_{compressor} * (1 - \eta_{compressor,electrical}) \tag{33}$$

Transportation

To estimate the energy needed in this phase and thus charge the electric trucks, it is necessary to know the distance traveled. One of the input values therefore is the distance per run (one way to the charging station and back). In case situations with more than one charging station are analyzed, the actual distance is defined with a diagram showing the location of each one. But in the end, the necessary value is the kilometers per run that the truck(s) need to travel.

For the transport phase in terms of the hydrogen solution, the truck's consumption is determined by the amount of kWh it consumes per kilometer driven. Therefore, energy consumption in the transport phase is determined by the following:

$$E_{charging} = Distance_{run} * Truck_{consumption} \tag{34}$$

Another important value to highlight is the kWh required for each kilogram that is transported, which is obtained as follows:

$$E_{transport\ consumption} = Distance_{run} * Truck_{consumption} * \dot{H}_{2\ production} \tag{35}$$

It is in this phase where the value of hydrogen to be transported per run is decided and taken as a fixed value. Due to the difference in pressures in the hydrogen tanks, 100% of the available capacity in the tanks is never transported. Therefore, for this phase, it is assumed that 90% of the maximum capacity in kilograms of hydrogen is transported. For all these reasons:

$$\dot{H}_{2\ production} = \eta_{truck\ ,losses} * Truck_{capacity} \tag{36}$$

Now, once these three phases of the solution have been defined, the energy required in each part of the process is obtained and, therefore, the electrical energy to be extracted from the wind farm.

Fuel Cell

In the last phase before providing power to the chargers, some relevant factors come into play. To begin with, it is modeled in such a way that there is a stationary fuel cell in each charging station that is proposed. Therefore, the number of units is the first value to be calculated in the solution:

$$n_{fuel\ cell(s)} = n_{charging\ stations} \tag{37}$$

This time, the input value given to the fuel cell is the amount of hydrogen transported to the station per run, which, as previously mentioned, is a value that is set as fixed in the first instance. Therefore, the main output value of the fuel cell is the energy obtained per run.

$$E_{fuel\ cell} = \dot{H}_{2\ production} * LHV_{H2} * \eta_{fuel\ cell,electrical} \tag{38}$$

It is important to remember that, in this first solution, the energy produced per run is a fixed value since the total amount of kilograms of hydrogen transported per run is fixed, in the same way as the value of the electrical efficiency of the fuel cell. What changes is the amount of hydrogen produced per day and, therefore, the capacity of the fuel cell adapts to the daily energy demand, the greater the number of cars that stop to refuel their vehicle, the greater the capacity of the fuel cell.

Therefore, it is decided that the capacity of the fuel cell(s) is adapted to the number of cars stopping at the station each day. The maximum number of cars at any one time at a given hour is used and multiplied by the average energy requirement per electric vehicle:

$$Fuel\ Cell_{capacity,i} = Max_{n\ of\ Evs} * EV_{consumption} \tag{39}$$

$$Total\ Fuel\ Cell_{capacity} = Fuel\ Cell_{capacity,i} * n_{fuel\ cell} \tag{40}$$

At this stage, given the current low efficiency of fuel cells, it is important to calculate the energy losses, which in this case are determined by the electrical efficiency of the cell. a value of 60% is assumed [54].

$$Fuel\ Cell_{losses} = \dot{H}_{2\ production} * LHV_{H2} * (1 - \eta_{fuel\ cell,electrical}) \tag{41}$$

3.3.4 Costs

Component Cost

The following Cost Scheme is used to evaluate the total investment and operational cost of the process. The full investment cost is simply the component cost and investment cost added. Each component has an Operational and Maintenance cost that is paid annually. In addition, only the values used for the hydrogen solution are shown in the following tables. For the profitability analysis, both these and the common costs for both solutions are used.

This analysis is useful to determine that, regarding the capital expenditure of the electrolyzer, after different studies together with data that the company has [87], it is established that the electrolyzers of lower capacity have higher initial investment cost value and as the capacity increases, this cost is reduced. Also, for the hydrogen distribution system in which the high-pressure hydrogen tanks are contained, an estimate has also been made based on the literature. Therefore:

Component	Capex [K€]	OPEX [% Capex/year]	Lifetime [years]	Source
Electrolyzer (0,25 – 0,5MW)	2000 [/MW]	3	10	[58],[88],[89]
Electrolyzer (≥0,5MW)	1000 [/MW]	3	10	[58],[88],[89]
Compressor(s)	5 [/kg/h]	2	10	[86],[90]
Distribution System	750 [/kgH_2]	2	10	[91]
Fuel Cell	2200 [/MW]	1.5	10	[92]

Table 6. Component costs for the hydrogen solutio

3.4 Common parameters

As previously mentioned, there are common parameters that were implemented in both solutions. The parameters are the energy source (BayWa r.e. renewable energy plant), common truck, same types of chargers at the charging stations and finally, the same cost of electricity and the same selling price of electricity.

Wind farm:

The sample wind farm is used in both solutions for either charging the batteries or generating hydrogen. Another commonality is the AC-DC conversion efficiency of 92% [75] which remained common to both the solutions. However, the solution then diverges out with the hydrogen-based solution requiring a higher level of energy from the wind farm owing to the large number of components when compared to the battery-based solution which uses the wind farm for charging the batteries.

Chargers:

The same set of 120 kW chargers are considered in both the battery and hydrogen solutions. The prices of 120 kW chargers can vary between €0-50 K USD based on the brand and country of origin. In this analysis an estimated price of 40 k USD/charger is considered as the price spent on procuring each charger. In addition, charger installation costs are considered. While grid connected chargers tend to be expensive from an installation perspective and could cost up to 60000 USD/charger [93], installing off-grid chargers can be simpler and hence cheaper in comparison costing about 10000 USD/Charger.

$$Cost_{charger} in\ USD = 40000 + 10000\ USD/charger \tag{42}$$

Based on the traffic data analyzed, the number of chargers is estimated using the formula:

$$N_{chargers} = \frac{0.1\ x\ N_{cars}}{2} + 1 \tag{43}$$

As in the case of batteries, the price is converted from USD to € before proceeding with the CAPEX and OPEX costs.

$$Total\ CAPEX\ on\ chargers\ in\ Eur = N_{chargers}\ x\ Cost_{charger} in\ Eur \tag{44}$$

By assuming the lifetime, the Price/Year, Price/day and Price/MWh$_{delivered}$ are then obtained using the formulas:

$$\frac{Cost}{year}_{chargers} = \frac{Total\ CAPEX\ on\ chargers\ in\ Eur}{Charger\ Lifetime} \tag{45}$$

$$\frac{Cost}{day}_{chargers} = \frac{\frac{Cost}{year}_{chargers}}{365\ days} \qquad (46)$$

$$\frac{Cost}{MWh_{delivered}}_{chargers} = \frac{\frac{Cost}{day}_{chargers}}{E_{car}/1000} \qquad (47)$$

The maintenance costs are also assumed to be around 4% of the total CAPEX costs like in the case of batteries and the following steps were taken to calculate the Price/MWh$_{\text{delivered charger maintenance}}$.

$$\frac{Cost}{year}_{charger\ maintainance} = \frac{Total\ CAPEX\ on\ chargers\ in\ Eur\ x\ 0.04}{Charger\ Lifetime} \qquad (48)$$

$$\frac{Cost}{day}_{charger\ maintainance} = \frac{\frac{Cost}{year}_{charger\ maintainance}}{365\ days} \qquad (49)$$

$$\frac{Cost}{MWh_{delivered}}_{charger\ maintainance} = \frac{\frac{Cost}{day}_{charger\ maintainance}}{E_{car}} \qquad (50)$$

Transportation:

With the biggest contributors to the battery solution coming in from the battery costs and transportation costs, there were two approaches considered while modelling the solution. The first approach aimed at minimizing the number of battery CAPEX by estimating the number of batteries needed to meet the daily demand. The number of battery deliveries from the wind park is limited to 2 per day.

The second approach aims at minimizing the number of trips undertaken by the truck by filling up the trucks completely to the weight limit. In this approach, the transport costs are reduced but the battery CAPEX rises since the requirements for the number of batteries increases. The calculations show that battery CAPEX has a higher driving cost and hence, the first approach has been considered while modelling the battery solution.

From information online, the cost to transport goods from one place to another is in the range of 3 €/km [94]. For transporting batteries, this is considered as an acceptable limit as no specialized storage conditions are needed for transportation. However, from the cost perspective, it is assumed that transporting compressed Hydrogen from one location to another will be more expensive since hydrogen requires special storage conditions and hence the price/km for transporting hydrogen is considered as 4 €/km when compared against the 3 €/km factor used in the battery-based solution.

Cost of electricity:

The cost of electricity plays a very important role in the development of the solution and serves as a source of revenue for an energy park operator. In both solutions, it is taken as a fixed value and considered as the primary source of revenue for the energy park operators. In both solutions, this figure has been fixed to 40 €/MWh [95].

Source of Income – Charging Station:

The charging station obtains its revenue by selling electricity to customers who wish to fast charge their vehicles. This price is the sole source of income for the charging station operator and in both the solutions, the price falls between 500-600 €/$MWh_{delivered}$ as an estimate [96].

3.5 Revenues

To evaluate the economic viability of the project, all the costs previously raised need to be considered. The operating income for each MWh of electricity sold to the customer is calculated by subtracting the costs that incurred during the CAPEX and OPEX along with additional costs which include the transportation costs and Cost of electricity/$MWh_{delivered}$ from the gross revenue. The gross revenue for both solutions remain common, varying between 500 and 600 €/$MWh_{delivered}$. While the same set of units have been used for calculating the net revenue in both solutions, the set of parameters used for calculating the same vary.

The following factors contribute to the costs:

Hydrogen solution - Components	Battery solution - Components	Costs
-	Batteries	€ [/MWhd]
Electrolyzer	-	€ [/MWhd]
Compressor	-	€ [/MWhd]
Transportation	Transportation	€ [/MWhd]
Distribution System	-	€ [/MWhd]
Fuel Cell(s)	-	€ [/MWhd]
Chargers	Chargers	€ [/MWhd]
Electricity	Electricity	€ [/MWhd]

Table 7. Cost components for both solutions

For each technology, CAPEX, OPEX, and finally the cost of electricity mentioned above, are considered.

With the Electricity selling price being the source of gross revenue for the station, the operating income is calculated by using the formula:

$$Operating\ Income = Gross\ Revenue - Total\ Costs \tag{51}$$

4. Results

4.1 Introduction

In this section, the results of both batteries and hydrogen-based solutions previously explained are presented. Certain situations that are analyzed and the reason for this choice will be explained.

Besides analyzing the feasibility and profitability of each solution under the scenarios considered, a comparison between them is carried out in order to identify which solution is most interesting in each scenario and highlighting the reasons for it. Therefore, once the results of both solutions are presented, a comparison process is carried out highlighting the most relevant information for the discussion of this work.

In the first instance, a base case is presented, relevant results will be shown and finally, a sensitivity analysis is carried out independently to see the impact on the viability and profitability of both processes.

4.2 Base Case

This first section shows the results obtained in a base case and provides an example of the results obtained each time a simulation is performed. Therefore, results will be shown independently and in the following sections both processes will be compared in the most relevant situations.

The section elaborates on the energy flow obtained in each simulation and the cost breakdown of each of the technologies involved in the solutions. A medium level distance and demand is considered in the base case for elaboration.

The common input values given to both solution models prior to their simulation are as follows:

INPUT VALUES		
Number of Charging Stations	1	unit(s)
Number of EVs	30	cars/day
Distance to Charging Station	40	km
Total daily energy needed	1650	kWh/day

Table 8. Input parameters in both solution models

Battery Results

After selecting the parameters, and in order to dimension the supply chain, it is needed to estimate the number of batteries required to meet the daily demand.

With each battery operating around the range of 20-80% SOC, the 281 kWh Northvolt Voltpack mobile should deliver around 169 kWh per run.

Total capacity of the storage system	281	kWh
Usable capacity (20-80% SOC) (E_{pack})	169	kWh
Efficiency of the battery $\eta_{battery}$	95%	%
Efficiency of the charger $\eta_{charger}$	97%	%
Number of batteries $N_{batteries}$	10	Unit(s)

Table 9. Battery estimation based on efficiencies and SOC

Through AC-DC conversion losses, more energy is required from the wind farm to charge the batteries. The charging time for the batteries is six hours.

Total desired capacity in the batteries ($E_{batteries}$)	1791	kWh
AC-DC conversion efficiency η_{wind}	92%	%
Total energy consumption from the wind farm (E_{wind})	1946	kWh
Charging duration (T_{charge})	6	hours
Total power required from the wind farm (P_{wind})	324	kW

Table 10. Wind power estimation

The remaining 8% of the power and energy lost during the energy conversion process is dissipated as heat.

Energy lost as heat ($E_{wind\ loss}$)	156	kWh
Power lost as heat ($P_{wind\ loss}$)	26	kW

Table 11. Energy losses between the wind park and batteries

For transporting the batteries, the 40 ft long container can carry 8 batteries in one run. In this case, these batteries are supplied to the charging station through two deliveries (5 + 5) and supply through this method will help in ensuring that battery CAPEX costs remain low. However, the two deliveries would result in 4 runs of 40 km each, thereby increasing the transportation cost.

Costs:

	Batteries
Capacity [kWh]	281
Units	10
CAPEX [€/kWh]	220
CAPEX [€/year]	62440
OPEX [€/year]	4

Table 12. Battery CAPEX and OPEX cost

	Chargers
Power (kW)	120
Units-Max needed in one hour	3
CAPEX [€/unit]	50000
CAPEX [€/year]	13900
OPEX [€/year]	560

Table 13.Charger CAPEX and OPEX cost

Considering two trucks:

	Transportation
Travel cost [€/km]	3
Total distance (km/day)	160
Travel cost [€/day]	480

Table 14. Transportation costs for battery base case

	Wind farm
Electricity Buying price [€/MWh]	40
Electricity procurement cost [€/day]	78

Table 15. Electricity procurement cost

Parameter	CAPEX	OPEX	TOTAL
Battery	104	4	**108 €/MWhd**
Charger	23	1	**24 €/MWhd**
Transportation	-	291	**291 €/MWhd**
Wind farm	-	47	**47 €/MWhd**

Table 16. Total costs per MWhdelivered for each parameter – Battery solution

Hydrogen Results

By entering the parameters previously described in the simulation model made for the process of using hydrogen as an energy carrier, the necessary values for further analysis are automatically calculated. These values consist of the amount of hydrogen, the energy flow and process costs.

As explained in the definition of the solution, and based on compressed hydrogen carrying capacity, the first value obtained is the amount of hydrogen to be transported per run. Considering efficiency:

RELEVANT PARAMETERS		
Max. Truck Capacity	**1000**	**KgH_2**
Transport Efficiency	**90**	**%**
Transported Hydrogen	**900**	**Kg/run**

Table 17. Relevant parameters – Hydrogen solution

Therefore, the energy contained in the hydrogen per run when transporting 900 kilograms in each truck will be:

H_2 Contained Energy	**30**	**MWhd/run**

By knowing the daily energy demand and the energy contained in each run when transporting hydrogen, the solution model generates the following results:

Number of runs	**0,0153**	**runs/day**
Time between trips	**10**	**days**
Hydrogen production	**90**	**Kg/day**

Table 18. Hydrogen produced per day.

The consumption of each technology and the energy losses due to the efficiency of each of the phases are shown below:

Components	Energy Consumption [kWh/run]	Energy Consumption [kWh/day]
Wind Farm	54284	5428
Electrolyzer	46108	4611
Compressor	2700	270
Transportation	48	5

Table 19. Energy consumption for each component

Components	Energy Losses [kWh/run]	Energy Losses [kWh/day]
Electrolyzer	16140	1614
Compressor	135	14
Fuel Cell	11988	1200

Table 20. Energy losses for each component

The losses help in determining the difference between the energy that needs to be obtained from the wind power plant and the energy that is provided for the recharging of electric vehicles.

Overall Energy Process Efficiency	33	%

Table 21. Overall energy efficiency

These results present the values obtained in terms of energy flow and the necessary hydrogen production. Now the breakdown of costs for each of the technologies present as well as the costs of the process as a whole are shown.

	Electrolyzer	Fuel Cell
Capacity [MW]	0.25	0.25
Units	1	1
CAPEX [€/MW]	2000000	2200000
CAPEX [€/year]	50000	55000
OPEX [€/year]	750	825

Table 22. CAPEX, OPEX and Power costs for electrolyzer and fuel cell

	Transportation
Travel cost [€/run]	160
Travel cost [€/day]	2.5

Table 23. Transportation costs for hydrogen base case

	Mobile Storage
CAPEX [€/kgH_2]	750000
CAPEX [€/year]	75000
OPEX [€/year]	15000

Table 24. Mobile storage costs for hydrogen base case

The cost breakdown for the total number of chargers is mentioned in the battery results part. It is a common parameter for both solutions. The table below summarizes all the costs per MWh delivered. It is considered relevant in order to know how much each technology contributes to the overall cost.

Technologies	CAPEX	OPEX	POWER (Electricity)	TOTAL
Electrolyzer	83 €	1 €	112 €	**195 €/MWhd**
Compressor	8 €	0,2 €	7 €	**15.2 €/MWhd**
Transportation	-	19 €	0,1 €	**19.1 €/MWhd**
Mobile storage	125 €	2,5 €	-	**127.5 €/MWhd**
Fuel Cell	132 €	2 €	-	**134 €/MWhd**
Chargers	23 €	1 €	-	**24 €/MWhd**

Table 25. Total cost per MWhdelivered for each technology – Hydrogen solution

Cost breakdowns

In this section, the cost breakdown of all the technologies present in the results obtained from the base case is shown.

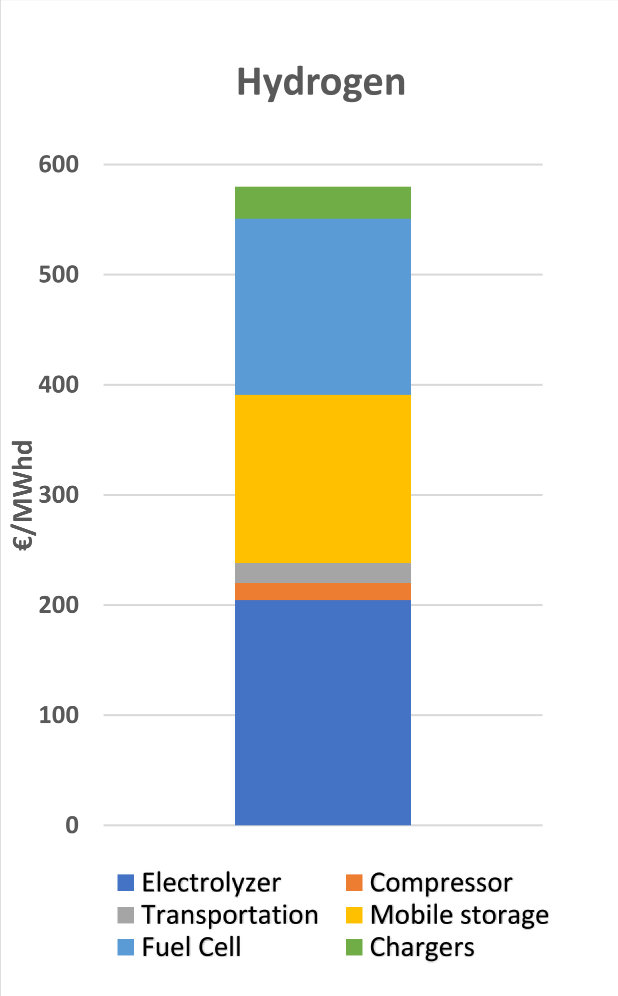


Figure 19. Cost Breakdown - Hydrogen Base Case

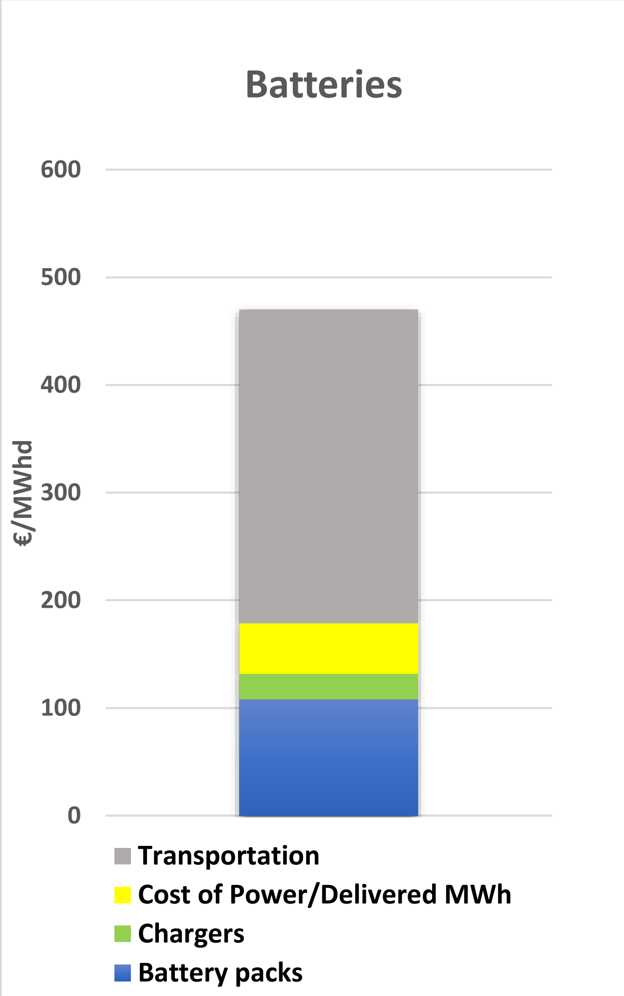


Figure 18. Cost Breakdown - Batteries Base Case

The cost stacks shown represent the cost of the technologies present for each MWh provided to the customer. To obtain it, the cost per day (representative cost) is divided by the MWh of daily demand at the charging station. In this way, the representation of each technology on the total cost of the process is seen graphically.

In the case of hydrogen, the first value represents the sum of all the costs present in the electrolyzer, its CAPEX, its OPEX and also the cost of electricity consumed to carry out the electrolysis process. The next one is the compressor, and it includes the same as for the electrolyzer.

As for the transportation costs, it includes the cost for the kilometers traveled by the truck. The mobile storage includes its CAPEX and operations and maintenance costs. Finally, the fuel cell represents both the initial investment required and OPEX.

Similar steps have been followed in the battery solution for preparing the cost stack of the same. The main technology involved in the solution is the ESS battery packs and the CAPEX and OPEX for them have been considered. The Cost of Power/Delivered MWh signifies the costs required for drawing energy from the wind park in order to charge the batteries. Contrary to the hydrogen solution, the transportation process in the battery solution is relatively simpler and considers the rates per kilometer driven.

To see a percentage representation of this cost breakdown, a pie chart is shown for both:

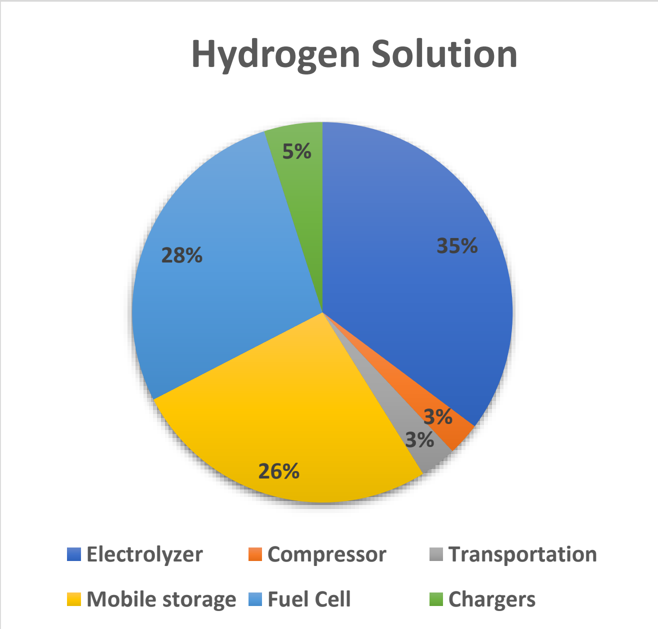


Figure 20. Hydrogen Cost Contribution Percentage - Base Case

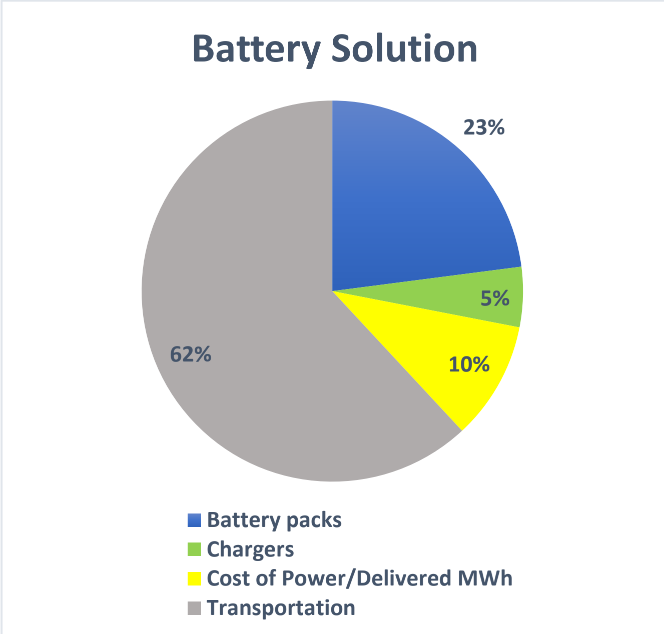


Figure 21. Batteries Cost Contribution Percentage - Base Case

The main contributors of the total hydrogen process costs for this case are the electrolyzer and the fuel cell, mainly due to their high initial investment cost. Followed by mobile storage, which also accounts for a high percentage of the total. Finally, the chargers, the compressor and transport represent between them about 10% of the total.

The cost stacks and pie chart of the battery solution show that Battery CAPEX and Transportation costs are the biggest contributors towards the overall costs. This is attributed to transportation costs originating from the number of trucks required for transporting the ESS battery packs. Hence during the sensitivity analysis, it is important to vary these two parameters and observe the impact they play on the overall cost and operating income.

4.3 Relevant results

After several simulations and different scenarios, the most relevant ones are discussed. The selected scenarios allow a useful comparison between the battery solution and the hydrogen solution.

4.3.1 Short Distance Scenario

First, a situation is considered in which the distance to be traveled by the truck between the wind farm and the recharging station is low. A scenario is analyzed in which the distance is approximately 15 km and simulations are performed for various energy demands.

To evaluate the profitability of both processes, it is observed whether costs exceed the gross revenues. The following graph shows the costs per MWh delivered to the customer for both solutions.

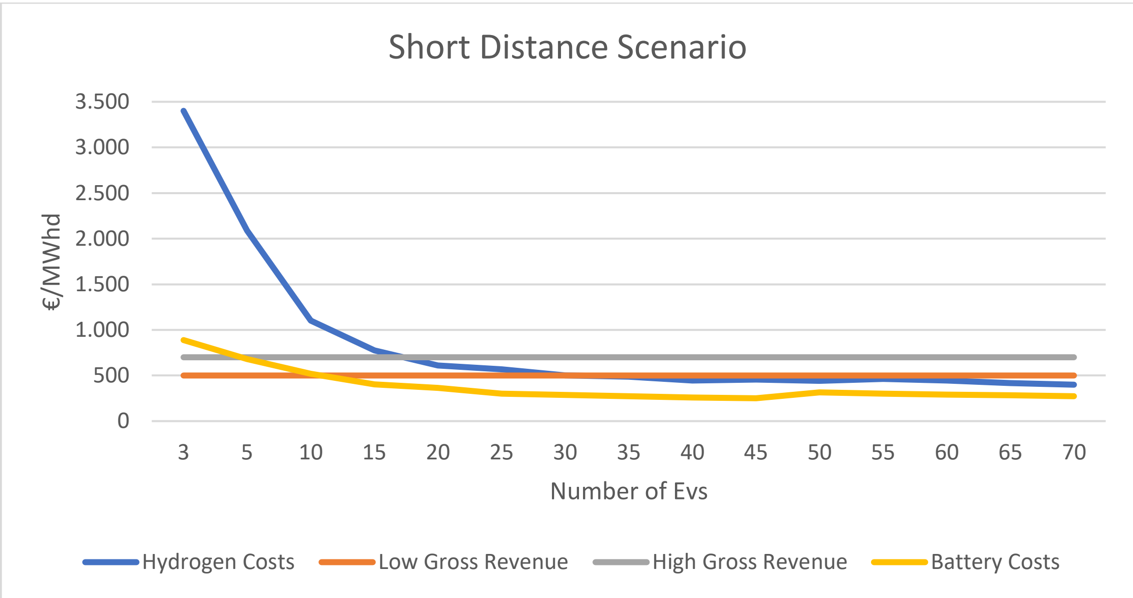


Figure 22. Costs vs Gross revenue – Low distance scenario

From the above trends, the battery solution has an edge over the hydrogen solution with regards to the overall costs and operating income. The reason behind a non-linear trend in the battery solution is attributed to the unoptimized supply chain process which in turn led to an increased number of trips. The hydrogen solution is highly unprofitable when demands are low but yields profitable results with a rise in demand. However, the overall costs of the battery solution are reduced at a higher rate. Hence, when distances between the wind park and the charging station are low, it is recommended for station operators to consider batteries over fuel cells when operating under off-grid scenarios.

4.3.2 Long Distance Scenario

In the second analysis, the distance between the two points is increased to 75 kilometers, with the truck traversing 150 kms in each run.

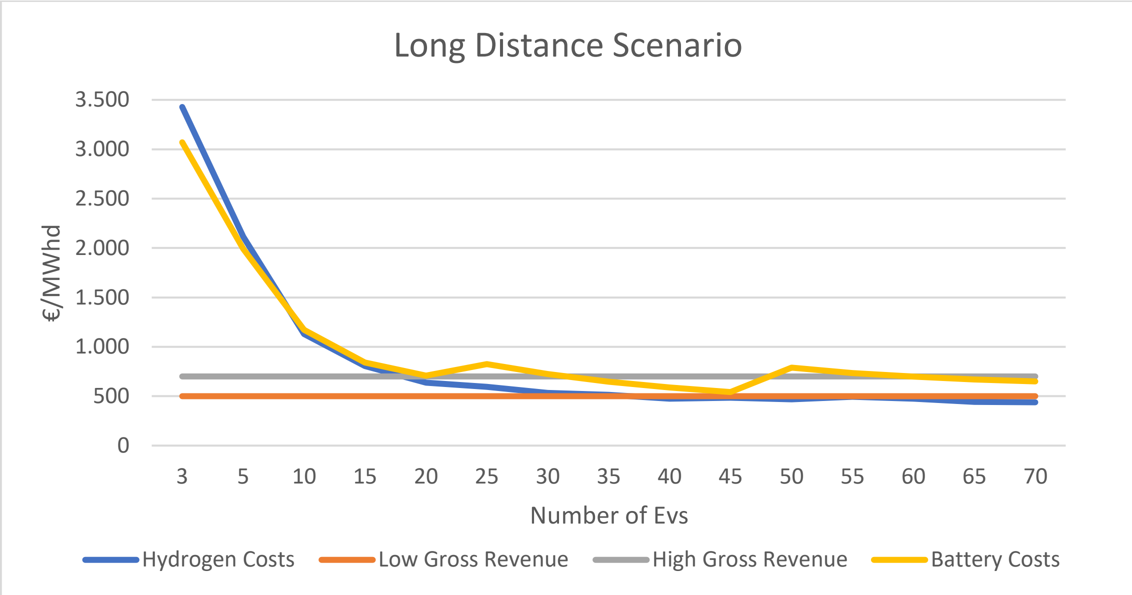


Figure 23. Costs vs Gross revenue – High distance scenario

With an increase in distance, the hydrogen solution performs considerably better than the battery solution. The reason behind this could be attributed to the low transportation costs that arise from the amount of hydrogen that can be delivered in one truck whereas the batteries with their low weight energy density would require more trucks to deliver the same amount of energy. The uneven trends in the battery model are attributed to the weight limits present in the truck which in turn increases the transportation costs. For e.g., a daily demand of 25 cars/day translates to 9 batteries and this means that 2 trucks will be required (8 batteries in truck 1 + 1 battery in truck 2) thereby sub optimizing the supply chain and raising the transportation cost. Furthermore, with long distances, the transportation cost in €/km is expected to be higher than the figure considered in the model since an additional driver might be required to support the delivery process. Hence, when the distances between the wind park and the charging station are high, it is recommended for station operators to consider fuel cells over batteries when operating under off-grid scenarios.

4.3.3 Increasing number of Charging Stations

As a third scenario that is considered relevant for the comparison of the economic feasibility between the two solutions, the following is proposed: A situation in which the daily energy demand of three different charging stations must be supplied. It is assumed that the number of cars stopping daily is the same for all three stations. The simulations are carried out by starting with demand of only 15 cars per day at each of them and by intervals of 5, increasing it to high demand of 50 cars stopping to recharge their battery at each station. The route to be taken by the trucks is as follows:

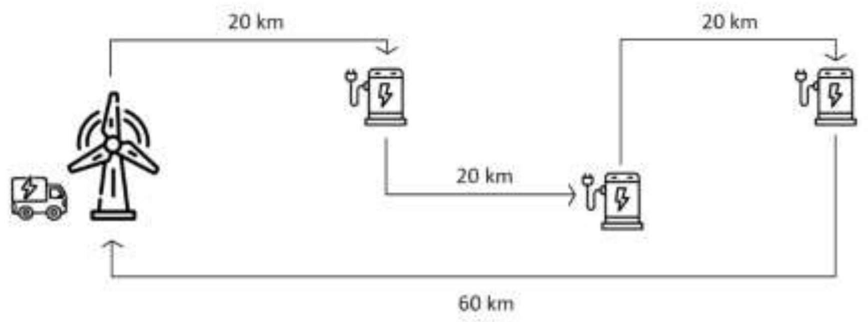


Figure 24. Illustrative diagram – Three stations

The following graph shows the difference between the common gross income and the total costs of each of the processes, batteries, and hydrogen.

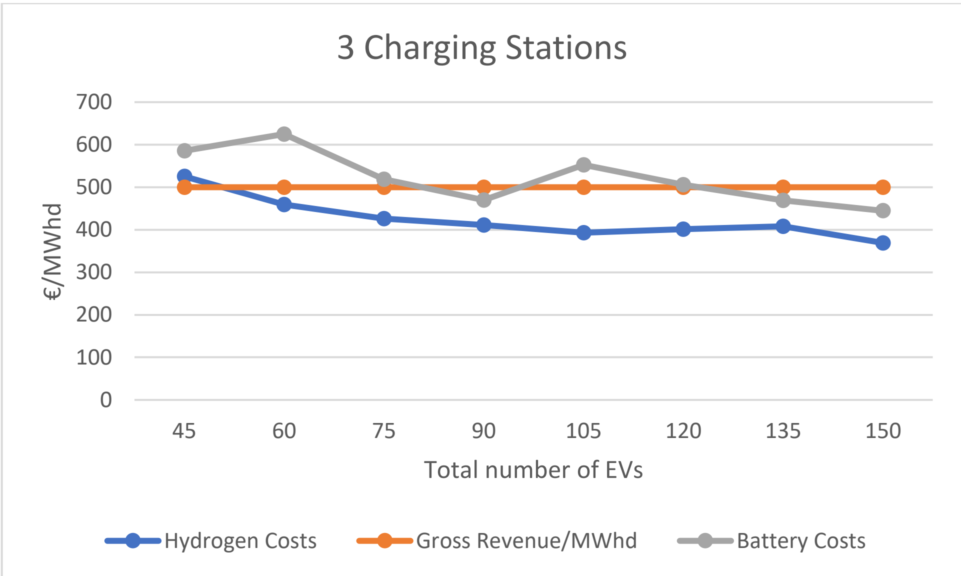


Figure 25. Costs vs Gross revenue – Three stations

With the idea of considering a mid-level distance, the maximum distance between a station and the wind park is 60 kms. However, for the process in which batteries are transported, the transportation costs involved deem the scenario unprofitable when the overall demand is low. In the case of hydrogen, with the transport capacity being so high and the frequency of trips lower than required, the greater energy demand would result in greater optimization of the technologies used and thereby help in generating a higher net income.

In order to see what the transportation costs are in each of the solutions, the percentage contribution of each of the technologies in both solutions is shown. The percentage cost split is shown for the case of 30 cars at each charging station.

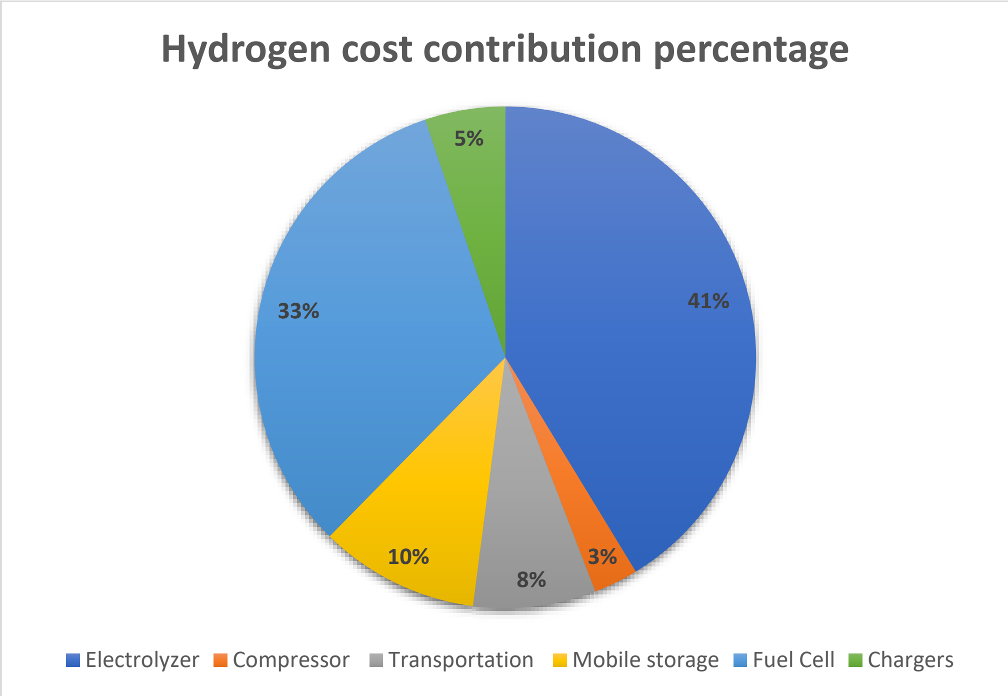


Figure 26. Hydrogen cost contribution chart – Three stations

As can be seen, transportation costs only represent 8% of the total costs since, with only a large capacity truck, and a travel frequency of 3 days, the costs are reduced to a total of 33 €/MWhd.

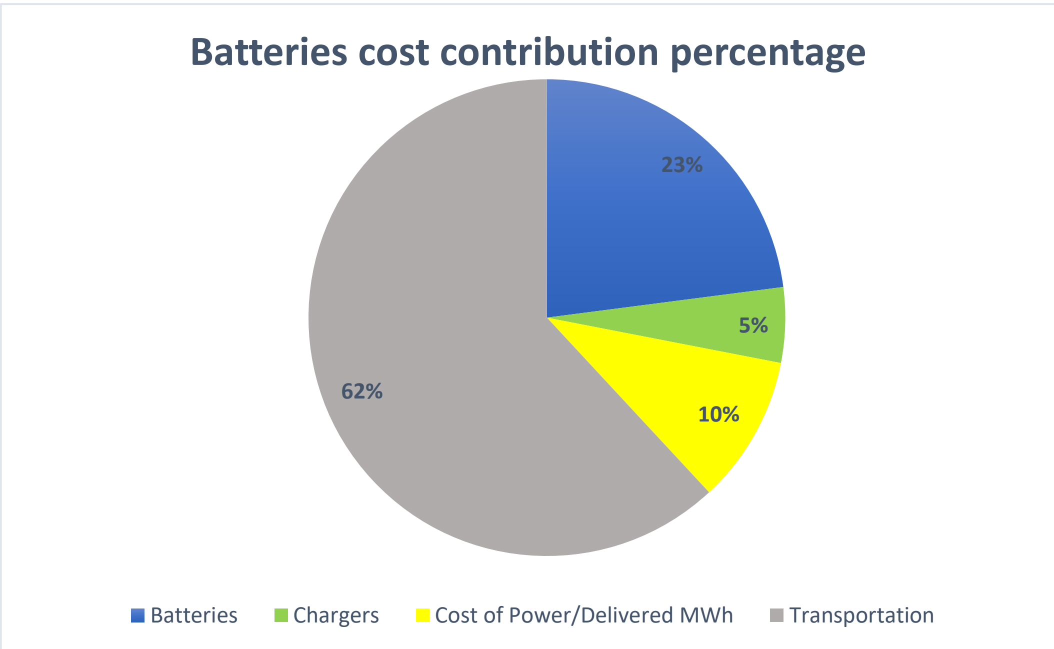


Figure 27. Battery cost contribution chart – Three stations

However, in the case of the battery solution, the pie chart shows that the high transportation costs coupled with the CAPEX needed for procuring the batteries made the scenario highly unprofitable despite the increase in demand. To summarize, the overall distance traversed by the trucks will play a crucial role in determining the overall profitability of the battery solution.

4.4 Sensitivity analysis

In this section, a sensitivity analysis of the results is performed, and then presented, analyzed and compared with the reference values from the base case. Parameters that are considered relevant and that have a major impact on the processes are considered. The analysis is performed separately for the battery and hydrogen solution.

4.4.1 Batteries

As observed in the previous results, battery CAPEX and transportation costs have played the biggest role in contributing to the overall costs. It is expected that varying these costs by around 15-35 percent could have an impact on the overall profitability of the battery solution.

Parameter	Original Price	Updated Price	Variation
Battery CAPEX	240 $/kWh	200 $/kWh	-16%
Transportation cost	3 €/km	2 €/km	-33.3%

Table 26. Price variation in the sensitivity analysis

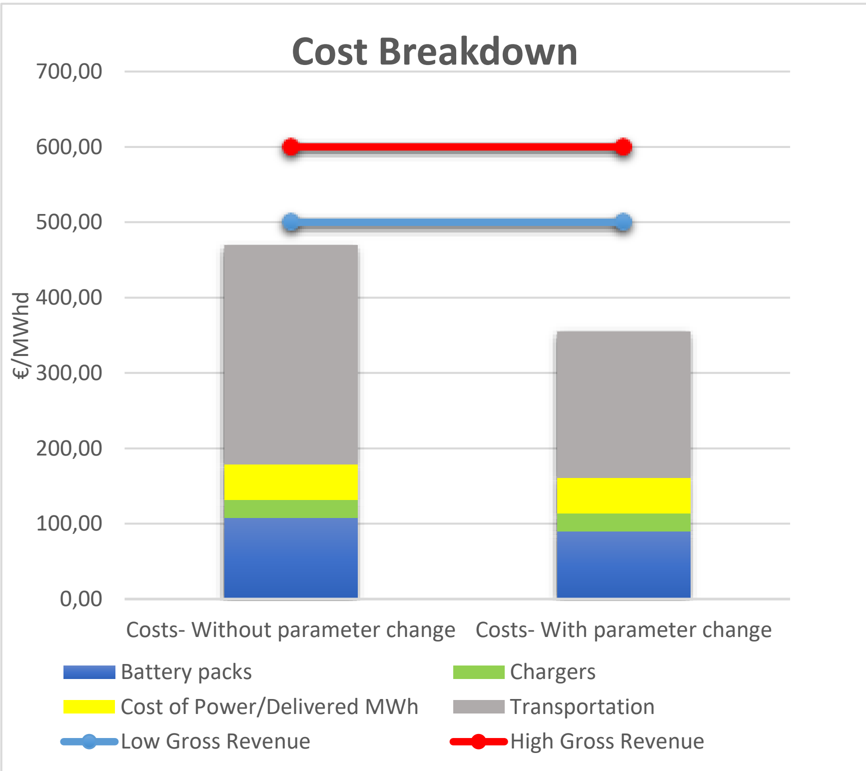


Figure 28. Cost Breakdown- New parameters in Battery solution

The cost breakdown above shows that reducing the battery CAPEX and transportation costs could help towards achieving higher profitability when distances are relatively high in the battery solution. With battery prices projected to fall in the coming decade [37], the battery solution supported by an optimized supply chain process has the potential to deliver profitable results to off-grid charging station operators even if the energy park is at a far distance.

The results show that by varying just two factors, the possibility of improving the overall profitability of the battery solution exists. From a futuristic perspective, battery technologies are expected to mature before hydrogen [97] which means that prices for batteries are expected to drop more rapidly than the technologies that are required for producing hydrogen. Hence, while the battery solution may not work relatively well against fuel cells for now when considering longer distances, the scope for batteries to do relatively well in the future remains. Furthermore, enhanced futuristic technologies in the field of supply chain like driverless trucks will also help lowering transportation costs significantly as the driver salary costs can be eliminated.

Another parameter is the weight energy density of batteries. In the coming years, solid state batteries could improve the weight energy density by almost 2.5 times thereby allowing larger amounts of energy to be stored in while having the same overall weight [98]. This would help to reduce the number of ESS packs needed for serving a charging station and thereby help towards optimizing the supply chain and reducing transport costs. However, during the advent of any technology, the price/kWh is expected to be relatively higher than the current prices due to which the higher battery CAPEX may not help in reducing the overall costs of the solution.

Lastly, in the scenario of an unoptimized supply chain, there is a possibility of replacing some batteries with solar panels or small-scale wind turbines which can directly be connected to the charging station. This will help in lowering both the battery and transportation costs and lowering these two cost parameters can play a pivotal role in improving profitability. However, it is to be seen whether the costs involved in the CAPEX and OPEX of solar panels with lower battery CAPEX and transportation costs will deter the overall profitability of the solution. Another issue with installing solar panels in Northern Sweden is the low irradiance during the winter months which may render the substitution of some batteries impossible. The feasibility of using solar panels has been analyzed in chapter 5.

4.4.2 Hydrogen

Efficiency of the technologies

The first parameter to be analyzed is the efficiency of the electrolyzer and the fuel cell. These are the most important systems in the process of using hydrogen as an energy carier. Both have increased by 10%. In the case of the electrolyzer, this increase means a lower electricity requirement in the electrolysis process, thus obtaining more kilograms of hydrogen for each kWh introduced to it. For the fuel cell, it means a lower need for hydrogen to generate more electricity at the points of demand, thus optimizing the process studied.

These are technologies that are currently evolving and gradually achieving better performance values. Therefore, it is considered appropriate to make an estimate with better efficiency values.

Technologies	Efficiencies	
	Reference	*Higher Values*
Electrolyzer	65%	75%
Fuel Cell	60%	70%

Table 27. Efficiency offset for the sensitivity analysis – Hydrogen solution

To see the impact that this improvement has, the values obtained in the situation presented as the base case are compared. Only one charging station and 40 kilometers away from the wind farm.

The first important value to comment on is the increase in the energy efficiency of the process. Although it is still low, the difference between the energy that must be fed into the electrolyzer at the beginning and the actual electricity available to the customer at the charging station is considerably reduced. There are fewer energy losses in the electrolyzer and fuel cell stages and thus higher overall efficiency.

Overall Energy Efficiency	*Reference*	*Higher Values*
	33,13%	44,21%

Table 28. Updated efficiency

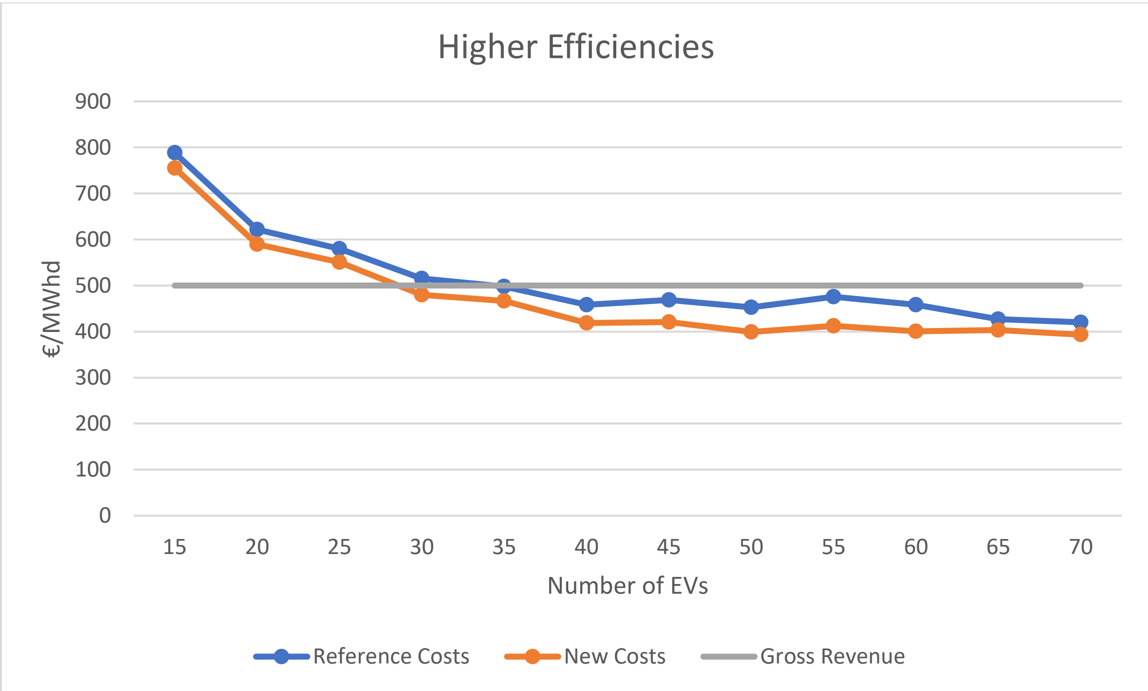


Figure 29. Costs vs Gross revenue – Hydrogen solution

The costs are represented by each MWh delivered to the customer. As seen in the graph, profits are achieved with lower daily energy demand. With these new efficiency values, net profitable income is achieved from less than 30 cars per day stopping to recharge batteries in contrast to the previous requirement of 35 cars/day. Therefore, in the coming years it will be possible to achieve the operation of these technologies for large-scale projects with better performance. With better efficiency, the production of electricity at the production site is higher for the same amount of hydrogen, thus reducing the need for transport. The difference is shown in the following graph:

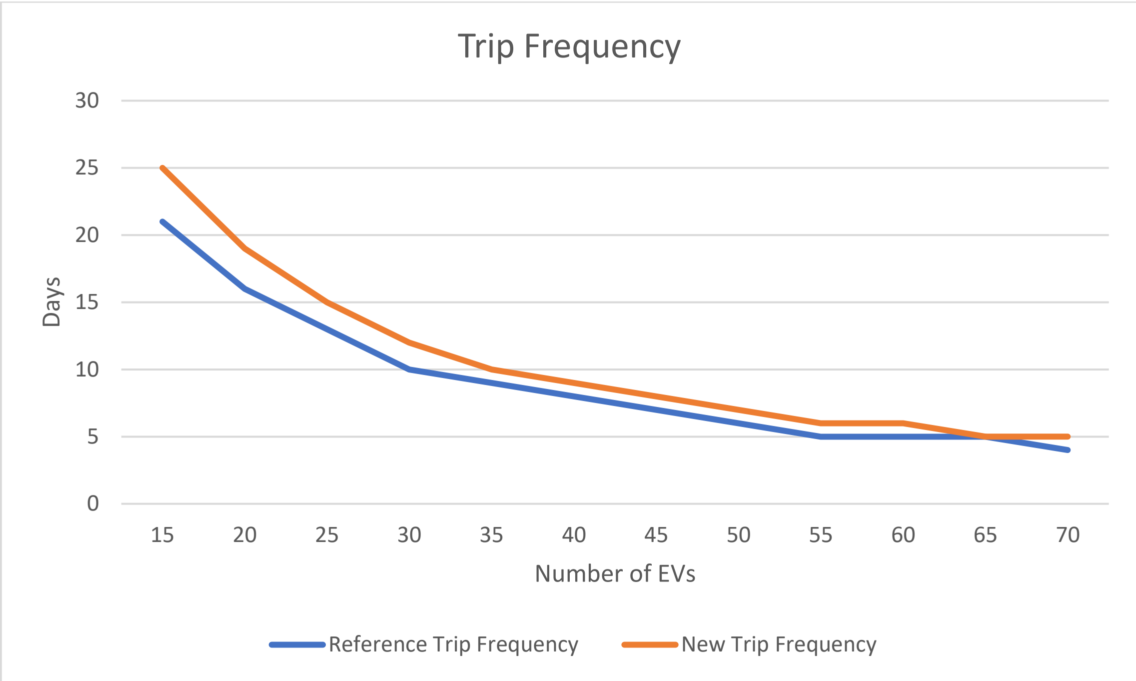


Figure 30. Updated trip frequency – Hydrogen solution

In-depth economic evaluation

It is considered appropriate to perform a more in-depth economic analysis in the sensitivity analysis section. Therefore, as a second parameter to be used, the results of the net present value for an established business duration is obtained.

For the calculation, initial values are given. The results are intended to be seen for a business duration of 15 years. The profitability of an investment is defined by the sign of the net present value (NPV). If it is positive, it indicates the profitability of the process.

Therefore, and for the base case previously described, the results obtained are as follows:

Total Capex	**2.230.888,89 €**
Annual Net Revenue	**214.092,21 €**
Payback period (years)	**10,42**
Discount rate	**5,5%**
Net Present Value (NPV)	**-81.920,96 €**

Table 29. In-depth economic evaluation - Hydrogen solution

The total CAPEX calculation considers the cost of each technology previously shown multiplied by its capacity. The annual net revenue considers the difference between the electricity sales price (500 €/MWhd is considered) minus the costs of operations, maintenance and electricity input. It can be seen that a discount rate of 5.5% gives a payback period of more than 10 years and a negative net present value, therefore, it is not economically profitable.

If we propose a less restrictive discount rate, and reduce it to 4,5% for the base case, we obtain:

Discount rate	**4,5%**
Net Present Value (NPV)	**68.364,23 €**

Table 30. NPV for a lower Discount Rate - Hydrogen solution

The total CAPEX, the annual net profit and the payback period remain constant with this change. On the other hand, at this discount rate value, a positive NPV is obtained, which represents profitability in the business.

Electricity Purchase Cost

The purchase price of electricity does not play a vital role in the development of the process of using hydrogen as an energy vector. If a percentage of the reference price is increased or decreased, the variation in terms of final net profit or total costs is not high. To do this, a comparison is made with the reference values to see what would happen if this purchase price were lower or higher. The reference value used in the development of the solution is modified by ±10%.

Electricity Purchase Cost	*Reference*	*Lower Cost*	Higher Cost
	40 €/MWh	36 €/MWhd	44 €/MWhd

Table 31. Updated electricity purchase cost

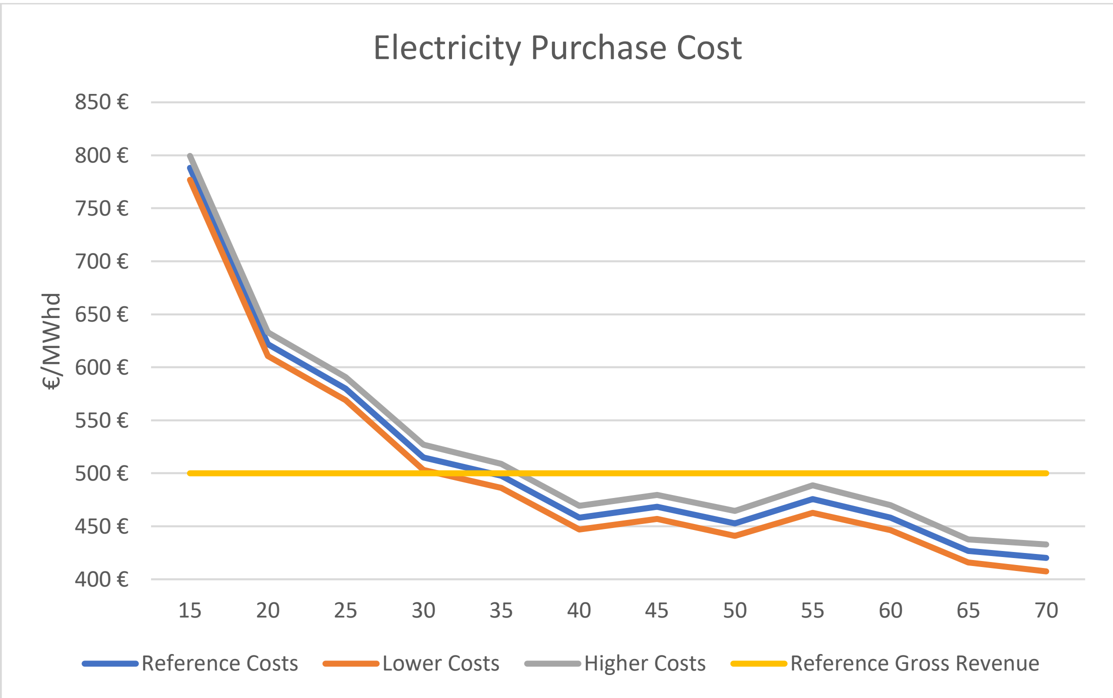


Figure 31. Updated costs vs Gross revenue - Hydrogen solution

The graphs shows that by modifying the purchase price of electricity, the energy demand necessary to generate profit does not have as much impact as the modificiations of other parameters previously analyzed. The costs shown in the graph are per MWh delivered to the customer and represent the situation in the base case.

5. Complementary studies and discussion

In this section, some complementary studies are carried out and a discussion of different aspects relevant to the processes described are made. In addition, the disparities between the actual and theoretical values used are explained in order to see the consequences in the results obtained.

5.1 Integrated solutions for batteries

The initial analysis undertaken investigates the potential of connecting ESS that will support weak grids in charging vehicles. No supplementary wind park or transportation system is considered for supporting the charging station. While the costs for procuring and maintaining batteries remains the same as the off-grid scenario, the installation cost of chargers, part of the CAPEX is considered as 60000 $/charger instead of 10000 $/charger considered in off-grid scenario since installing grid connected chargers require larger costs owing to the civil works involved in installing them when compared to off-grid chargers which are simpler to install [37].

As part of the analysis, two scenarios are considered and within each scenario, the grid power varies between 30 kW, 50 kW and 80 kW.

First Scenario:

INPUT VALUES		
Number of EVs	10	cars/day
Total daily energy needed	550	kWh/day

Table 32. Input values – Weak grid scenario 1

Energy Deficit-10 cars/day

Grid power supplied	Energy Deficit	Number of ESS packs needed
30 kW	320 kWh	2
50 kW	200 kWh	1
80 kW	90 kWh	1

Table 33. Power Deficit over a twenty-four-hour period - Scenario 1

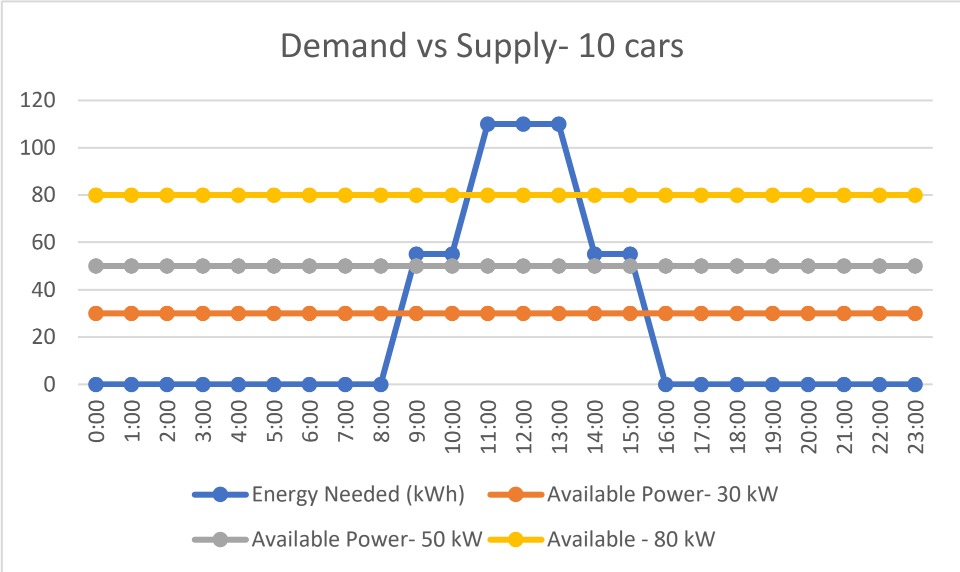


Figure 32. Energy demand vs Supply – Scenario 1

Costs:

The total costs incurred when operating under a 30-kW grid power are higher with the CAPEX for the ESS being higher.

Grid Power	Total Costs
30 kW	224 €/MWhd
50 kW	179 €/MWhd
80 kW	179 €/MWhd

Table 34. Total costs incurred – Scenario 1

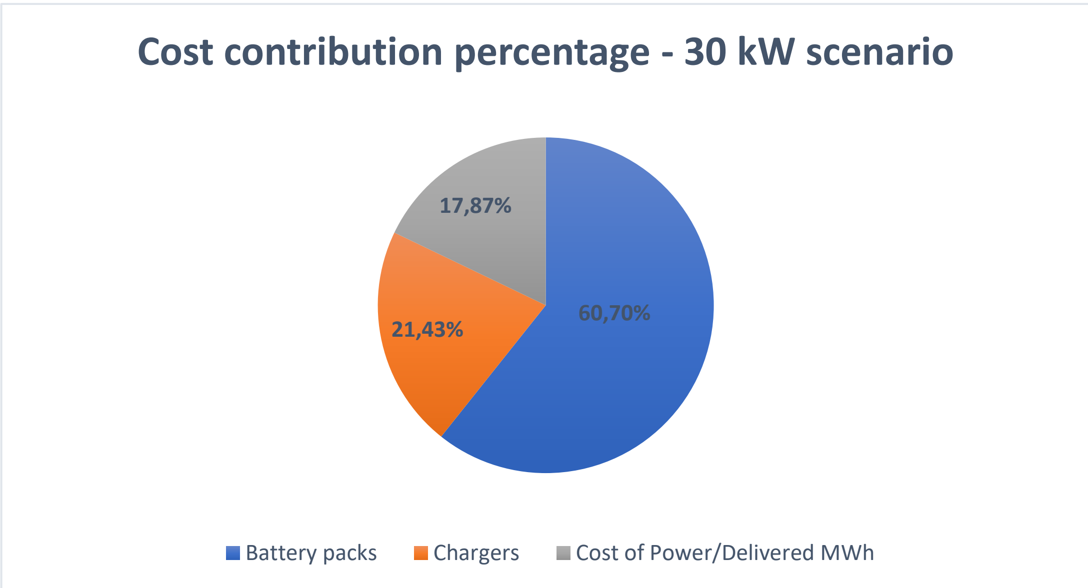


Figure 33. Cost contribution percentage – 30 kW

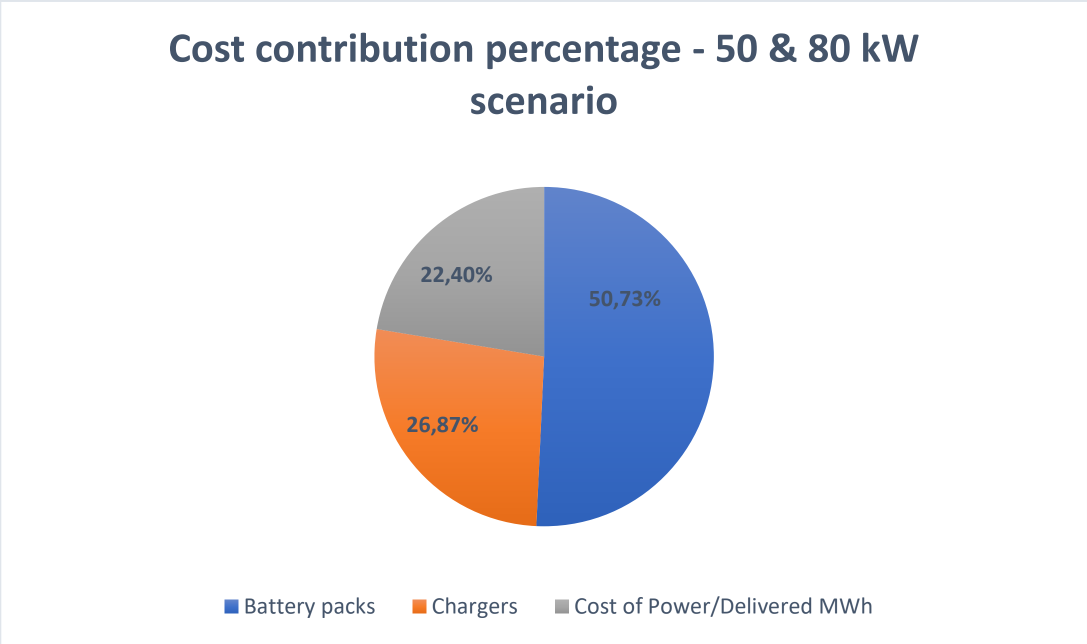


Figure 34. Cost contribution percentage – 50 & 80 kW

Considering the overall costs and gross revenues which fall between 500-600 €/MWhd, it is said that operating a charging station with a demand of 10 cars/day is feasible. As the grid power increases, the contribution of battery costs towards the overall costs decreases while the cost of electricity increases.

Second scenario:

In the scenario, the energy requirements and costs are analyzed after doubling the demands,

INPUT VALUES		
Number of EVs	20	cars/day
Total daily energy needed	1100	kWh/day

Table 35. Total costs incurred – Scenario 2

Energy Deficit-20 cars/day

Grid power supplied	Energy Deficit	Number of ESS packs needed
30 kW	770 kWh	Deficit exceeds grid supply
50 kW	550 kWh	4
80 kW	320 kWh	2

Table 36. Power Deficit over a twenty-four-hour period – Scenario 2

Over a twenty-four-hour period, a 30-kW grid supply is unable to supply more than 720 kWh of electricity. Since the power deficit exceeds this figure, a weak grid supply of 30 kW cannot support a daily demand of 20 cars/day or more.

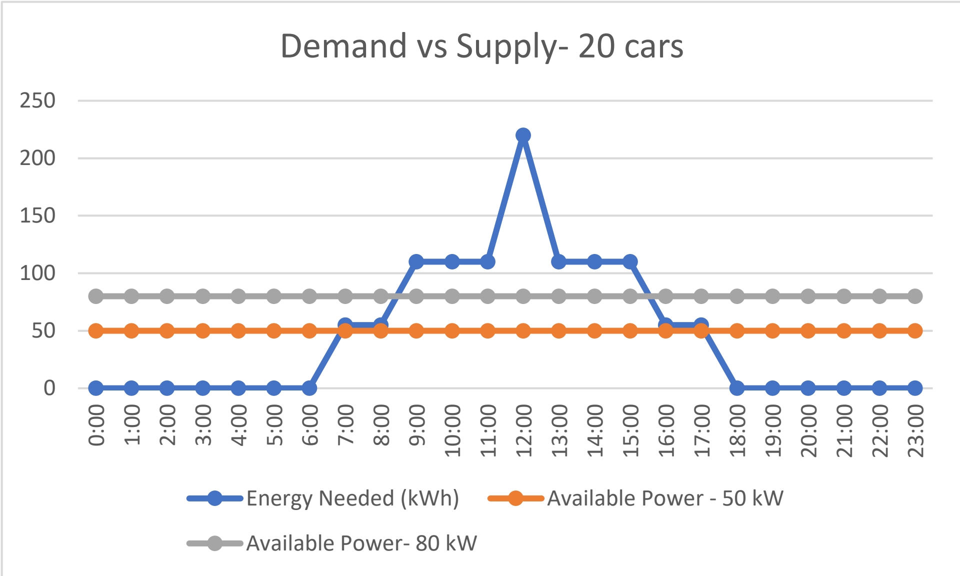


Figure 35. Energy demand vs Supply – Scenario 2

Costs:

As was observed in the first scenario, the CAPEX spent on the ESS resulted in higher costs when the grid power was 50 kW.

Grid Power	Total Costs
50 kW	201.19 €/MWhd
80 kW	155.90 €/MWhd

Table 37. Total costs incurred- Scenario 1

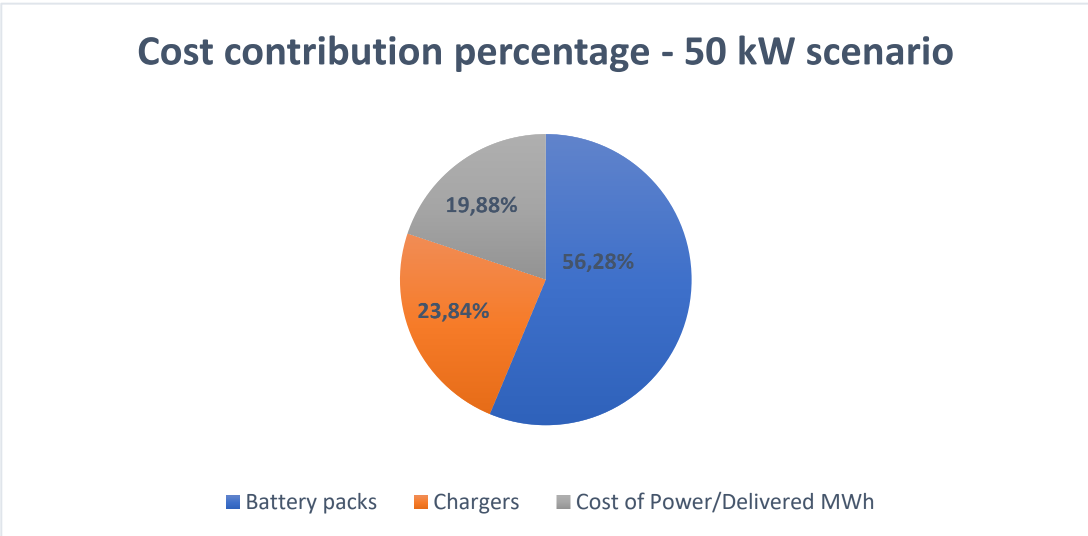


Figure 36. Cost contribution percentage – 50 kW

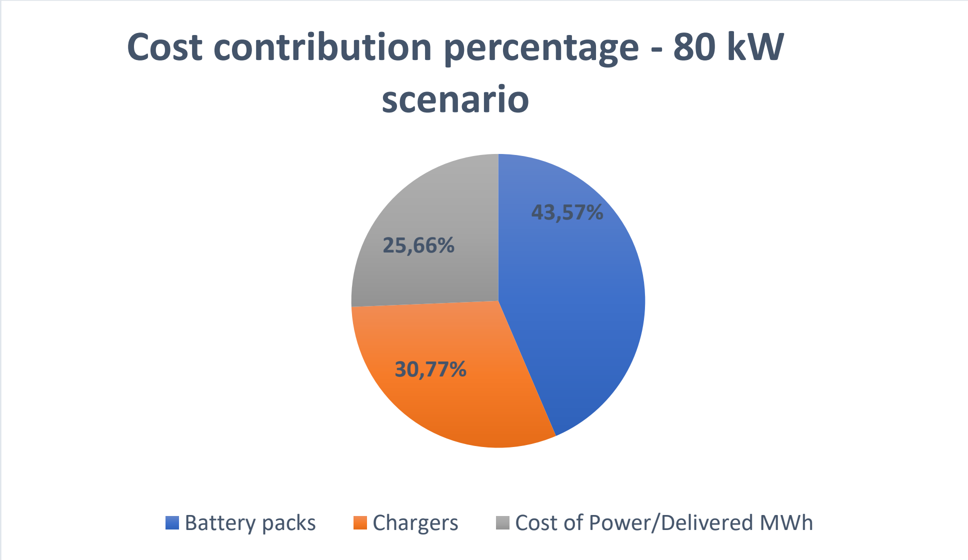


Figure 37. Cost contribution percentage – 80 kW

Overall, connecting weak grids and providing electricity for charging stations where the demand remains low is possible and provides profitable results to station operators. However, the increase in demand requires additional power supply from either solar panels or small-scale wind turbines that are installed near the charging station or battery/hydrogen that get charged or produced from wind/solar parks as seen in the off-grid scenarios.

Solar Panels:

Considered solely for battery solution, solar panels connected to the charging stations are analyzed. Since solar energy is weather dependent, it is also assumed that the charging station is connected to a weak grid. This helps in ensuring that the station is able to obtain extra power when the panels and ESS are not able to provide enough power while also providing a way to generate extra revenues by selling electricity during times of excess production.

As part of the analysis, a scenario of 50 cars/day is considered. The reason behind considering this scenario was due to a reasonable demand and serving this demand made the supply chain process highly unoptimized when operating under an off-grid scenario.

INPUT VALUES		
Number of EVs	50	cars/day
Total daily energy needed	2750	kWh/day
Number of batteries	18	units
Grid power	30	kW
Distance between WP and station	50	Km

Table 38. Input values – PV scenario

With each truck capable of carrying 8 ESS packs, a scenario of 50 cars/day require three trucks (8+8+2) and using a third truck with just 2 batteries makes the supply chain highly unoptimized. Hence, these two ESS packs are replaced by solar panels that could provide the same amount of energy. With 60% of each pack's capacity being used, the annual energy needed to supplement the batteries is obtained.

Energy supplied by two ESS packs (considering efficiencies)	**311 kWh/day**
Annual energy supply by two ESS packs	**113416 kWh/year**

Table 39. Energy provided by two ESS packs

It is recommended to size the solar panels in a way that they can provide more energy than the energy required. Hence, the solar panels are sized in a way that they provide 1.5 times the annual energy output of the battery packs [99]. The irradiance data for Utansjö is obtained using PVGIS.

Annual energy output from solar panels	**170124 kWh/year**
Maximum irradiance obtained for selected location	**687 W/m^2**
Panel efficiency η_{panel}	**22%**

Table 40. PV panel dimensioning

To generate this energy annually, around 183 kW$_{,peak}$ needs to be installed. With a 500 W panel providing 200 W$_{,peak}$/m^2, around 915 m^2 of roof surface area is required to install the panels or roughly around 366 panels of 2.5 m^2 each.

While the methodology behind calculating the costs for all the other parameters remains the same, the solar panel costs must be included in cost calculations.

	Panels
Peak Power [kW$_{peak,year}$]	183
CAPEX [€/kW$_{pear,year}$]	800
CAPEX [€/year]	14640
OPEX [€/year]	146

Table 41. PV Panel – CAPEX and OPEX

The initial CAPEX suggests that solar panels are relatively cheaper and even if a large area is being covered, the costs involved are not very high. Since solar panels may generate more energy than required in some instances, the additional power is then sold to the grid and the revenue generated will help in improving the operating income.

Parameter	CAPEX	OPEX	TOTAL
Battery	199	8	**207 €/MWhd**
Charger	28	1	**29 €/MWhd**
Transportation	-	218	**218 €/MWhd**
Wind farm	-	43	**43 €/MWhd**
Solar Panel	15	0.15	**15.15 €/MWhd**

Table 42. Total costs per MWhdelivered for each parameter – PV scenario

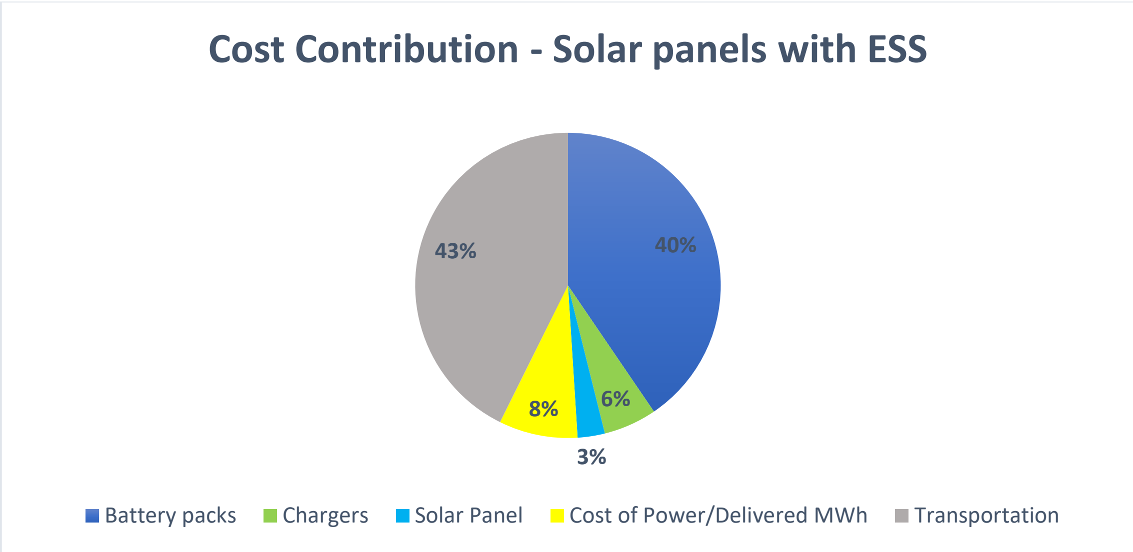


Figure 38. Cost contribution chart – PV panel scenario

Total Costs	512	€/MWhd

The contribution pie chart further solidifies the fact that the costs involved in procuring and maintaining solar panels do not play a major role in the overall costs involved in setting up and operating a charging station. As in the case of the battery solution for off-grid charging, the costs for transportation, procuring and maintaining batteries contribute the most towards the overall costs despite an optimized supply chain being achieved in this case. Nevertheless, the overall costs suggest that operating a charging station with these costs yield profitable results if implemented in the future. Hence, installation of solar panels in areas of weak grids could potentially support the operation of a charging station and it is up to the discretion of the project developer when it comes to sizing the panels. The sizing could be based on whether there is an energy park in the vicinity or not and the land availability for installing solar panels.

5.2 Low-Demand scenario for the hydrogen process

As can be seen in the results obtained for the different scenarios, the hydrogen process is not profitable for low energy demand scenarios.

The main reason for this low profitability is the oversizing of the technologies. During the construction of the solution model and the presentation of results, the focus has been to obtain the costs of each technology for each MWh delivered to the customer at the refueling station. In this way, it is possible to see what the cost per unit of sale is, being the most indicative way to draw conclusions from an economic point of view.

Therefore, with a low daily energy demand, the necessary production and its reconversion into electricity is reduced. When technologies are designed to operate in large-scale scenarios and with large capacities, if only a small percentage of them are used, the optimization of the process is completely forfeited. The cost of the technologies per unit of sale increases considerably and the process loses any economic profitability it might have.

As explained from the beginning, the solution model has been designed for large-scale situations, with the capacity to transport hydrogen at a great distance from the production point and optimizing the supply chain and thus achieve a model capable of adapting to different situations posed. Therefore, it is assumed that the capacity of the mobile storage is 1000 kg, reducing as much as possible, as explained above, the frequency of trips between the production and demand points. If smaller capacity mobile storages were used, the initial investment costs would increase and not only that, but the frequency of trips would increase, thus increasing transportation costs.

But in scenarios where few cars need to recharge their batteries at charging stations, even if the frequency of trips is very low, the oversizing of technologies such as the electrolyzer and its high CAPEX, completely preclude any potential profitability.

In order to improve the cost picture for low-demand scenarios, some alternatives are mentioned below.

As a first alternative, knowing the average energy demand of a demand point and previously analyzed and studied, the main objective would be to reduce as much as possible the initial investment costs of the technologies present in the process. There is still a long way to go for technologies such as electrolyzer to have a place in the market with competitive prices. In order to reduce the economic losses that this situation would generate, it would be necessary to receive subsidies from the country and get companies that are developing projects such as this one to acquire the necessary budget to start them up. Also, a good option would be to supply hydrogen to a larger number of stations with considerable distance, thus increasing total demand and minimizing economic losses.

Recently, the Danish company Everfuel received a total of approximately 45 million SEK from the Swedish Environmental Protection Agency under The Climate Leap (Klimatklivet) [100]. The project that the company is carrying out consists in the commissioning of two green hydrogen refueling stations in the Swedish region of Värmland.

This partial financing of the project represents the union between the Swedish partners and, in this case, Everfuel, with the common goal of decarbonizing transport. They intend to open up to a total of 15 green hydrogen refueling stations by the end of 2023.

Another situation, in which a remote location with low but constant energy demand is to be supplied, would involve raising electricity selling prices considerably in order to generate some profit or at least reduce losses.

In remote regions and given the scarcity of charging points or the weakness of the grid, it is difficult to find the necessary power to charge electric vehicles. Therefore, it is necessary to increase the number of stations with different solutions (i.e., batteries or hydrogen) in order to keep pace with the growth in demand for electric vehicles mentioned above.

As a third alternative to face the low profitability of the process in situations of low demand, the rental of the present technologies is proposed as an option. With the objective of saving initial investment costs, one option is that there is a joint venture between different companies for the rental of the most relevant technologies in the process of using green hydrogen as an energy vector.

By renting electrolyzers, compressors or fuel cells, the costs are considerably reduced and there could be a certain profitability in carrying out projects in which little energy demand has to be supplied.

5.3 Disclaimer for both solutions

As previously mentioned, the costs that arise during the development of these solutions, encompassing both battery and hydrogen utilization, are meticulously derived from reliable sources and the comprehensive information provided by BayWa r.e. The selected approach, which comes from the aforementioned sources, is representative of current costs and does not account for any anticipated fluctuations in the ensuing years.

It is worth noting that, while the chosen scheme effectively encapsulates prevailing costs, numerous alternative sources within the literature review offer divergent values for these expenses. Furthermore, technological advancements and the consequential cost reductions in pivotal components like the electrolyzer, compressor, or fuel cell are expected to manifest in the future. Therefore, it must be acknowledged that results obtained from prior studies may exhibit disparities when compared to alternative investigations or real-life scenarios.

These potential disparities are attributable to the dynamic nature of the renewable energy landscape, where continual advancements and evolving market conditions can significantly impact the costs associated with battery and hydrogen technologies.

It is important to note that the primary objective of this research is to enhance our understanding of the practical application of batteries and green hydrogen as energy vectors for charging electric vehicles in remote regions. Through a comprehensive economic analysis, we have gained valuable insights into the profitability and feasibility of such projects.

It is essential to approach the economic figures presented herein with a degree of caution. While they provide valuable indicators, it is important to recognize that they may not necessarily represent definitive or universally applicable values. Various factors, including market dynamics, technological advancements, regulatory changes, and unforeseen circumstances, can significantly impact the actual economic outcomes of individual projects. Therefore, it is crucial to view the economic figures provided as indicative rather than representative.

6. Conclusion

While integrated charging solutions remain popular in many off/weak grid locations, this paper investigates the potential of charging batteries or generating hydrogen from large scale energy parks and then using electric trucks for transporting the same. This solution can be a win-win situation for both the charging station operator and the energy park operator. With a sample remote location considered, the battery and hydrogen solutions are analyzed for a range of demands and distances.

The results show that transporting ESS packs yields profitable results if the distance between the energy park and the charging station is relatively low. Modular nature of the batteries and the weight limits in transporting them plays a critical role in the supply chain and in many instances, the supply chain was unoptimized due to which the trucks had to carry more ESS packs than requires which resulted in higher CAPEX costs. On the contrary, the hydrogen process may not prove to be highly unprofitable for low demands due to the high energy required for producing hydrogen. However, with the high volumetric energy density of compressed hydrogen, large amount of energy can be transported in a single truck, something that cannot be achieved with batteries and this lowers down the transportation cost of the hydrogen solution thereby making fuel cells ideal for situations where the demand and distances are high. Furthermore, the hydrogen solution yields more profitable results when multiple charging stations are considered with significant distances.

The sensitivity analysis shows that varying the transportation costs and battery CAPEX by a small percentage can lead to creating profitable scenarios for longer distances.

For hydrogen, it is observed that one of the most important factors that most influences the viability of the process are the energy efficiencies of the two main technologies, the electrolyzer and the fuel cell. As mentioned above, an improvement in their efficiency in the future would lead to great improvements in hydrogen production and distribution. Greater energy efficiency would be obtained and therefore, a reduction in costs. The thesis has found that the price of electricity is not a factor of great importance compared to the costs of the components present in the process.

Under a low demand scenario, weak grids are able to support the operation of a charging station if ESS systems are installed for capturing additional energy which can support the operation during peak periods. However, a rise in demand would mean that additional energy sources would be required to support the operation. Installing solar panels can be an effective method to support the operation of charging stations during high demands. The analysis finds that supplementing even two ESS packs would result in a large area of paneling required for meeting the demand. In addition, the weather conditions could result in requirements for higher energy sourcing from the parks as was in the case of off-grid systems. Solar panels are relatively cheap and replacing additional battery costs with panel costs could yield profitable results.

Overall, the concept of using battery/fuel cell technologies for charging BEV’s in remote locations seems extremely promising and a live example of the battery solution can be seen in the Swedish ski resort town of Åre. Northern Sweden is home to around 41000

EV´s and houses numerous renewable energy parks. An effective partnership between station and energy park operators in these areas will help both parties to generate higher incomes while giving an opportunity for station operators to decide on which technology would be more suitable based on the average daily demand and the proximity between their station and the energy park. In addition, these technologies can be used in other fields outside the automotive domain and the study for that can be undertaken as part of the future work.

7. Future work

The work undertaken during this project demonstrates the ability of mobile ESS and hydrogen-fuel cell systems to deliver profitable results for charging station operators. In the coming years, real life pilot projects in addition to the one in Åre related to both solutions can be undertaken to substantiate the claims made in this paper. Furthermore, the paper has concentrated specifically on using these off-grid solutions for charging BEV's but the potential for using these solutions in other industries also exists.

The telecom industry is another key area where the potential for using these solutions exists since advanced telecom towers require substantial amounts of energy for operating and installing them in areas of grid absence or weak grids will render the process impossible unless external support is provided. Like in the case of the charging station, it can be assumed that fuel cells will perform better than batteries if the tower is located at a large distance from the charging station while the usage of batteries for supporting these systems can be challenging since the energy demand could fluctuate daily and the transportation costs could be relatively higher depending on the distance.

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