Treball de Fi de Grau (Bachelor's degree Final Project)

Bachelor's degree in Industrial Technologies and Economic Analysis

Prediction analysis for maximizing wind power generation through decentralized storage systems in the European energy grid and its economic and sustainable feasibility

MEMÒRIA (Project Report)

Autor: Marc Macía García
Director: Josep Bordonau Farrerons

Convocatòria: Juny 2023 (June 2023)

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Summary

The technological advancements in the field of renewable energies and storage systems for electricity have been huge in the past twenty years. Nevertheless, feasible, mass scale solutions for energy storage are taking longer than the energy production of some technologies like wind and solar photovoltaic. Thus, there are large amounts of renewable energy that are available, but not generated when the electricity demand is low.

The purpose of this work is to analyze how decentralized and semi-decentralized storage systems can increase the energy generated by wind turbines. It will be centered in battery electric vehicles (BEVs) and hydrogen generation for fuel cell electric vehicles (FCEVs). It is worth mentioning that electric vehicles' energy stored can be used for driving and to deliver electricity to the grid (e.g. Wallbox technology). In this project, it will be only for driving.

The biggest benefit of predicting the viability of maximizing wind power generation is to unlock new profits for stakeholders in the industry which will allow to rethink the wind capacity that is viable to be installed, as well as reducing the carbon footprint due to the introduction of EVs in the market as a substitute for Internal Combustion Engine (ICE) vehicles.

Part of the project will be based on the previous analysis done by Joan Pedret as this is the continuation of the analysis. The main uses of the previous project will be the energy generation and pollution savings thanks to the introduction of EVs. This work introduces important corrections on the previous analysis, as well as the incorporation of FCEVs to unlock more of the energy that was not considered useful before. Moreover, the feasibility of the two technologies (from the raw materials to the technological and economical perspectives), and the health benefits of introducing EVs will be analyzed.

The final result of the project demonstrates that it is possible to introduce 19,538,369 light BEVs and 88,842 heavy-duty FCEVs. This combination allows to maximize the amount of energy generated by wind power in Europe, without leaving a potential GWh unused. The use of the non-generated energy could generate 6.9 billion euros yearly in revenue for the renewable energy sector value chain and the savings on oil amounts for 7.1 billion euros yearly. The yearly health benefit of introducing this amount of BEVs is 14.5 million euros in externality avoidance.

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Resum

Els avenços tecnològics en el camp de les energies renovables i els sistemes d'emmagatzematge d'electricitat han estat enormes en els últims vint anys. No obstant això, les solucions factibles a gran escala per a l'emmagatzematge d'energia estan trigant més que la producció d'energia d'algunes tecnologies com l'eòlica i la solar fotovoltaica. Així, hi ha grans quantitats d'energia renovable que estan disponibles, però no es generen quan la demanda elèctrica és baixa.

L'objectiu d'aquest treball és analitzar com els sistemes d'emmagatzematge descentralitzats i semi descentralitzats poden augmentar l'energia generada pels aerogeneradors. Se centrarà en els vehicles elèctrics de bateria (BEV) i la generació d'hidrogen per a vehicles elèctrics de pila de combustible (FCEV). Val la pena esmentar que l'energia emmagatzemada dels vehicles elèctrics es pot utilitzar per a la conducció i el subministrament d'electricitat a la xarxa (per exemple, la tecnologia Wallbox). En aquest projecte, serà només per conduir.

El major benefici de predir la viabilitat de maximitzar la generació d'energia eòlica és desbloquejar nous beneficis per a les parts interessades de la indústria (stakeholders) que permetran repensar la capacitat eòlica que és viable instal·lar, així com reduir la petjada de carboni a causa de la introducció dels vehicles elèctrics. al mercat com a substitut dels vehicles amb motor de combustió interna (ICE).

Una part del projecte es basarà en l'anàlisi prèvia feta per Joan Pedret ja que aquesta és la continuació de l'anàlisi. Els principals usos del projecte anterior seran la generació d'energia i l'estalvi de contaminació gràcies a la introducció dels vehicles elèctrics. Aquest treball introdueix correccions importants a l'anàlisi anterior, així com la incorporació de FCEV per desbloquejar més energia que abans no es considerava útil. A més, s'analitzarà la viabilitat de les dues tecnologies (des de les matèries primeres fins a les perspectives tecnològiques i econòmiques) i els beneficis per a la salut de la introducció dels vehicles elèctrics.

El resultat final del projecte demostra que és possible introduir 19.538.369 BEV lleugers i 88.842 FCEV de gran grandària. Aquesta combinació permet maximitzar la quantitat d'energia generada per l'energia eòlica a Europa, sense deixar un potencial GWh sense utilitzar. L'ús de l'energia no generada podria generar 6.900 milions d'euros anuals d'ingressos per a la cadena de valor del sector de les energies renovables i l'estalvi en quantitats de petroli per 7.100 milions d'euros anuals. El benefici per a la salut anual de la introducció d'aquesta quantitat de BEV és de 14,5 milions d'euros per evitar externalitats.

Resumen

Los avances tecnológicos en el campo de las energías renovables y los sistemas de almacenamiento de electricidad han sido enormes en los últimos veinte años. Sin embargo, las soluciones factibles a gran escala para el almacenamiento de energía están tomando más tiempo que la producción de energía de algunas tecnologías como la eólica y la solar fotovoltaica. Por lo tanto, hay grandes cantidades de energía renovable que están disponibles, pero que no se generan cuando la demanda de electricidad es baja.

El propósito de este trabajo es analizar cómo los sistemas de almacenamiento descentralizados y semi-descentralizados pueden incrementar la energía generada por aerogeneradores. Se centrará en vehículos eléctricos de batería (BEV) y generación de hidrógeno para vehículos eléctricos de pila de combustible (FCEV). Vale la pena mencionar que la energía almacenada en los vehículos eléctricos se puede utilizar para conducir y entregar electricidad a la red (por ejemplo, tecnología Wallbox). En este proyecto, será solo para conducir.

El mayor beneficio de predecir la viabilidad de maximizar la generación de energía eólica es desbloquear nuevas ganancias para las partes interesadas en la industria que permitirán repensar la capacidad eólica que es viable instalar, así como reducir la huella de carbono debido a la introducción de EV. en el mercado como sustituto de los vehículos con Motor de Combustión Interna (ICE).

Parte del proyecto se basará en el análisis previo realizado por Joan Pedret ya que este es la continuación del análisis. Los principales usos del proyecto anterior serán la generación de energía y el ahorro de contaminación gracias a la introducción de los vehículos eléctricos. Este trabajo introduce correcciones importantes en el análisis anterior, así como la incorporación de FCEV para desbloquear más energía que antes no se consideraba útil. Además, se analizará la viabilidad de las dos tecnologías (desde las materias primas hasta las perspectivas tecnológica y económica) y los beneficios para la salud de la introducción de vehículos eléctricos.

El resultado final del proyecto demuestra que es posible introducir 19 538 369 BEV ligeros y 88 842 FCEV pesados. Esta combinación permite maximizar la cantidad de energía generada por la energía eólica en Europa, sin dejar un GWh potencial sin utilizar. El uso de la energía no generada podría generar 6.900 millones de euros anuales en ingresos para la cadena de valor del sector de las energías renovables y el ahorro en petróleo asciende a 7.100 millones de euros anuales. El beneficio anual para la salud de la introducción de esta cantidad de BEV es de 14,5 millones de euros para evitar externalidades.

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State of the art

The realization of this project comes from previous research made by other students from the Escola Tècnica Superior d'Enginyeria Industrial de Barcelona - UPC BarcelonaTech. The start of this research comes from Cristina Verdaguer, who analyzed the effect of electric vehicles' growth in Spain on the wind power generation surplus storage. Later, Joan Pedret Botey analyzed this but for Europe [1] and pointed out which are the regions that can benefit the most from wind power generation. Joan's work will be stated as: the previous analysis from now on.

As previously mentioned, there have been studies of technological diffusion such as the Curves introduced by *Hall, B. H., & Khan, B. (2002)* [2].

There are also analyses on raw materials on BEVs that will be useful to understand the feasibility of producing a certain amount of BEVs [97] and studies about health benefits of introducing EVs while replacing ICE vehicles [58].

Summary

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1. Glossary

This glossary contains terms that might be useful for the reader to understand the project:

Term	Definition
Electric vehicles (EVs)	Vehicles powered by electric motors that use electricity stored in batteries or fuel cells, eliminating the need for internal combustion motors and reducing emissions.
Grid	A network of electricity lines and infrastructure that distributes electricity from consumer electrical plants.
GDP (Gross Domestic Product)	A measure of the economic performance of a country, which represents the total value of goods and services produced within its borders.
Internal Combustion Engine (ICE)	A heat engine that burns fuel inside its combustion chamber to generate mechanical energy.
Transmission System Operators (TSO)	Entities responsible for managing the transmission of electricity through high voltage networks and guaranteeing the balance of supply demand.
Regional Groups (RG)	TSO divisions based on geographical areas for efficient management and coordination.
Synchronous regions	Areas connected by an electrical system with the same frequency, which allows energy exchange and collaboration.
Onshore wind turbines	Wind turbines installed on the ground.
Offshore wind turbines	Wind turbines installed in bodies of water, typically the sea.
Hydro pump storage	A method to store excess energy when pumping uphill water towards deposits and release it to flow downhill through the turbines when necessary.
Gravitational storage	A conceptualized energy storage method that implies the use of highly energy heavy blocks and then drops, transforming potential energy into kinetic energy and generating electricity.
Wind power density	The amount of energy available per unit of wind area.
Weibull distribution	A probability density distribution used to describe the variation in wind speeds and estimate the potential electricity generation.
Field factors	Factors that influence the generation of wind energy, including land conditions, roughness and characteristics of the local landscape.

Roughness Class	A classification system based on the length of the roughness of the terrain, which affects wind speed.
Surface Wind	The wind near the surface of the earth influenced by temperature, pressure and terrain.
Turbulence	The irregular and chaotic air flow characterized by swirls and rapid fluctuations in wind speed.
Betz's Law	An aerodynamic principle that indicates the maximum energy conversion limit for wind turbines.
Battery Electric Vehicle (BEV)	An electric vehicle that works with electricity and is fed by rechargeable batteries
Plug-in hybrid electric vehicle (PHEV)	A hybrid vehicle that uses batteries to feed an electric motor and can be recharged from an external energy source, but also incorporates a smaller internal combustion engine.
Hybrid electric vehicle (HEV)	A vehicle that combines an internal combustion engine with electric motors that run out in a battery for greater efficiency
Fuel cell electric vehicle (FCEV)	A vehicle that uses a highly efficient electrochemical process to convert hydrogen into electricity to feed an electric motor
Alternative Propulsion Vehicles (APVs)	Vehicles that use alternative forms of propulsion, such as electric motors, hybrid systems or fuel cells, instead of traditional internal combustion motors
Battery management systems (BMS)	Systems in electric vehicles that monitor and control the performance, load and download of the battery, ensuring its efficiency and protection
Cradle-to-Grave	An approach that considers the entire life cycle of a product, from its creation (cradle) to its disposal (grave), taking into account the environmental and social impacts at each stage.
Pyrometallurgical Recovery	A recycling process that implies high temperature treatment to extract metals from battery components, such as cathodes or anodes, to recondition and reuse.
Hydrometallurgical Metals Reclamation	A recycling process that uses chemical solutions to separate and recover metals from the battery components, allowing its reuse in new batteries.
SPOT market	A market where financial instruments, such as basic products, currencies and values, are negotiated by immediate delivery
OTC	Extraction of the sale, referring to contracts that are made through a stockbroker network instead of a centralized exchange

Liquidity	The ease with which an asset or security can be purchased or selling without causing a significant price change
Rare earth metals	A group of elements that are crucial for several advanced technologies, including batteries and electronics.
Reserves	Known mineral deposits or resources that can be extracted economically
SMR	Steam methane reform, a process to produce hydrogen by reacting steam with methane
Grey hydrogen	Hydrogen produced through steam methane reform (SMR) using natural gas, but generating large amounts of carbon dioxide
Blue hydrogen	Hydrogen produced through SMR, but with an additional passage of carbon capture and storage, resulting in reduced environmental impact
Green hydrogen	Hydrogen produced through water electrolysis using electricity from renewable sources, such as wind or solar energy
Electrolysis	The process of use of electricity to divide water into hydrogen and oxygen
Alkaline electrolysis	Electrolysis that uses a liquid alkaline solution such as electrolyte
PEM electrolysis	Polymer electrolyte membrane electrolysis that uses a solid specialized plastic material such as electrolyte
Solid Oxide Electrolysis	Electrolysis that uses a solid ceramic material such as electrolyte
S curves	Graphic representations of the adoption and dissemination of new technologies over time, which generally show an initial slow growth, followed by rapid acceleration and finally reach a plateau
Oligopoly	Market structure dominated by some large companies
Entso-e	The European Network of Operators of the Transmission System for Electricity is the Association for the Cooperation of Operators of the European Transmission System (TSO). The 39 TSO members representing 35 countries are responsible for the safe and coordinated operation of the European electrical system, the largest interconnected electrical grid in the world.
Elexon	It is the business that implements the processes to resolve payments between generators, suppliers and merchants to keep the lights on in the United Kingdom.
Li-ion	Lithium ions, in reference to the batteries that use the reversible reduction of the lithium ions as a way of storing

	energy.
Eurelectric	Represents the European Association of Electricity
ICCT	International Clean Transportation Council
DNV	Det Norske Veritas, a Norwegian shipping company
Carbon credits	Units that represent a metric ton of carbon dioxide emissions reduced or eliminated from the atmosphere
Gender perspective	Considering the impact on genres and addressing gender inequalities
Carbon offsetting	Compensation of carbon emissions through activities that reduce or eliminate CO2 from the atmosphere

2. Preface

2.1. Project origin

Power generation and storage are one of the world key issues to solve if we want to reduce the effect of climate change in the world. It is expected that the population will grow until 2050, reaching 11 billion people on the planet, which will require more resources to tackle their needs.

Considering the environmental constraints faced by climate change, the energetic mix in the next few years needs to grow in sustainable sources of energy and not in fossil fuels. The straightforward way to increase the piece of the pie of sustainable energy generation is to install more capacity and currently there are a lot of plans for that to happen. Nevertheless, there is another way to increase that mix and is to maximize the energy power generated by the current and future installed systems. Besides, this possibility increases the chances of a virtuous loop where more capacity is installed due to higher revenues from the same installation.

This thought process comes from one of the central critique about renewable energies: their dependency on external factors (e.g. if there is wind during night and no one needs that energy, then it is lost), meaning that energy is not generated if no storage systems are provided, decreasing the total amount of renewable energy that could be produced.

The actual capacity of storage systems does not cover all the potential energy that could be produced during the night but the future looks promising. As nations commit billions of dollars to electrify the economy and reduce the use of fuel motors and increase the use of electric vehicles more electricity will be inserted into the grid during the night which can be used during the day for transportation.

There exist technologies that allow consumers to charge their BEVs only during the most cost-effective hours of the day (which is at night).

The implications of this are great as the more people switch to BEVs, the more efficient renewable energy will become.

2.2. Motivation

The author of this project has a clear plan on what he wants to achieve in the next years of his career. His interest leans towards the private sector and in product development and business creation. At the moment of writing he is working in Amazon Luxembourg for a 6 month internship. That is why this was one of the few opportunities left before fully entering into the professional world to do research in a key topic and industry that he does not know a lot about: energy.

Opening your mind to new experiences and perspectives is always positive and this project is the perfect opportunity for that. The energy sector is really interesting and not investigating this industry would be a missed opportunity.

During the last 5 years, the author has been interested in the topic of world electrification. Although understanding the controversial figure of Elon Musk and the negative side of his personality, he has been inspired by his mission to accelerate the world's transition to sustainable energies. Elon's efforts have made the industry really attractive to both professionals that are research-focused and business-minded. And when a lot of great minds gather in the same place, magic starts to happen.

One of the key elements why the project is potentially viable to happen in the near future is not only due to investments from the public sector but also because of the Tesla Model 3 and the supercharger network. This car has made clear that economies of scale for EVs is possible and ramped up business plans from all the other automakers in the world.

The author also values the opportunity to work alongside Josep Bordonau, who is an important contributor to projects such as InnoEnergy. He has had the opportunity to attend a group of seminars in the Electronics (ITEA) course. They consisted in generating an idea and presenting it using Lean Startup methods and were taught by Josep. He believes the way he organized them and how positive he felt after, made him decide to pursue this project.

3. Introduction

3.1. Project objectives

The main objective of this project is to find out the energy storage system mix of decentralized and semi-decentralized technologies to maximize the power generated by wind turbines. It will be centered around battery electric vehicles (BEV) and hydrogen generation for Fuel Cell Electric Vehicles (FCEVs).

Moreover, it is an objective to understand the feasibility of the technologies from a technological and economical perspective, considering also the raw materials extraction capacity from earth and the recyclability of the technologies.

3.2. Project scope

The framework for the work will be based on the European Union grid system. This limitation comes from the practicality of Europe being an interconnected common market and the necessity of analyzing a common market that will have similarities in comparison with others such as the US.

The project is written in English and will use the common signs in that language. For example, a decimal separator will be a dot "." (e.g. 26.32), while the comma will be used to separate the thousands (e.g. 54,034).

It is worth noting that the part of the data that will be worked with will be previous to the Russian invasion of Ukraine, which has shifted public policy regarding energy markets and investment in technology

4. Context

4.1. Climate change

The United Nations describe Climate change as long-term shifts in temperatures and weather patterns. These shifts can happen naturally (e.g. due to variations in the solar cycle). Nevertheless, the climate change we refer to is the one that has been occurring due to human activities since 1800. The industrialization of the world, although having provided immense benefits and well-being to a lot of people, has caused collateral effects that are disrupting the world's ecosystems. The biggest driver of this change has been the intensive use of fossil fuels, generating greenhouse gas emissions that act as a layer in the atmosphere trapping heat that raises global average temperatures [3].

Ecosystems are delicate and take time to adapt to new conditions. That is why, this massive extraction of greenhouse gasses to earth's atmosphere poses a big risk. Nevertheless, the biggest risk in the long term is the sustainability of our civilization [4]. The effects of climate change could generate much more difficult and dangerous living conditions than the ones that exist today. At least in the short term (in Earth's life scale).

Nevertheless, multicellular life on earth will continue to exist long after our civilization and humans will be extinct.

As stated before, the clearest signal from climate change right now is global average temperature rising levels. Considering the time span of 1880 to 2020, it can be seen that since 1976, the global average temperature has been increasing constantly. The picture below shows clearly how the average temperature and the actual temperature differ by almost 1ºC [5].

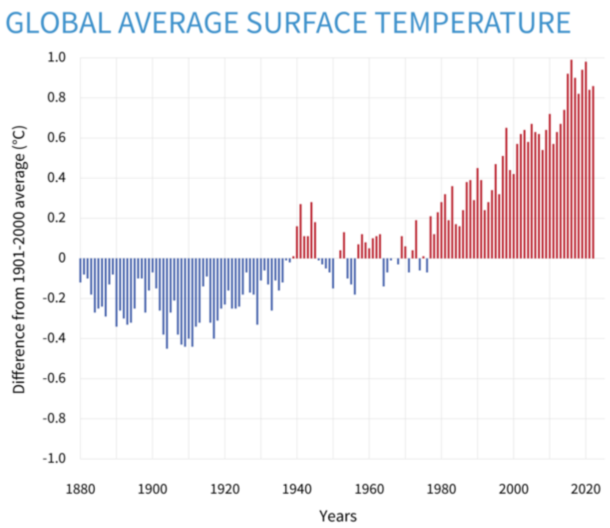

Figure 1: Global average surface temperature from 1880 [5]

The problem with the increasing temperature is as said, disruptions and collapses in ecosystems. Here are some of the problems that can be originated:

1. Rising sea levels due to ice melting: the current increase in temperatures are causing the ice reservoirs in the Arctic and Antarctic to melt faster than they recover their ice through snow precipitation. This causes impactful problems:
    a. Higher sea levels equals losing the coastal line, with a decrease in the GDP and migration of millions to landlocked areas.
    b. Ecosystems lost
    c. Loss of water reservoirs
2. Hurricanes: there is correlation between temperature increase and hurricane frequency. For instance, Saunders, M. A., & Lea, A. S. (2008) concludes that a 0.5ºC increase during August and September is linked to around 40% increase in frequency. Considering that this will continue, the number of economical losses in hurricane-affected areas will increase, making life more costly for households there [6].
3. Massive migratory human and animal movement: rising temperatures will make the climate more extreme (arid places will become more arid and rainy places more rainy). For example, regions in Africa will have severe droughts more often. This will cause more and more people to move from some countries to others, causing millions what has been termed as “climate refugees”. This can have deep political and economic implications in EMEA (Europe, Middle East and Africa).

4.1.1. Greenhouse gasses

As stated in the previous section, greenhouse gasses are the major contributor to global warming. Nevertheless, it is not only carbon dioxide that is responsible for climate change. As they are depicted in the image, this are the most problematic gasses:

1. Carbon dioxide: it is the most common greenhouse gas emitted by human activities. The main ones being burning fossil fuels and deforestation (which comes from urbanization, industrialization and intensive agriculture). Also, it comes from natural causes such as forestal fires and volcanic eruptions.
2. Methane (CH_4): If related from human activities, this gas is extracted from fermentation (anaerobic digestion of bacteria). The activities causing methane releases to the atmosphere are:
    a. Livestock farming (cows being one of the main emitters of this gas).
    b. Agriculture (e.g. rice cultivation).
    c. Marshy areas.
3. Nitrous oxide (N_2O): provoked mainly due to the massive use of nitrogenated fertilizers. Other sources are plane motors, thermal power plants or cars.
4. Chlorofluorocarbons (CFC): they are artificial chemical compounds that are present in small concentrations in the atmosphere but that are extremely powerful greenhouse-effect agents. Their main use is refrigeration.
5. Tropospheric ozone (O_3): originated by burning fossil fuels [7].

Some of them can be seen in the image below:

Greenhouse effect and climate change : scientific basis and overview

Table 3. Estimates of direct GWPs for major greenhouse gases (from Houghton *et al.* [9])

Gas	Lifetime (years)	Direct effect for time horizons of 20 years	100 years	500 years
CO_2	~120	1	1	1
CH_4	10.5	35	11	4
N_2O	132	260	270	170
CFC-11	55	4500	3400	1400
CFC-12	116	7100	7100	4100

Figure 2: Greenhouse gasses time in the atmosphere [8]

It has been seen that the problem with carbon dioxide (CO_2) comes from:

- The amount of it poured into the atmosphere, and
- the fact it stays in the atmosphere for around 120 years.

That is the reason why renewable energies play a critical role in tackling climate change. Reducing the weight of fossil fuels will reduce the amount of carbon dioxide extracted to the atmosphere.

4.1.2. Reducing greenhouse gasses emissions

There are several actions (individual and collective) that can be taken to reduce emissions [9]:

- Minimize the use of Internal Combustion Engine (ICE) cars. Transportation is one of the sectors that pollutes the most and contributes to global warming. For example, driving 50 km less every week reduces 450 kilograms of emitted CO_2.
- Prioritize sustainable mobility. Instead of using private transportation (e.g. car or taxi), use public transport, shared mobility or micro mobility services (e.g. bikes, e-scooters, e-bikes).
- Reduce flight habits. A trip from London to New York produces 986 kg of CO_2.
- Consume renewable energy: installing auto consumption sources of energy such as solar panels or hiring a renewable energy distribution company will help you reduce emissions and keep a better track of them. Besides, owning a battery pack or an Electric vehicle that can be plugged into the grid will store energy when it is the cheapest (low demand) and will consume it when needed to save money.
- Improve energy efficiency. Keeping the thermostat 2º degrees less than usual in winter and keeping it up 2ºC in summer reduce emissions by 900 kg.
- Keep a low carbon footprint diet. Food corresponds to 20% of the greenhouse gas emissions. Vegan, vegetarian and local-source diets are the most low-carbon ones. Nevertheless, some proteins like chicken are efficient to obtain too (in comparison with beef, lamb or farmed shrimp).
- Increase vegetation footprint. Forests and mangroves are CO_2 consumers. The more vegetation can be planted, the less CO_2 will be in the atmosphere.
- Institutional action. Governments and public organizations are the ones who can impact the most in reducing emissions. Changing laws regarding allowed emissions, creating incentives or creating emissions markets can make a big difference in the efforts to reduce greenhouse gas emissions. One of the most important governmental acts has been the Paris agreement [10]. It is a legally

binding international treaty on climate change. It was adopted by 196 parties at the UN Climate Change Conference (COP21) in Paris, France on 12 December 2015. It entered into force on 4 November 2016. The goal is to hold “the increase in the global average temperature to well below 2°C above pre-industrial levels” and pursue efforts “to limit the temperature increase to 1.5°C above pre-industrial levels.” Other actions can be remodeling cities to make them pedestrian-centered (reducing the use of cars and, as a consequence, the pollution inside cities).

4.2. European electrical sector

Europe’s energy system is interconnected between European countries. This allows power to flow from one country to another and benefit from energy surplus or lack of energy. For example, France is an important stakeholder when it comes to providing nuclear power to its neighbors and Spain is supplying green, cheap energy when available.

The system is managed by Transmission System Operators (TSO), who are in charge of the gross transmission of electric energy through high voltage networks. Their aim is to calculate the power flux to balance supply and demand the most efficient way possible. Besides, they work in providing access to the network to the different market agents transparently, secure trust in supply, plan the network’s evolution and maintenance [11].

TSO’s are divided in 5 different Regional Groups (RG) of Europe:

1. RG Continental Europe
2. RG Baltic
3. RG Nordic
4. RG British
5. RG Irish

A RG is an area of connected countries by an electric system. All 5 regions have the same frequency (50 Hz) but perturbations only have effect in the region itself. Every SR is connected to the others by High-voltage Direct Current (HVDC), which will start to work when there is not enough energy supplied in the region.

There are benefits to be organized in Synchronous regions [12].

- Pooling of generation, resulting in lower generation costs.
- Pooling of load, resulting in significant equalizing effects.
- Common provisioning of reserves, resulting in cheaper primary and secondary reserve power costs.

- Opening of the market, resulting in possibility of long term contracts and short term power exchanges.
- Mutual assistance in the event of disturbances.

4.2.1. Power supply in Europe

The European energy mix has been evolving heavily for the last 20 years. The most relevant shift has been the decrease in use of oil and petroleum products, substituted primarily by the higher use of gas and renewable energies. It can be also seen in the image below that there has been a decrease in the use of Nuclear power. This could be driven by the Fukushima incidents, where the public opinion on Nuclear power shifted and Germany decided to close all Nuclear plants. Nevertheless, it can be observed that the peak of Nuclear Power generation happened before the events. Also, it needs to be taken into account that the data is previous to the Russo-Ukrainian war [13] .

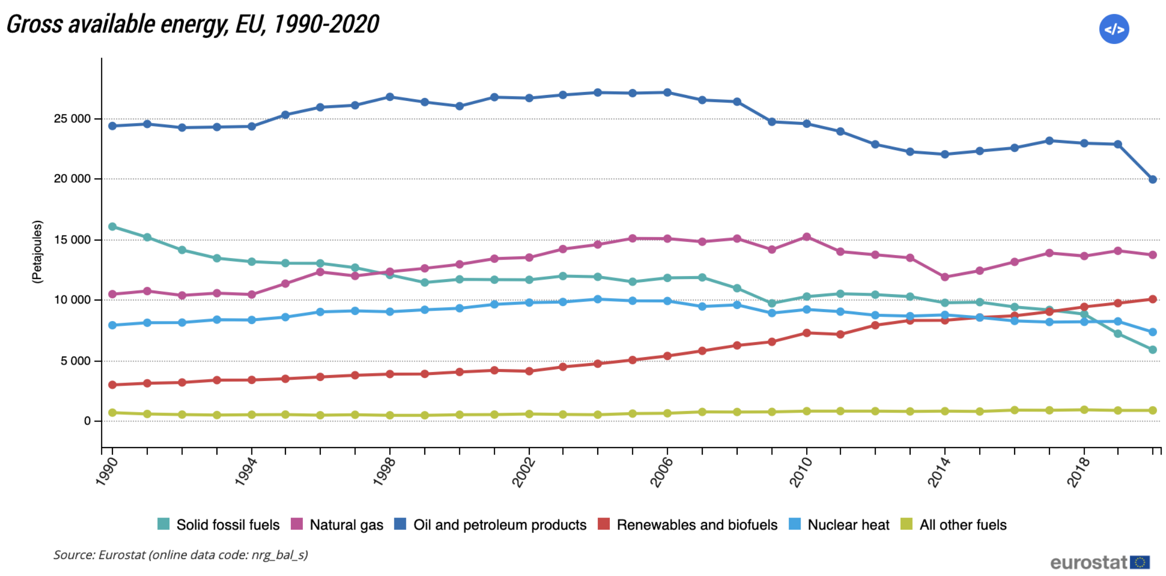

Figure 3: Gross available energy in the European Union from 1990 to 2020, by type [13]

Nevertheless, the mix above is not the same in different countries. For example, Spain's solar or nuclear power generation represents a higher percentage of the mix while Germany's mix is more dependent on coal and nothing on Nuclear, as discussed before.

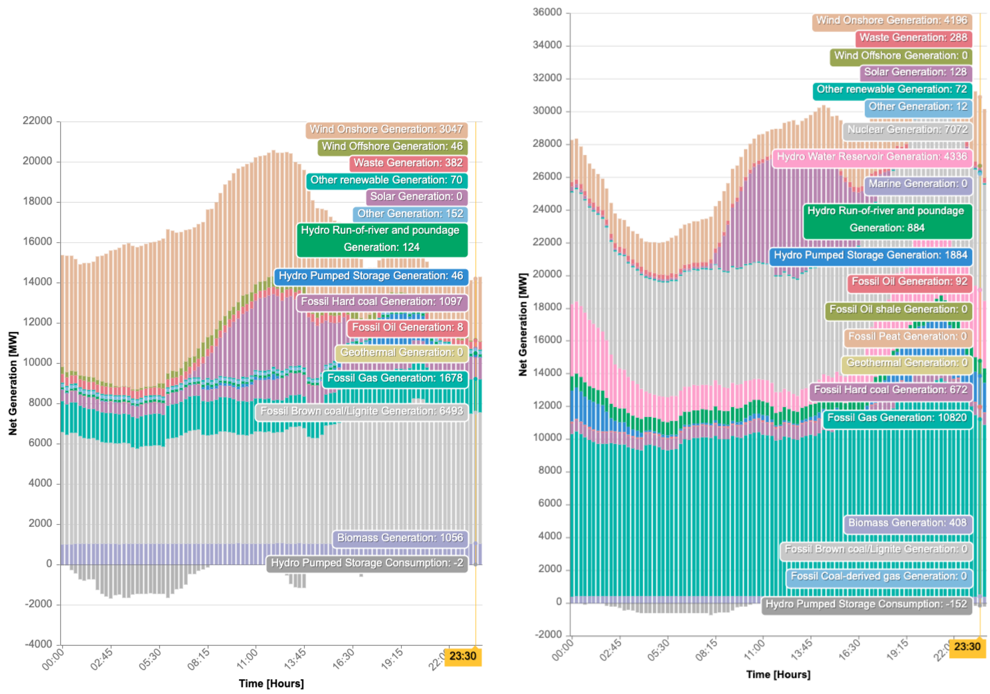

Figure 4: Germany and Spain power generation in 03/05/2023 [14] [15]

The percentage of power generated by fossil fuels has gone down. This has been due to a decrease in the price of renewable energy while the governmental incentives have been increasing. For example, Solar power has become the cheapest way to produce power.

To focus on this project, it can be seen how the wind power percentage of the mix has increased a lot during the last decade. The production of wind will be analyzed during this work.

4.2.2. Wind power in Europe

Wind power occurs due to the transformation of the kinetic energy from the wind to generate electricity. To achieve this transformation, the use of wind turbines is needed.

It is considered a renewable energy source because the supply of air does not decrease because of generating this electricity. In comparison, fossil fuels like natural gas or coal have finite supplies of raw material to produce energy which makes them a bad source of power generation in the long run. Besides, in comparison with fossil fuels, wind power does not generate byproducts like greenhouse gasses except the production of the wind turbines.

There are two types of turbines that can be installed: on-shore or off-shore. The last ones are becoming more popular, for example in countries like Denmark. One requirement that they have is the need of low sea depths (to decrease the cost of the turbine manufacturing and maintenance and make it technically feasible).

There are several benefits of using turbines to generate power. The footprint needed for wind farms is low in comparison with solar energy. Besides, it does not affect agriculture nor livestock exploitation except some noise and worsening the landscape. The historical complaints come from this last aspect. The cost of installation is low relative to the overall cost of the installation. The problem of wind power comes with the irregular availability of wind. It can be calculated approximately how much wind will be during one year in one spot but the availability of it will be unknown, meaning that there should not be a full reliability on this energy. Unless the energy can be stored, all the energy in low demand hours will not be useful, then it will not be generated.

There are several ways to store the power generated by wind turbines.

- Batteries:
- Hydrogen generation: In hydrogen energy storage, electricity is converted into hydrogen through electrolysis. Then, hydrogen can be stored and later re-electrified. The problem with this is that all the process reduces efficiency making the technology less efficient than other storage technologies. Despite this, interest in hydrogen energy storage is growing due to its higher storage capacity compared to small scale solutions like batteries or large-scale options like Hydro pump [16].
- Hydro pump storage: Hydro pump storage uses energy that would not be produced otherwise to pump water uphill into reservoirs during periods of low demand. When energy is needed, the water is released to flow downhill and turn turbines, generating electricity.
- Gravitational storage (solid): Hydro pump storage is also a type of gravitational storage. In this case, gravitational storage (solid) is a conceptualized solution where heavy blocks are risen with excess energy until the ceiling of an industrial building and when the energy is needed it is left to transform potential energy into kinetic energy and then electricity. Energy vault is the company behind the concept. The concept is yet to be proven viable and match efficiency with Hydro pump storage [17]. Nevertheless it seems too complicated in comparison to the current available solution.

In this project the focus on storage systems will be on the two first alternatives as they are more decentralized and provide differentiated uses between each two. For example, hydrogen can be kept for longer periods of time in comparison to energies inside batteries. In the case of areas with variation of winds between weeks instead of during the day, hydrogen can be a better solution than batteries.

4.3. Wind

Wind is defined as a current of air moving approximately horizontally, especially one strong enough to be felt [18].

Studying wind in this project is critical as it is necessary to know its behavior to estimate which is the maximum power that can be generated by the wind turbines.

4.3.1. Wind classification

Winds can be either Small-scale or Large-scale.

Small-scale winds are those originated by a difference in pressure and temperature. The best example is the sea breeze. On sunny days during summer, the sun rays heat up water on the sea surface more than the ground because it has more capacity to absorb the rays than the ground. That means that a difference in temperature between the ground and the sea is created. The ground heats up the air around it, making it less dense, which makes it rise. Nevertheless, the air over the sea remains cooler and, thus, denser, making the pressure higher than inland, provoking a difference in pressure which makes the air from the sea area move inland to balance the difference [19].

Large-scale winds follow a similar process but, as the name suggests, on a larger scale (global). In this case, the sun's rays reach the earth's surface in polar regions at a much more diagonal angle than in the equator, meaning that a pressure difference will be set between the poles (high pressure) and the equator (low pressure). This creates a global wind circulation as the cold polar air tries to move southwards to replace the rising tropical air. This effect is complicated by earth's rotation (Coriolis effect). Earth's rotation makes the air not flow directly from high to low pressure but be deflected to the right.

The air that has risen at the equator and then moves towards the poles, then cools and sinks around 30 degrees latitude north or south of the equator. Then, some of it returns to the south, completing a whole circulation as it can be seen in the image below.

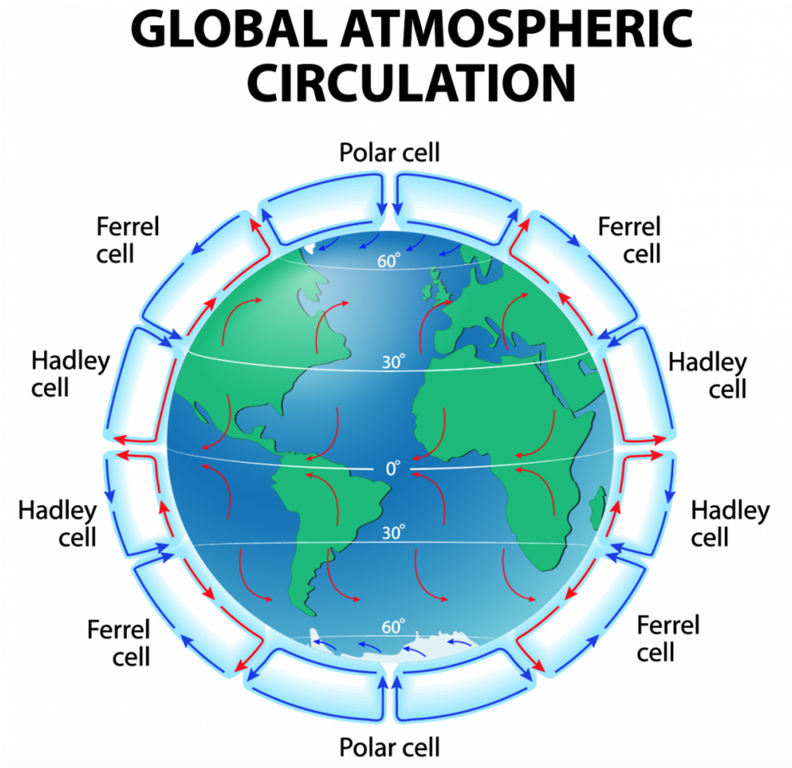

Figure 5: Global atmospheric circulation [20]

Some of the other air that moves polewards meets the cold air spreading southwards from the poles. This “clash” happening around the UK's altitude is what defines our weather systems. The warm air is less dense than the polar air and tends to rise over it. This motion generates low-pressure systems, bringing wind and rain to the surface in our coasts. This part of the global circulation is known as the mid-latitude.

In the case of wind turbines, it is interesting to study those winds that are small-scale. So those that are caused by the difference in temperature and pressure. It has been put as an example of the sea breeze but mountain winds are also causing these winds that are critical for wind power generation [21]. So mainly all those winds that are also affected by the terrain structure should be included.

4.3.2. Wind power

Wind power is that obtained by harnessing the energy of the wind. It depends on the speed of the air [22].

The wind power is calculated in function of the speed of the wind, defining density of air as a constant (normally the density of dry air at 15ºC and at 1 atm) which is 1.225 kg/m^3 and r being the radii of a The wind power is given in Watts per meter squared [W/m^2] [23]:

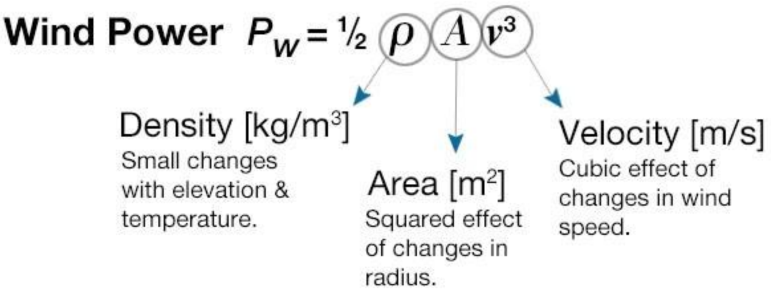

Figure 6: Wind power formula [23]

Then, theoretically, the plot of this formula is this one, which follows the plot of the speed to the cube:

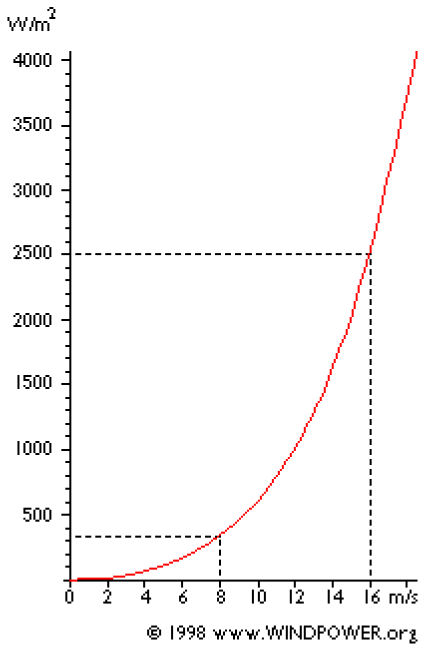

Figure 7: Theoretical power per meter squared based on the wind speed [24]

Nevertheless, the wind turbines will not be able to take all the power the wind has. As it can be seen in the following image, the rated power of the turbines gets to 1000 W/m2 and after they stay flat until the speed is 25, the shut-down wind speed.

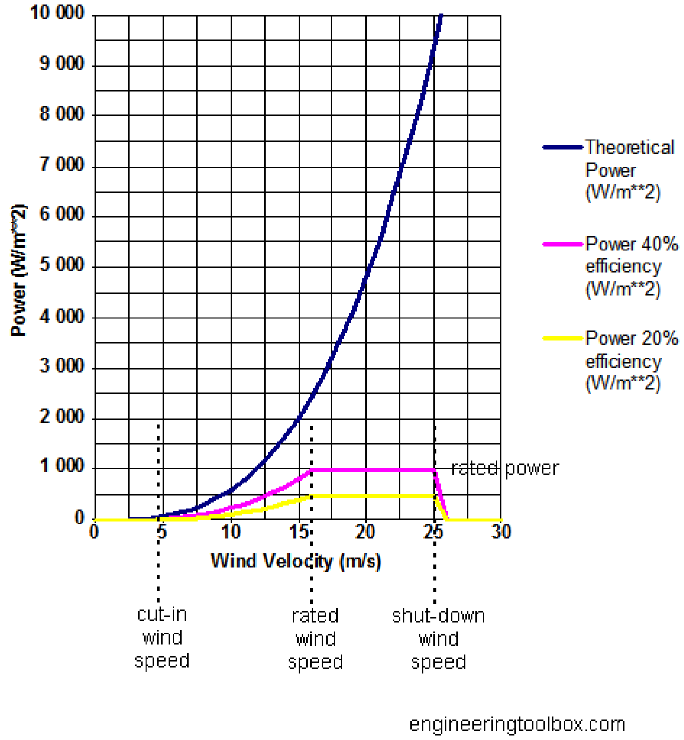

Figure 8: Theoretical power and rated power depending on different efficiencies [25]

Wind power is a variable renewable energy (VRE) or intermittent renewable energy source (IRES). VREs are renewable energy sources non-dispatchable (cannot be programmed) due to their fluctuating nature. In comparison, hydroelectric power or biomass can be controlled, and geothermal energy is a constant source of energy.

Large amounts of power in VREs require grid redesigns and need the use of storage when supply and demand is unmatched.

Wind is variable but predictable in the short term (89% chance of wind output changing less than 10% in an hour and 40% chance changing 10% or more in 5 hours). This makes short-term planning feasible [26].

4.3.3. Weibull distribution

It is very important for the wind industry to be able to describe the variation of wind speeds. Turbine designers need the information to optimize the design of their turbines to minimize generating costs. Turbine investors use this information to estimate their income from electricity generation.

To solve the problem, a statistical description of wind speeds is needed. For that, a probability density distribution called the Weibull distribution is used.

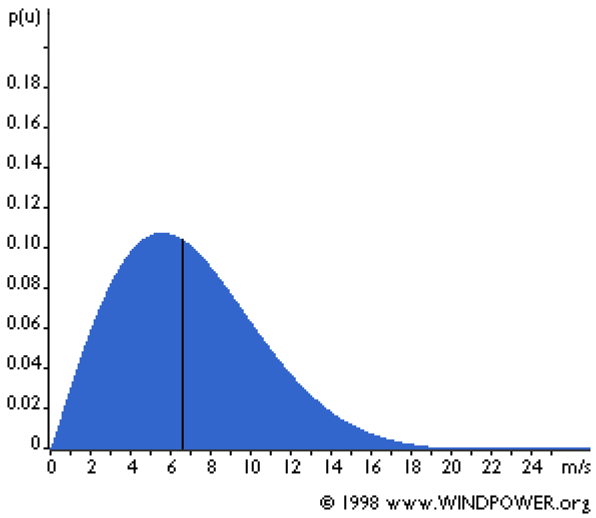

Figure 9: Weibull distribution [27]

The area under the curve is always exactly 1, since the probability that the wind will be blowing at some wind speed including 0 must be 100 per cent.

The line that divides half of the blue area is at 6.6 meters per second. This is called the median. The mean is at 7 meters per second for the site analyzed in the picture. It can be seen that the plot is not symmetrical, leaning towards weaker winds, which are more probable to occur.

The Weibull distribution varies thus in shape and mean value depending on the place analyzed and it helps identify the potential Return on Investment from the wind farms.

In the image below, it can be seen an analysis of the quantity of hours of each wind speed, which is equivalent to the Weibull distribution.

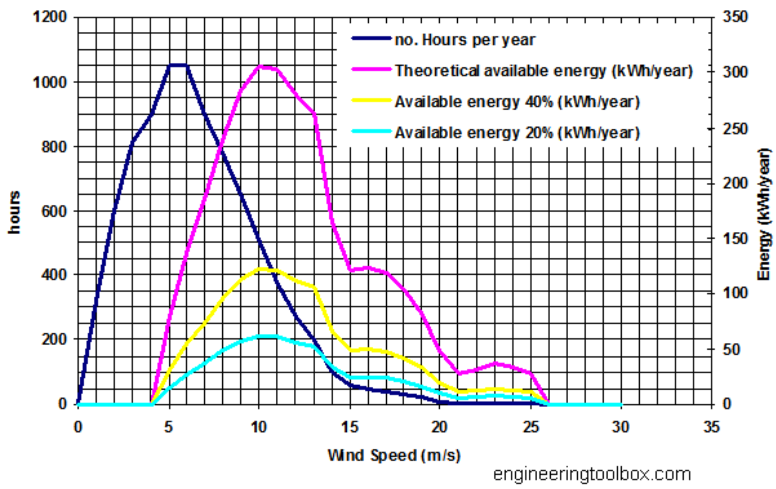

Figure 10: Weibull distribution with different available energies [28]

4.3.4. Field factors

The winds that are interesting for the wind turbines are those Prevailing winds that are highly affected by the terrain they go through. Depending on the terrain conditions it will be more easy to obtain the wind power or not. For example, in a mountainous area, the face that is less angulous will have more laminar winds while rocky surfaces, high ridges, steep valleys and cliffs contribute to turbulence and unpredictable flow patterns [21].

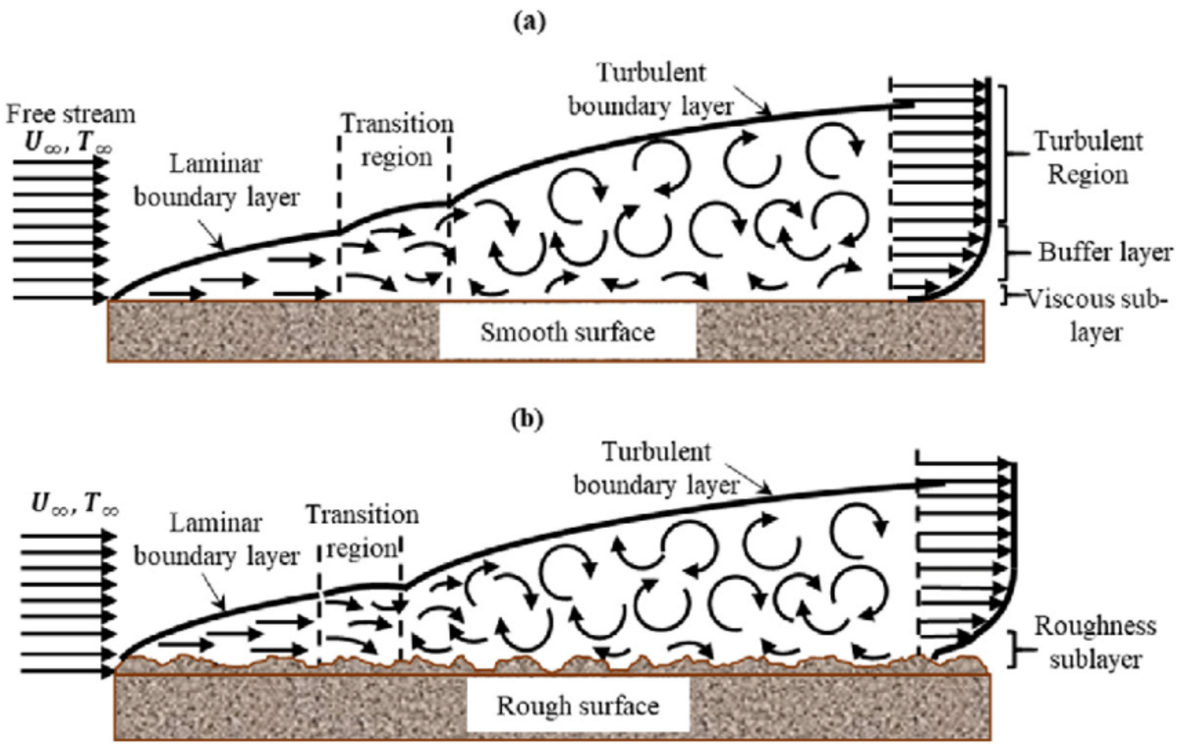

Figure 11: Boundary layer in different surface types [29]

Rugosity of the terrain highly determines the energy that can be extracted from wind. The more rugosity you have (the higher the length) the less energy you can obtain. That is because rugosity affects the laminar boundary layer of wind, making the turbulent layer quicker to appear, which reduces the effectiveness of wind turbines transforming wind into electricity.

The velocity of wind [m/s] will depend on the height Z [m] above ground and a reference velocity V_{ref} [m/s] at a reference height z_{ref} [m] at a rugosity length Z_0 [30].

$$V(z) = V_{ref} \frac{ln \frac{z}{Z_0}}{ln \frac{z_{ref}}{Z_o}} \quad (1)$$

Roughness Class RC	Roughness Length, Z_0 [m]	Energy Index [%]	Local Terrain type, landscape, topography, vegetation
0	0.0002	100	Water surface
0.5	0.0024	73	Completely open terrain with a smooth surface, such as concrete runways in airports, mowed grass.
1	0.03	52	Open agricultural area without fences and hedgerows and very scattered buildings. Only softly rounded hills.
1.5	0.055	45	Agricultural land with some houses and 8 meter tall sheltering hedgerows within a distance of about 1250 meters.
2	0.1	39	Agricultural land with some houses and 8 meter tall sheltering hedgerows within a distance of about 500 meters.
2.5	0.2	31	Agricultural land with many houses, shrubs and plants, or 8 meters tall sheltering hedgerows within a distance of about 250 meters.
3	0.4	24	Villages, small towns, agricultural land with many or tall sheltering hedgerows, forests and very rough and uneven terrain.
3.5	0.8	18	Larger cities with tall buildings.

4	1.6	13	Very large cities with tall buildings and sky scrapers.

Table 1: Roughness classes and energy index

4.3.5. Wind during night

The project will specifically tackle how wind behaves during night, as it is the time of the day with the lowest demand of electricity. It will be important to note that there is less wind during the night than during the day. That will imply less potential power not generated due to low demand.

These diurnal variations are due to the strong surface heating during the day, which causes turbulence in the lower levels. The result of this turbulence is that the direction and speed of the wind, the higher levels tends to be transferred to the surface. Since the wind direction at the higher level is parallel to the isobars and its speed is greater than the surface wind, this transfer causes the surface wind to increase in speed. During night, there is no surface heating, and therefore there is less turbulence and the surface wind tends to resume its normal direction and speed [21].

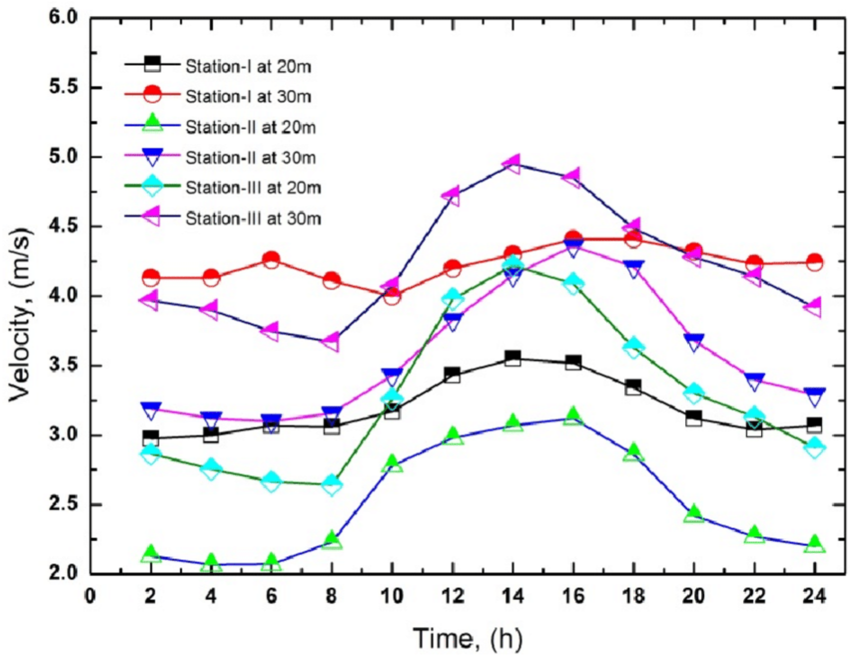

Figure 12: Wind speed at each hour of the day, in different stations [31]

4.4. Wind turbines

Wind has been used by humans for centuries to transform the kinetic energy of the wind into mechanical energy. The first windmill appeared in Persia in the 9th century and the vertical windmill was created in Europe in the 12th century [32].

Wind turbines do the same as windmills but instead of transforming kinetic energy to just mechanical energy, this is transformed into electrical energy. Just as windmills, wind turbines are mounted on a tower to capture the most energy. Around 30 meters, wind turbines can take out most of the fast, non-turbulent wind. The turbines are made by 2 or 3 blades that rotates perpendicular to the ground with the effect of the wind [33].

A blade acts much like an airplane wing. When the wind blows, a pocket of low-pressure air forms on the downwind side of the blade. The low-pressure air pocket then pulls the blade toward it, causing the rotor to turn. This is called lift. The force of the lift is actually much stronger than the wind's force against the front side of the blade, which is called drag. The combination of lift and drag causes the rotor to spin like a propeller, and the turning shaft spins a generator to make electricity at around

The typical operating sequence of a wind turbine is as follows [34]:

- When the wind speed reaches around 4 meters per second, the turbine blades will spin up to operating speed, usually around 14 to 29 rpm (varies by turbine model), and starts generating electricity
- As the wind speed increases, the generator output increases
- When the wind speed increases to the rated wind speed (usually around 12-13 meters per second), the generator will output its nameplate-rated capacity (i.e. a 2.3MW turbine would now output 2.3MW)
- As the wind speed continues to increase, the generator output will remain at the rated capacity (i.e. 2.3MW) until the wind reaches the cut-out speed (usually around 25 meters per second)
- At this wind speed, the turbine will deploy its tip-brakes and then apply its disk brake, stopping the blades in a few revolutions
- It will then rotate itself 90 degrees out of the wind and park itself
- If the wind speed drops to a level below the cut-out speed for a sufficient length of time, the turbine will point itself back into the wind, release the brake, and resume power production.

To summarize, wind turbine is made from these parts:

Rotor Blades - The rotor blades of a wind turbine operate under the same principle as aircraft wings. One side of the blade is curved while the other is flat. The wind flows more quickly along the curved edge, creating a difference in pressure on either side of the blade. The blades are "pushed" by the air in order to equalize the pressure difference, causing the blades to turn.

Nacelle – The nacelle contains a set of gears and a generator. The turning blades are linked to the generator by the gears. The gears convert the relatively slow blade rotation to the generator rotation speed of approximately 1500 rpm. The generator then converts the rotational energy from the blades into electrical energy.

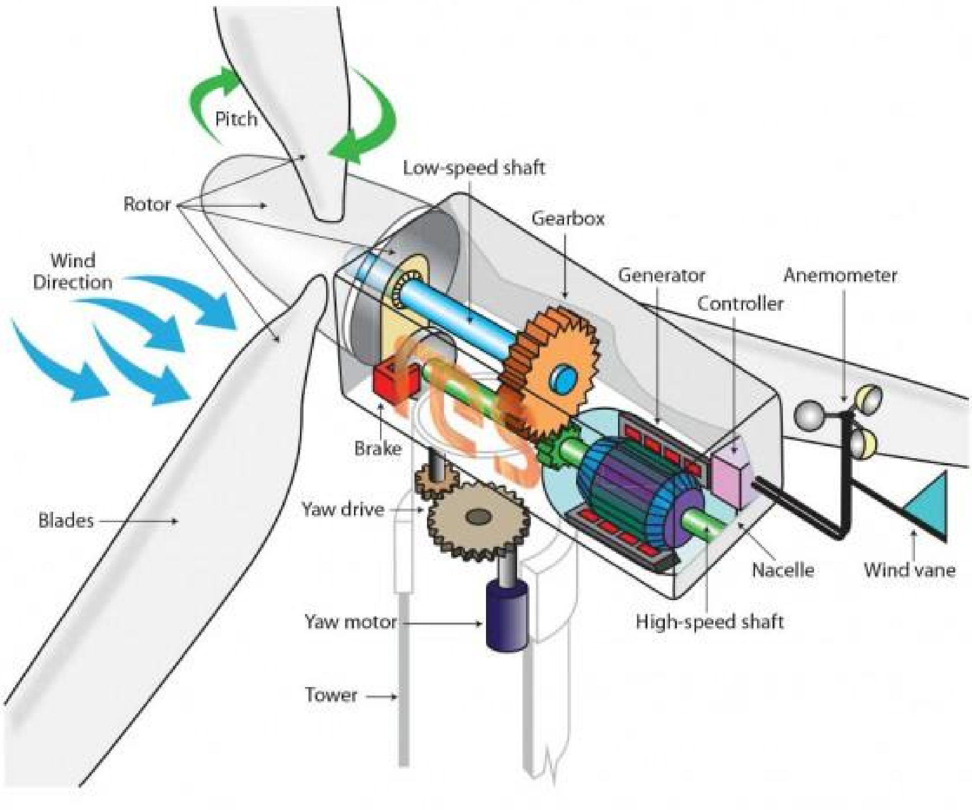

Figure 13: Nacelle of a wind turbine [34]

Tower – The blades and nacelle are mounted on top of a tower. The tower is constructed to hold the rotor blades off the ground and at an ideal wind speed. Towers are usually between 50-100 m above the surface of the ground or water. Offshore towers are generally fixed to the bottom of the water body, although research is ongoing to develop a tower that floats on the surface.

4.4.1. Wind turbine characteristics

Brand and model

There are many manufacturers that have ventured into the construction of wind turbines. Most of them are assemblers, that is, companies that take standard equipment from the market, perform integration engineering and produce turbines without manufacturing any of their components, which they acquire from the market [35].

Power

Power is the main characteristic parameter of a wind turbine, and expresses the energy it is capable of generating in a unit of time. Small wind turbines for domestic self-consumption start at 1 kW, while offshore wind turbines can reach 10 MW, and even more according to the latest news transmitted by leading wind turbine manufacturers are promissing.

Wind response curve

It is the power-wind speed curve of a wind turbine, and is divided into three regions:

- the region in which the speed is insufficient to start production,
- the range of speeds from the speed at which synchronization with the grid occurs and maximum power,
- the speed until the wind turbine can remain in operation with gusty wind, the speed at which the wind turbine can remain in operation with sustained wind and the range of speeds from which the wind turbine must stop.

Type of gearbox

There are different types of gearbox available in the market:

- Parallel axis gearboxes, with one or several stages
- Planetary axis gearboxes, with one or several stages
- Mixed gearboxes, which are the most common for high power wind turbines.

Number of blades

Horizontal axis wind turbines can have one, two or three blades, although smaller models may have more than three (always an odd number).

Gondola height

The height at which the gondola is located is measured from its base to the center of the gondola, or rotor shaft height. Heights are very variable, and depend on the power, which in turn defines the blade length. Heights ranging from 25 meters for wind turbines of hundreds of kilowatts are common, to over 100 meters for those with powers greater than

2 MW.

Blade length

The blades are responsible for converting the kinetic energy of the wind into rotational mechanical energy, and their length depends on the power of the wind turbine. Blade lengths range from 5 meters for low power generators to over 80 meters for larger ones. Of course, such length generates transportation problems, requiring special transport in most cases to carry the blades from the factory to the wind turbine location.

Maximum height

This height, which is a data point to be taken into account by civil aviation authorities, is the sum of the gondola height plus the blade height.

Efficiency

The efficiency of the wind turbine depends on the speed curve, which means that it varies depending on that speed. The maximum efficiency is achieved at the speed at which power reaches its maximum (generally around 10-12 m/s). According to Betz's law, it cannot be higher than 59%. Efficiencies of 35-40% are considered acceptable today.

Swept area

It is the area of the circle that the blades draw when rotating.

Rotation speed (range)

In most wind turbines, it is a range, not a speed. For high-power wind turbines used for grid-connected electricity generation, this speed is around 15 revolutions per minute (rpm), varying up to 10-15% according to wind speed. The larger the size, the lower the rotation speed.

Blade type

The type of blade that a wind turbine can have is very varied. The blade for large wind turbines is always the same but in the market there exists several options.

Blade orientation system

There are wind turbines with three types of blade orientation systems:

- Without blade orientation system.
- With a hydraulic blade orientation system.

- With an electric blade orientation system.

Generation voltage

Wind turbines generate at low voltage, with the most common voltages (measured at the generator terminals) being 400 volts and 690 volts, both in three-phase current.

Output voltage of the wind turbine

For domestic or low-power generators, it is possible for them to generate directly at low voltage, and therefore the generation voltage and the output voltage coincide. But it is more usual, for medium to high power turbines, to have a transformer between the generator and the substation connection, normally situated in the gondola or at the base of the tower, that elevates the voltage until the connexion with the substation.

Type of transformer

The possible types of transformer for raising the voltage from the generation voltage to the transport voltage to the substation are the integral filling transformer and the dry transformer, with the latter being much more common (the first one is possible, but it is rare).

Transformer location

The step-up transformer can be located either behind the nacelle, and therefore at the top of the wind turbine, or at the base of the tower.

Nacelle dimensions

Height, length, and width of the nacelle are three important parameters to define because they have implications for transportation to the site and for assembly.

Weight of the nacelle

The weight of the nacelle, like its dimensions, is important to know the type of transportation that will be necessary to hire for the complete transfer of the nacelle from the factory to the final location and to hire the necessary lifting equipment to position the nacelle at the top of the tower.

4.4.2. Onshore wind farms

Onshore wind energy is the one that is generated by wind turbines that are located on land and are driven by the natural movement of the air. Normally, they are located in rural areas, where there is less population and there are no buildings nor obstacles that interrupt wind [36].

Onshore wind farms were the first to be commercialized as they are less complex projects than offshore wind farms.

There are several advantages from onshore wind power:

- Reduced environmental impact: An onshore wind farm's construction and operation creates significantly less emissions than other energy source, while not requiring a big footprint as the sites they are placed on can still be farmed (for example, compared with solar farms).
- Cost effective: Wind power is one of the cheapest forms of renewable energy (along with solar photovoltaic power) and significantly less expensive than offshore wind power. Cheaper infrastructure and costs to run means onshore farms can help lower electricity bills.
- Quicker installation and easier maintenance: Onshore wind farms can be constructed in months, at scale, and are relatively cheap and cost-effective to maintain compared with offshore wind farms.
- Job creation: The analysis made by nationalgrid.com “Job That Can't Wait” reveals that 400,000 jobs are needed in the energy sector to deliver net zero by 2050 - being 60,000 of those jobs in building and maintaining onshore and offshore wind farms.

But there are some disadvantages also:

- Changing wind speeds: the consistency of electricity generation from wind farms can be challenged by varying wind speeds and changes in wind direction.
- No wind or intermittent generation: when the win dis intermittent (or non-existent) electricity generation is not possible. To meet energy requirements, a mix of solutions is needed, including other renewable energy sources, as well as receiving clean energy through interconnectors and improved management of energy demand.
- Effect on people and nature: some people complain about the landscape effects of wind farms as well as noise. There are also concerns of wind turbines posing a threat to birds (although it is smaller than skyscrapper risks and climate change).

4.4.3. Offshore wind farms

Offshore wind farms generate electricity from wind blowing across the sea. They are considered more efficient than onshore wind farms, thanks to higher speed of wins, greater consistency and lack of physical interference that the land or human-made objects can present (with a roughness close to 0, they have a high energy index).

Offshore wind contributed to 13% of UKs electricity needs in 2020.

There are some advantages of offshore wind power:

- Offshore wind turbines are more efficient: higher wind speeds and consistency in direction means offshore installations require fewer turbines to produce the same amount of energy as onshore wind farms.
- Reduced environmental impact: being miles out from the coast, offshore turbines are further away from the local population. Restricted access to their sites may even help to protect the surrounding marine ecosystems.
- More space to construct in: Oceans provide the perfect location to build wind farms in terms of scale and openness. More wind farms being built means more clean, sustainable energy can be produced.

Disadvantages of offshore wind power:

- Higher cost: Offshore wind farms require more complex infrastructure to support them and, as a result, are more expensive to construct.
- Maintenance and repairs: Higher wind speeds, strong seas and accessibility issues makes offshore wind farms more challenging to maintain.
- Less local involvement: while onshore wind turbines can be owned or operated by local cooperatives, or even individually owned, offshore wind turbines require a considerable scale of investment that means they are usually corporately owned. However, they do provide significant employment for the development and working life of the wind farm.

4.4.4. Betz's law

Betz's law is an aerodynamic law that indicates the maximum power that can be extracted from the wind, independent of the design of a wind turbine in open flow. Ut was published in 1919 by the German physicist [37].

The law is derived from the principles of conservation of mass and momentum of the air stream flowing through an idealized "actuator disk" that extracts energy from the wind stream. According to Betz's law, no turbine can capture more than 16/27 (59.3%) of the kinetic energy in the wind. The factor 16/27 (0.593) is known as Betz's coefficient. Practical utility-scale wind turbines achieve at peak 75-80% of the Betz limit.

The reason for this to happen is found in Newtonian fluids. If all of the energy coming from wind movement through a turbine were extracted as useful energy, the wind speed afterwards would drop to 0. If the wind stopped moving at the exit of the turbine, then no more fresh wind could get in; it would be blocked. Then some speed is needed after passing through the turbine. This law shows that as air flows through a certain area, and as wind speed slows from losing energy to extraction from a turbine, the airflow must distribute to a wider area. As a result geometry limits any turbine efficiency to a maximum of 59.3 % .

4.4.5. Wind turbine power curve

The wind turbine power curve is a graph representing how much power a turbine can produce in function of different wind speeds. This is really useful to identify possible sites for wind farms or home wind power installations as it helps calculate the potential return on investment (ROI) of the installation [38].

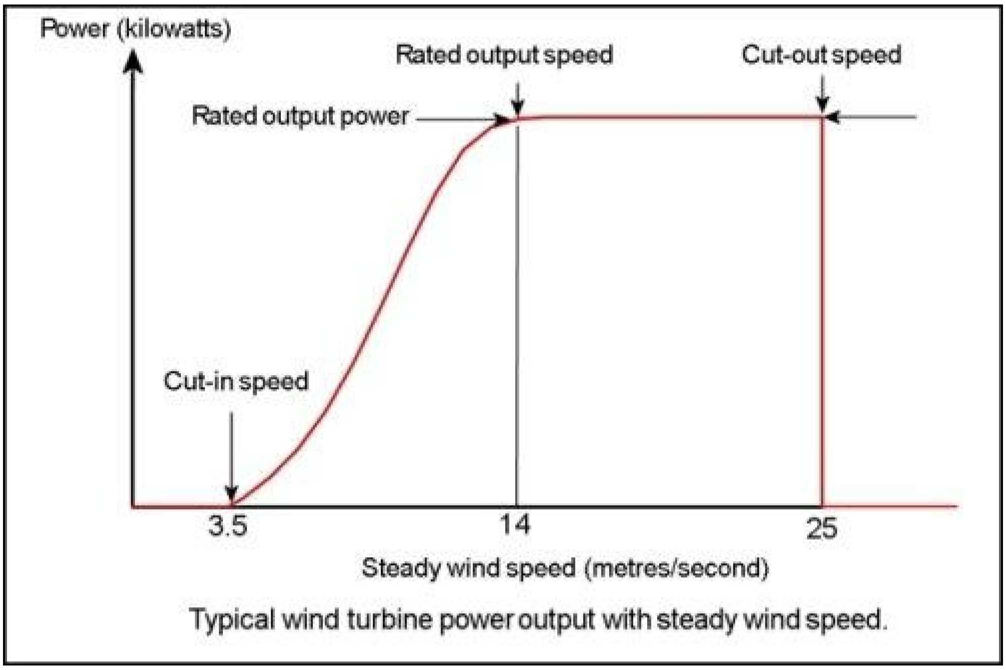

Figure 14: Wind turbine theoretical power curve [38]

To calculate the wind turbine power curve you need the actual turbine and an anemometer close to the turbine to measure the wind at a certain time while the turbine generates power. The scatter plot originated from the data intake would give values that would not be exactly the plot shown above but one that is close to it.

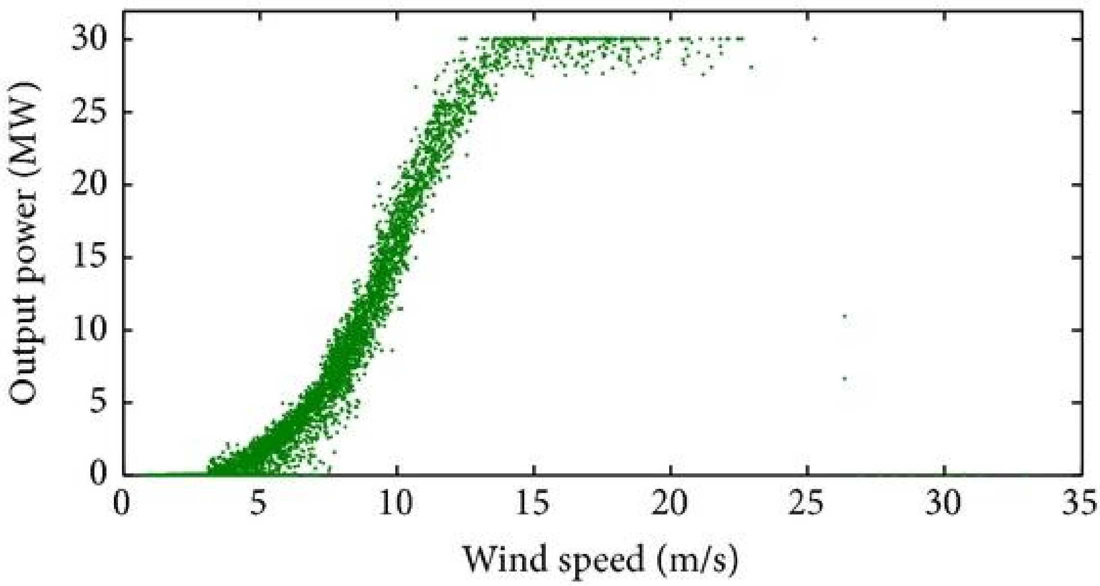

Figure 15: Wind turbine power curve [39]

As it can be seen in both pictures, at very low speeds there will be no output power generated. That is because there is insufficient torque exerted by the wind turbine on the turbine blades to make them rotate. However, as the speed increases, the wind turbine will begin to rotate and generate power. The cut-in speed is the one where the turbine first starts to rotate and it is typically between 3 and 4 meters per second.

As it can be seen, around 12 to 17 meters per second, the power output reaches the limit that the electrical generator is capable of. This limit is called rated power output and the wind speed at which it is reached is called the rated output wind speed. At higher wind speeds, the design of the turbine is arranged to limit the power to this maximum level and there is no further rise in the output power. How this is done varies from design to design but typically with large turbines, it is done by adjusting the blade angles so as to keep the power at a constant level.

Then, at around 25 meters per second, the forces on the turbine structure continue to rise and, at some point, there is a risk of damage to the rotor. As a result, a braking system is employed to bring the rotor to a standstill. This is called the cut-out speed and is usually around 25 meters per second.

The available power in a stream of wind of the same cross-sectional area as the wind turbine has been shown in section 4.3.2. "Wind power". If the efficiency is needed, it will be compared the real power produced versus the theoretical power that can produce:

$$\mu = \frac{Power}{\frac{1}{2}\rho U^3 \frac{\Pi d^2}{4}} \quad (2)$$

4.5. Electric vehicle (EV)

An Electric Vehicle (EV) is a vehicle that uses one or more electric motors for propulsion. They have existed since the 19th century. In the 1900s Electric Vehicles accounted for 28% of the cars on the road in the US [40]. Nevertheless, they had the disadvantage of range (electricity storage in a single charge) so to compete in markets where long road infrastructures were being built and the discovery of large reserves of petroleum was driving oil prices down, making them a really small niche when economies of scale worked for the automotive industry. Not only that, at least in the US, big companies surrounding the automotive industry and oil, lobbied themselves to push even further ICE Vehicles. One example of what was done is the purchase and dismantlement of the tram lines by GM and Standard Oil of California around the country to replace them with GM buses. Others came to the infrastructure development of the US during the 20th century. The automotive lobbies have defined the way cities look in the US, making them dependent on private vehicles in comparison to other ways of transportation [41].

For that and other reasons, right now Internal Combustion Engine (ICE) vehicles dominate the automotive market. Nevertheless, key inventions during the last decades as well as action and incentives from governments have made EVs competitive in the market. For example, in Norway, the share of sales of EVs in 2022 was 80%. It must be said that Norway is a small and rich market that, although it extracts a lot of petroleum, has a society really environmentally conscious [42].

But most importantly, due to several reasons, margins in electric vehicles from the market-leading brand Tesla have been positive in the last quarters. The Profit margin for Q3 in 2022 was more than 9000 €. That is almost 5 more times from the following competitor (General Motors). This has given the company the ability to decrease prices considerably to push prices down and make EVs even more affordable. This reduction in prices also comes from a cooling market due to macroeconomic conditions (e.g. rising interest rates slows down consumer spending).

The reason why Tesla business case is critical is because it is proving that economies of scale is possible in electric cars and it is just a matter of time that production will be scaled even further and prices will potentially go down even more. Concerning the project, that also means that EVs will be more widely available in the near future which will increase the amount of energy generated by wind farms during night.

4.5.1. Types of EVs

There are several types of EVs in the market, being BEV the most popular one. Nevertheless, there are other types of EVs that are also relevant for the transition from ICE Vehicles.

- Battery electric vehicles (BEVs): they run on electricity and need to be charged from an external power source. They are propelled by one or more electric motors powered by rechargeable battery packs. As a reference, the Tesla Model 3 has a range of 500 km and a Silence S01+ motorbike has a range of 133 km. Depending on the use you give to a vehicle, right now, BEVs are a compelling alternative to ICE vehicles.
- Plug-in hybrid electric vehicles (PHEVs): they also use batteries to power an electric motor and can be recharged from an external power source, but they incorporate a smaller internal combustion engine that can recharge the battery. PHEVs can usually drive moderate distances using only the battery. This reduces their emissions under typical driving conditions, since most trips are short.
- Hybrid electric vehicles (HEVs): they are powered by a combination of an internal combustion engine with electric motors running off a battery pack for greater efficiency. The batteries of an HEV cannot be recharged from an external source.
- Fuel cell electric vehicles (FCEVs) use a highly efficient electrochemical process to convert hydrogen into electricity, which powers an electric motor. FCEVs on the market today are not designed for recharging their battery from an external source. They are fueled with hydrogen gas that is stored in a tank on the vehicle.

In this work, the focus will be on Battery Electric Vehicle (BEV) as they are the ones that have more battery capacity and the ones that have more potential to have economies of scale at least until this point. FCEVs will also be studied for the case of heavy duty vehicles although there is still no implementation of the technology nor the infrastructure but they could become important due to several advantages with respect to BEVs.

4.5.2. Number of EVs in Europe

Europe reached an important milestone in 2022. More than 50% of the new cars registered in the EU have been Alternative Propulsion Vehicles (APVs). In the case of BEVs, it accounts for 12.1% of the total market share, compared to 9.1% in 2021 or 1.9% in 2019 [43].

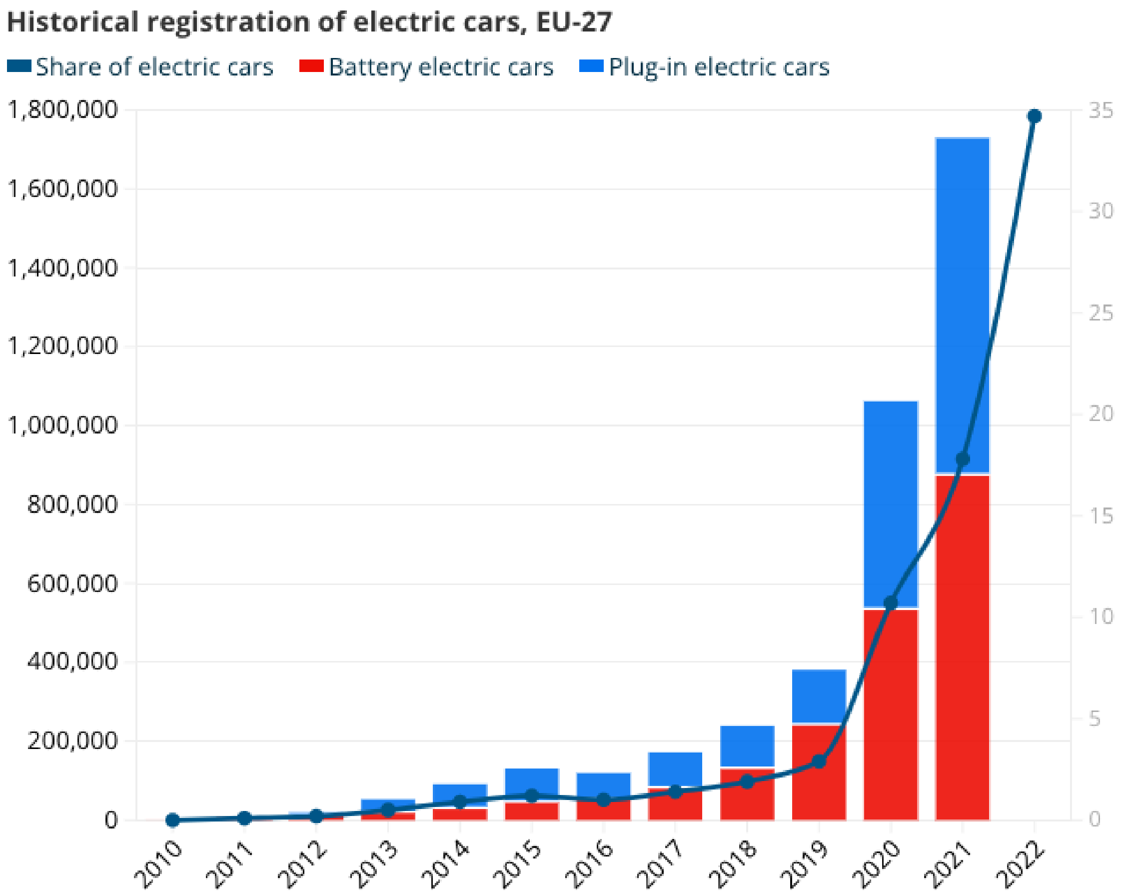

Figure 16: Registration of Electric cars in EU-27 from 2010 to 2022 [43]

In the EU, there is an agreed ban on Petrol and Diesel cars for 2035. From that point, the bare minimum will be hybrid vehicles. Besides, lots of cities prohibit the circulation of some gas cars at least at certain times of the year or of the day. Lyon, for example, will prohibit diesel vehicles and a large proportion of petrol cars by 2026.

The EU's target is to have 30 million zero-emission cars by 2030. This is the minimum number of cars necessary to be on track for achieving climate neutrality by 2050 [44].

As part of the analysis made in this project comes from the previous analysis, the sources for the number of BEVs that will be used will be the same.

Taking into account that sources, in 2021, 1.2 million BEVs and 1 million PHEVs were registered according to the European Automobile Manufacturers' Association (ACEA) [45].

The data point that is relevant for this study is how many plug-in cars are circulating everyday in Europe.

4.5.3. BEVs type of charge

Charging is one of the critical points that makes somebody decide to buy or not an BEV. One of the biggest advantages of ICE vehicles is that they can be refilled in 5 minutes. This makes them really convenient for long trips (although resting should be essential in any trip) or for places where there is no great availability of charging stations like the countryside.

In comparison with ICE vehicles, the charging systems are different. There exists 3 levels of BEV charging: Level 1, Level 2, and Level 3. Level 3 is broken into DC Fast Charging and (Tesla) Supercharging (which is now a standard). The higher the level of charging, the faster the charging process, as more power is delivered to the vehicle. It is important to notice that different BEVs charge at different speeds on each level, because each BEV can accept different levels of power from the charger or also called Electric Vehicle Supply Equipment (EVSE).

For that difference to not cause a problem, when the car is plugged in, there’s a communication process before the charger is energized: the car “asks” the charger how much power it can deliver, and then the car calls for the maximum amount of power that the station can deliver and the vehicle can accept.

The car always determines how much power it accepts, meaning that the car will never receive more than the acceptable amount of power the vehicle can handle [46].

Level 1 Charging

The charging speed in this Level is from 3-7 Miles per hour. It can be found at houses, workplaces or in public places. It can take from 22 to 40 hours to fully charge a BEV.

It uses a 120 volt household outlet which provides between 1kW and 1.8 kW of power and it is only available in the US. This type of charging is not practical in reality as the maximum time it should take to charge is 8 hours (during night) [47].

Level 2 Charging

In this case, this level of charging uses a 208 volt to 240 volt outlet in North America and 230-volt (single phase) or 400-volt (three-phase) outlet in Europe. In North America, Level 2 chargers top out at 19.2 kW (80 A), and in Europe, it’s 22 kW. A Level 2 charger can come with various additional functions and features, such as RFID cards, load balancing and OCCP (Open Charge Point Protocol) networking.

It is 19 times faster than a Level 1 charger depending on the power output and the charge acceptance rate of the vehicle you are charging. It can provide from 16 to 120 kilometers per hour of range.

This type of charging is found either in public charging stations or households, offices and others in the case that the proper equipment can be installed.

The use case is overnight charging.

Both Level 1 and Level 2 are AC-type while Level 3 is DC.

Level 3 Charging

Level 3 BEV charging (also called DC fast charging) is significantly faster than Level 2 BEV charging. The charging stations are the market's quickest and most powerful EV charging option. A level 3 charging station utilizes a three-phase supply, 480 volt in North America and 400 volt in Europe, with chargers capable of outputting up to 360 kW of power.

A Level 3 charging station also comes with various functions and features, such as dynamic power distribution, multi-charging protocol cables, and networking via OCPP.

The importance of Level 3 charging is how quick it is to give range to BEVs. In 15 minutes the vehicle gets 1.5 hours of driving depending on the charge acceptance rate. In some cars, within 30 minutes the battery is at 70% of capacity. This brings BEVs competitiveness with respect to ICE vehicles. Nevertheless, the cost of this technology is higher than the other two and it puts more pressure on the grid system in comparison to the others.

4.5.3.2. Charging times

There are several factors that need to be considered when calculating the charging time of an BEV. The following factors will follow the previous work.

- Battery capacity: it indicates the quantity of power that can be stored as electricity. This capacity is measured in kWh. The higher the capacity, the more it will take to charge the car.
- Charging power: it is the rate of charging the battery (how quick it is to charge). The magnitude used is the kW. The more power used, the quicker the battery will be fully charged. To know the power, it is needed to know the type of current used (AC or DC), the tension and the current.
- Type of current: either if it is direct, single-phase or three-phase.

Knowing these 3 data points, it is possible to calculate the time necessary to charge the batteries:

Time necessary (t) in hours calculated as capacity (C) in kWh divided by the power (P) in kW. The capacity as a percentage (from 0 to 100%) will be further studied in Section 4.5.4.

$t = \frac{C}{P}$ (3)

The power if it is a single-phase or DC station will be calculated as the product of tension (V) in Volts and the current (I) in Amperes.

$P = VI$ (4)

In the case of three-phase current, it is calculated with a multiplying factor of 1.73.

$P = 1.73VI$ (5)

With these formulas it is possible to know the necessary time to bring the battery of an BEV to a certain percentage.

4.5.4. Useful life of electric batteries

- How much do they last
- Capacity when to change
- Problems with batteries

Batteries in BEVs are made of thousands of rechargeable lithium-ion (Li-ion) cells, which are connected together to form the vehicle's battery pack. They have a far higher energy density than most other types of batteries, being able to store more energy in a given volume. Not only that, they are more efficient when discharging their energy and require little to no maintenance [48].

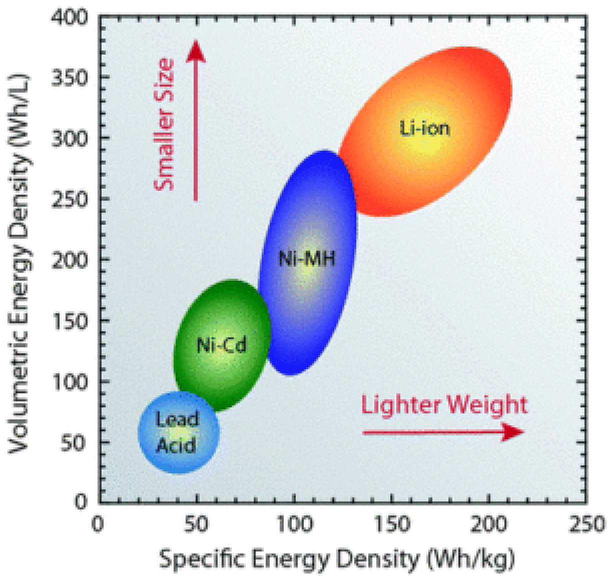

Figure 17: Volumetric Energy Density of different materials with respect to specific Energy Density [49]

One of the main concerns of potential customers of BEVs is how the battery in an BEV will degrade. It is easy to compare BEVs batteries with laptops or smartphones batteries, and knowing how fast they degrade, the concerns are reasonable [48].

Nevertheless, the reality is far from what people might think. In comparison with phones, batteries in BEVs are made to last longer. Besides, they are used differently and have built-in protection mechanisms like battery management systems (BMS). BEVs do not need to be constantly charged and can last multiple days until charging is required.

Batteries are expected to last from 161,000 to 320,000 kilometers (more or less 15 to 20 years). The average lifespan of a car is 12 years, then batteries outlast the vehicle they are in.

It is considered that a battery is not useful anymore for a BEV when it only has 80% of its total capacity available.

Besides, battery aging is almost imperceptible for the driver. The loss of battery per year is 2.3% meaning that purchasing a BEV today with 240 km range, will mean that you will have a loss of 27 km of accessible range after five years.

To further reduce the battery degradation, it is recommended to stay between 20 and 80 percent charge. To achieve that, it is recommended not to charge BEVs every night and use smart charging stations that can help make the battery not go beyond those limits.

Batteries have some downsides regarding their useful life. One of them being their recyclability which will be discussed later. Also, they are heavy, which provides less efficiency while driving (but increases the safety with car rollover). To finish, it is important to mention that they can become a safety hazard as if they are not properly engineered and manufactured they can explode or begin fires. This is because the cells have flammable electrolytes. One of the main developments from Li-ion batteries has been providing innovations to make them safer [50].

4.5.4.1. Battery life cycle handling

There are several key aspects about battery life cycle. Considering a “Cradle-to-grave approach”, the main problems of these batteries are in the Cradle and grave part.

Regarding the first part of the life cycle, the batteries are composed from several elements that need to be extracted and not all of them are found in countries with strict labor regulations, leading to potential human right violations buying materials to countries in conflict (e.g. cobalt trade). Besides, materials like lithium require great amounts of water usage. This has led to more investigation in new types of batteries as well as improving mineral efficiency.

When it comes to the last part of the life cycle, it is complex as there are several ways to reduce BEVs Li-ion batteries' overall environmental impact. First of all, it is possible to reuse the batteries one, two or even three times before stopping using them. As the minimum capacity they will reach in a car is 80%, there is still a lot of uses for those batteries.

For example, it is possible to use them as energy storage in a household or repurposed for other products. When the reuse cycle has finished, there is still not an effective, scaled way to recycle them but some investigators have found processes that will make it easier to recycle batteries. Processes like the pyrometallurgical recovery, hydrometallurgical metals reclamation or direct recycling. The last is the most cost effective one as it consists of removing the cathode or anode from the electrode, reconditioning it and then reusing it in a new battery. Mixed metal-oxides can be added to the new electrode with very little change to the crystal morphology. The process generally involves the addition of new lithium to replenish the loss of lithium in the cathode due to degradation from cycling. The drawback of the method lies in the condition of the retired battery and that the design of the batteries after 10 years probably will be different so it is not that adaptable [50].

To maximize the lifespan of a battery, there are several actions to be taken:

- **Minimize exposure to extremely high temperatures when parked:** BEVs have automated temperature control systems installed to keep the temperature of the car down. The problem this brings is the use of the batteries to keep the car at optimal temperature. the best solution is always try to keep BEVs in the shade or plugged.

- **Minimize charging the batteries until 100%:** BEVs have installed a battery system that avoids them being charged and discharged at the extreme state of charge. The best option is to keep the battery between 25 and 75 % of charge. There exists systems that already allow for intelligent charging.
- **Avoid using fast charging:** Using fast-charging is convenient but inputting too much current into the batteries in a short period strains the battery and degrades it in the long run. Standard charging gives 10% more battery life compared to 8 years using fast charging.
- **Control the optimal battery state during long storage:** Parked BEVs with an empty or full battery also degrades the battery. If it is needed to charge the car, as it has been said, it is better to keep the battery between 25 to 75 % [51].

4.5.5. Charging stations in Europe

The transition to an electrified future cannot be done without proper infrastructure. Wide availability of charging stations are one of the most important milestones for BEVs to be fully competitive.

One of the main examples of infrastructure is Tesla's supercharging network. By 2022, Tesla had 40,000 superchargers around the world, making it the largest global DC fast-charging network. This network has been one of the most differential points in Tesla's strategy to success and probably one of the most disruptive moves from the last decades in the automotive industry. Last year, they made the superchargers accessible for non-Tesla EVs [52].

Nevertheless, Tesla is not the only player in this field. In 2021 there were a total of 375000 charging stations in Europe. In the most conservative predictions in a McKinsey analysis made for the ACEA, it is suggested that EU-27 will need at least 3.4 million operational public charging points by 2030. Besides, extensive utility grid upgrades will be required to distribute electricity to these new charging stations and for the increased renewable-energy Europe's future EV's will need to run on cleaner power. It is estimated that 240 billion euros will be needed to complete this plan by 2030 [53].

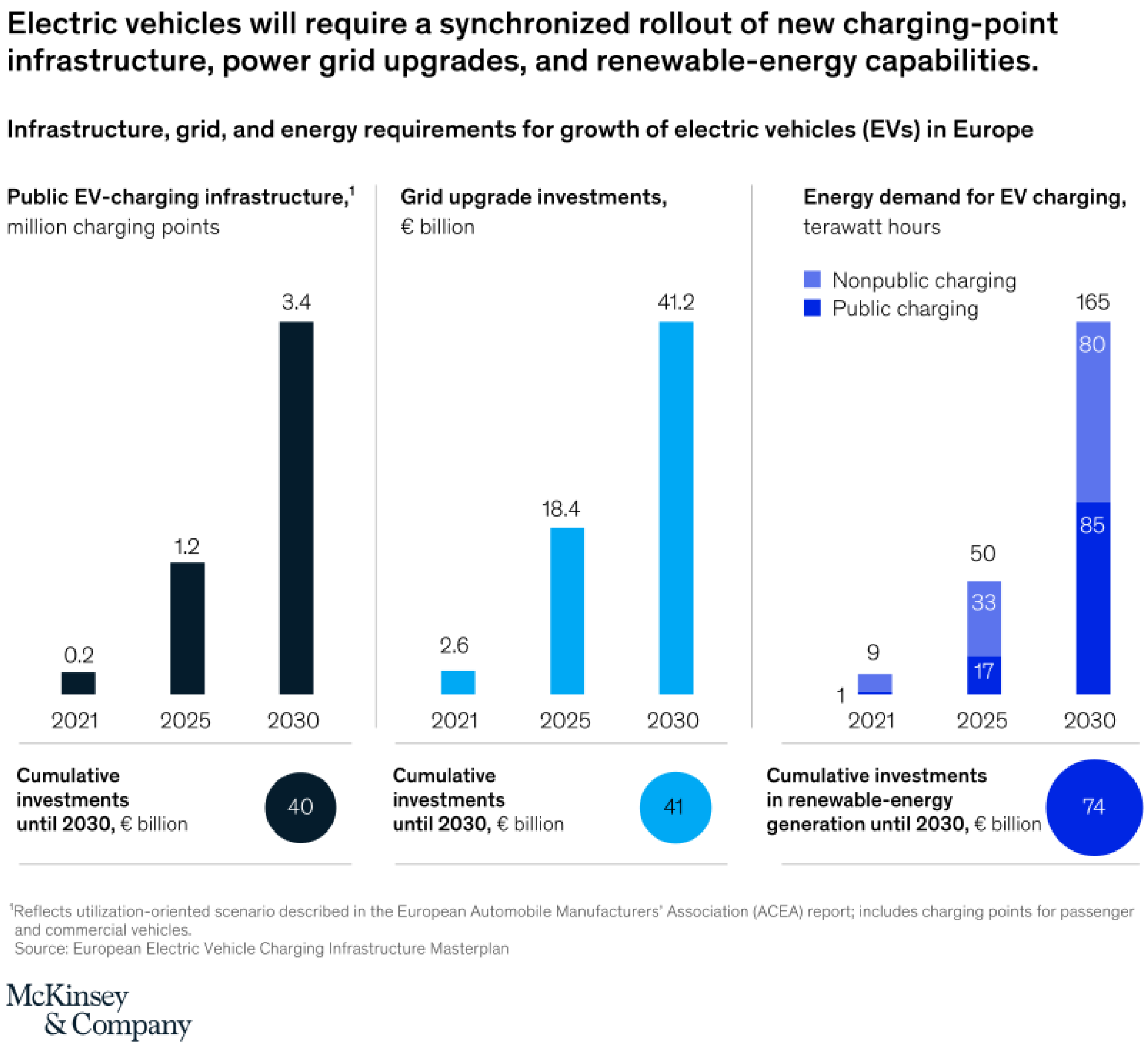

Figure 18: Investment of EV infrastructure [53]

One of the key issues that can be found in the creation of the infrastructure is the second point in the picture, the investment needed to upgrade the grid system. In the Mckinsey article, it is mentioned that fast charging of 20 trucks and 10 cars could experience peak electricity demand of about 20 megawatts - equivalent to that of a city with 20,000 inhabitants.

Nevertheless, what is interesting for this project is the simultaneous charging of vehicles in households. Overnight charging will be the necessary type to analyze. As the charging is done through slow alternating current (AC) of 3 to 11 kilowatts of electricity, there will be less strain on the grid.

One of the aspects about charging stations to consider is the number of stations per EV. This is a key performance indicator (KPI) on how easy it will be to increase the number of cars in each country. Ideally, the number should be between 10 and 15 EVs per charging station [54].

4.5.6. Environmental impact of a BEV

To analyze the Environmental impact of an EV, it will be compared with an ICE vehicle. The final goal of EVs is reducing the impact of greenhouse gas emissions. ICE vehicles are one of the biggest contributors of CO2e emissions and it pollutes the air and causes health issues (it will be studied later) [55].

EVs are not 100% clean as their production is carbon-intensive (particularly the battery) and depending on the source of energy they receive when charged, there is CO_2e extracted to the atmosphere.

In this analysis, it is considered a “cradle to grave” view: studying the vehicle from production to disposal.

Some hypotheses need to be made to be able to calculate which is the environmental impact of an EV. First of all, it is decided that the car reference for this analysis is a Hyundai Kona, as there exists the ICE vehicle model and the EV model. In the following table, there are the assumptions and data related to CO2 consumption.

Characteristics	
Battery capacity (kWh)	39
Useful life (years)	13
Travel distance per year (km)	15000
Total distance traveled (km)	195000
Battery emission per kwh (kg CO2)	177
Gasoline from extraction to consumption(kg CO2/l)	2.157
ICE Consumption (l/100 km)	5.9
ICE Emission of CO2 (kg)	0.12
EV consumption (kwh/100 km)	17
EV Consumption (kg CO2 /kWh)	0.265

Table 2: Characteristics of EV and ICE vehicles to compare their pollution. Appendix 13, section 9.

Element	ICE Vehicle (kg CO2)	EV (kg CO2)
Vehicle body	4219	4219
Motor	1274	1070
Inversor	0	641
Battery	0	6903
Sum prod	5493	12833
Energy	48216.285	8784.75
Scrapping	65	65
Total	53774.285	21682.75

Table 3: Pollution of each type of vehicle. Appendix q3, section 9.

The total shows there is a reduction of 60 % in CO2 consumption with respect to the ICE vehicle. Nevertheless, it is seen that it depends on the useful life that has been defined.

4.5.6.1 Health impact of EVs

One of the most important aspects of increasing EV share is the positive health impact that they have in comparison with ICE vehicles. The main positive effect is the reduction in pollutants inside cities as the pollutants shift to the power generation areas.

External costs

An external cost or externality is a cost or benefit caused by the producer that is not financially incurred or received by that producer. An externality can be both positive or negative and can stem from either production or consumption of a good or service. The costs and benefits can be both private - to an individual to an organization - or social, meaning it can affect society as a whole.

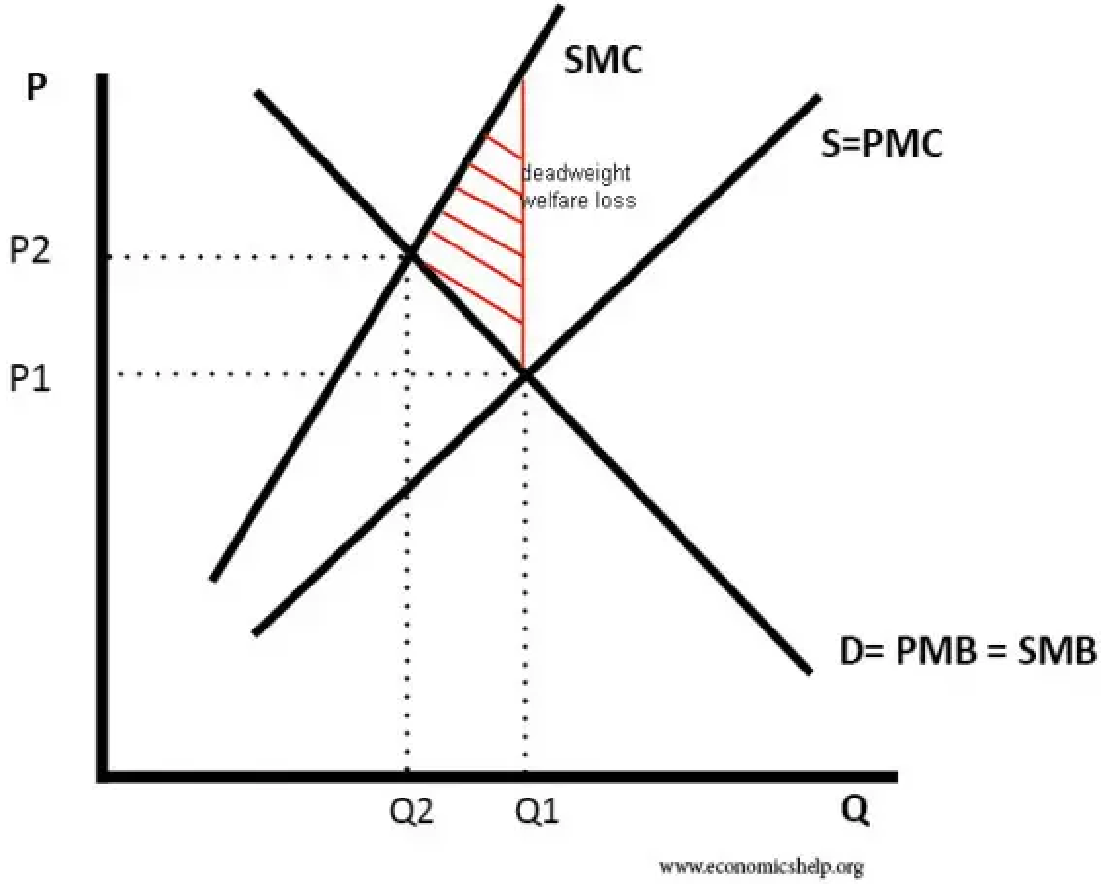

Figure 19: Supply and demand curves with social cost and without social cost considered [56]

- P = price
- Q = quantity
- SMC = Social Marginal Cost
- PMC = Private Marginal Cost
- D = Demand

To understand externalities in economics terms, above there is the supply and demand diagram. The horizontal axis represents the quantity of the good being produced and consumed. The vertical axis represents the price of that good.

The demand curve is downward sloping representing the willingness of consumers to purchase goods. The supply curves are upward sloping ones and represent the willingness of producers to supply the goods at various price levels.

In a normal supply and demand curve there would be only one supply curve. In this case there are two. The supply curve steepness depends on the marginal cost to produce the goods. In the case of the normal cost the curves cross in Q1 and P1. This is the market equilibrium. The problem in some cases is that the equilibrium price produces a quantity of the good that produces a social cost. Calculating this cost and adding it into the supply curve gives the second supply curve. The area between Q2 and Q1, the demand curve and the supply curve considering the externality is the deadweight welfare loss (the amount of harm from producing the quantity Q1). The problem comes on how to assign the property rights on these externalities.

One approach to solve this issue is introducing taxes to increase the price of the good and, if the demand is elastic, the quantity demanded will decrease. The Coase Theorem states that under ideal economic conditions, where there is a conflict of property rights, the involved parties can bargain or negotiate terms that will accurately reflect the full costs and underlying values of the property rights at issue, resulting in the most efficient outcome (a Pareto efficient allocation). So Coase was implying that the problem is not that markets do not work well, but that there are "missing markets.". Instead of taxing certain activities, the regulator should design rules and institutions that would reduce transaction costs and enable effective negotiations. This is the theory behind the creation of a carbon market, critical in the next years for transitioning to a sustainable economy [57].

As said, externalities can be both negative or positive. A negative externality would be the pollution of a river by a chemical company, intoxicating and killing fish in a large area of the river and thus eliminating the source of income of populations along the river. A positive externality can be beekeepers. They take revenues from the bee production of honey. And an increase in bee population has a positive effect on the ecosystems due to pollination. Following the Coase theorem, the fisherpeople (or government) would compensate the company to stop producing that amount of goods, or benefit them from improving their technology to reduce the social cost, while in the second example the bee keepers would receive a compensation from farmers to increase the quantity of honey produced (more bees, better crops).

Usually, human interaction with the environment tends to negative externalities and thus solutions need to be provided to reduce them. The current proposals are taxes, subsidies and regulations or creation of markets (like the creation of a carbon credit market).

In the automotive industry, externalities are related to air pollution (Euro/tonne pollutant emitted) for electricity production and for conventional transport for ICE vehicles are country specific as they depend on geographical, meteorological and orographic factors

Buekers, J., et. al. (2014) [58] analyses which are the health benefits of the replacement of an ICE vehicle with an BEV. The battery production is not accounted in the following table:

32 *J. Buekers et al./Transportation Research Part D 33 (2014) 26–38*

Table 5
External costs (health and climate impact) for the replacement of a car with internal combustion engine (ICE) with an electric vehicle (EV). For ICE cars WTT and TTW emissions were taken into account and for EV electricity production assuming different fuel mixes in 2010 and 2030. Battery production for EV was not accounted for in this table. Energy efficiency of EV was set at 0.25 kWh/km.

Country	External costs (Eurocent 2010) per kWh electricity*					
	2010**			2030**		
	Health	CO_2	Total	Health	CO_2	Total
Belgium	−1.6	−0.9	−2.4	−1.4	−0.4	−1.8
Bulgaria	−0.4	−0.5	−0.9	−0.5	−0.7	−1.2
Czech Republic	−0.6	−0.3	−1.0	−0.7	−0.5	−1.2
Denmark	−0.7	−0.6	−1.2	−0.7	−0.8	−1.5
Germany	−0.9	−0.5	−1.4	−0.9	−0.5	−1.4
Estonia	−0.2	0.2	<0.01	−0.3	<0.01	−0.3
Ireland	−0.8	−0.4	−1.2	−0.9	−0.6	−1.4
Greece	−0.3	−0.1	−0.3	−0.4	−0.4	−0.8
Spain	−0.6	−0.6	−1.3	−0.7	−0.8	−1.4
France	−1.5	−1.1	−2.6	−1.5	−1.1	−2.7
Italy	−0.9	−0.5	−1.4	−1.0	−0.8	−1.8
Cyprus	0.8	0.4	1.2	−0.2	−0.4	−0.6
Latvia	−0.6	−0.9	−1.5	−0.4	−0.9	−1.4
Lithuania	−0.7	−0.5	−1.2	−0.8	−1.0	−1.8
Luxembourg	−1.8	−0.5	−2.3	−1.8	−0.5	−2.3
Hungary	−0.6	−0.7	−1.3	−0.5	−0.8	−1.3
Malta	−0.7	0.5	−0.3	−1.3	−0.4	−1.7
Netherlands	−0.8	−0.5	−1.3	−0.8	−0.6	−1.5
Austria	−1.5	−0.9	−2.3	−1.4	−0.9	−2.3
Poland	<0.01	<0.01	<0.01	−0.1	−0.1	−0.3
Portugal	−0.4	−0.6	−1.0	−0.4	−0.8	−1.2
Romania	0.1	−0.6	−0.5	−0.1	−0.8	−0.9
Slovenia	−1.0	−0.7	−1.7	−1.2	−0.9	−2.1
Slovakia	−0.8	−0.8	−1.6	−0.7	−0.8	−1.5
Finland	−0.6	−0.8	−1.5	−0.7	−1.0	−1.6
Sweden	−0.8	−1.2	−2.0	−0.8	−1.2	−2.0
UK	−0.7	−0.5	−1.2	−0.8	−0.8	−1.6

* A negative external cost in the table indicates a net benefit.
** Fuel mix electricity production for the year 2010 & 2030 is published by the EC (2010).

Table 4: External costs of replacing an ICE vehicle with an EV [58]

It makes a comparison between 2010 and 2030 and includes the change in the fuel mix use in every country. A negative external cost in the table is a net benefit. The health benefits from shifting to BEVs is dependent on the energy mix of that country. For instance, if energy production is highly reliant on oil, coal and other fuels, the health benefit is not going to be great. Cases include Romania and Cyprus.

In the analysis, it will be calculated which are the health benefits of the BEVs necessary to maximize wind power generation. The limitation of this analysis comes from the fact that energy mixes will be considered when calculating the BEVs introduced, while the BEVs that will be introduced will be powered by wind power, a clean energy source, that will produce close to zero CO_2 kg, then the result found will be conservative and the potential benefit of these BEV introductions are greater.

4.5.7. BEVs raw materials

Raw material availability is a necessary study to be made to check if the transition to an electrified future is possible and to understand what is the environmental impact of an EV.

Although BEVs parts go beyond the battery, it is this component the most important and complex one as it includes several types of materials that might be difficult to extract, find in large quantities, easily increase production or recycle. For example rare earth metals and lithium. Nevertheless, the whole car includes other important materials whose price can have large variations due to energy prices, being aluminum the best example of an energy-intensive material to produce.

In the case of lithium, there are several studies analyzing the possible future scenarios of the material. Bajolle, H., et. al. (2022) [59] do a qualitative study based on experts opinions, market trends and price scenarios.

It is difficult to estimate the price scenario in the next few years as it is based on interrelated factors such as market demand, innovation, public policies and learning effects. For example, situations like the supply chain crisis derived from COVID and Ukraine's war have raised the price of Lithium, increasing battery pack costs but potentially fostering new mining as it is an attractive opportunity for new players to enter the market.

Besides, the lithium market does not work like commodities such as iron, ore, grains or wheat which are based on transparent global prices fully dependent on supply and demand in a stock exchange (SPOT market). The spot market is where financial instruments, such as commodities, currencies, and securities, are traded for immediate delivery. Delivery is the exchange of cash for the financial instrument [60]. Although a SPOT market for lithium exists, this is only used for speculative purposes and the majority of lithium exchanges are carried out over-the-counter (OTC), meaning that the contracts are done via a broker-dealer network. A similar scenario happens with cobalt, having markets characterized by a lack of liquidity, opacity in contract prices and production capacities.

Innovation in batteries will be the main driver of price reduction while materials will probably have the opposite effect: temporal scarcity of several materials will increase the prices of battery packs. Innovations regarding materials will be centered around the reduction of different types of materials (e.g. rare earth metals) and the recyclability of batteries. Most of the experts in the analysis agree that the price of Batteries will stabilize but there is more divergence between raw materials physical supply being or not being an issue.

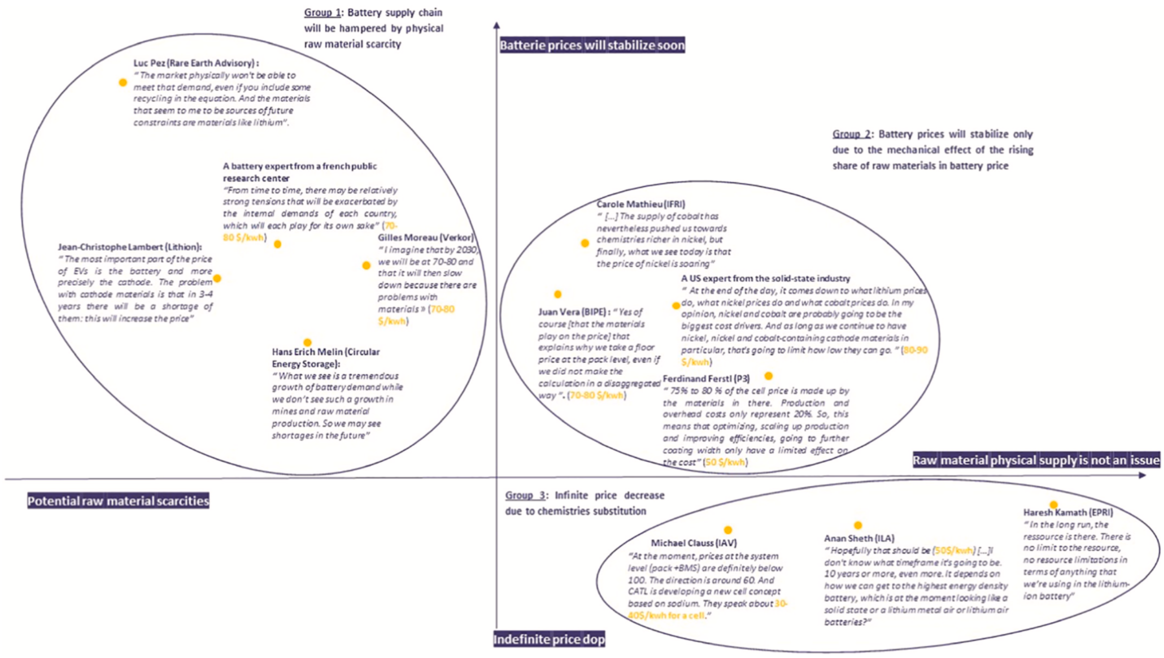

Figure 20: Lithium expected price movement, qualitative [59]

The main problem with ramping up new raw material extraction is not the unavailability of it in the Earth's crust. The 2022 US Geological Survey estimates the known global reserves of lithium at 22 million tonnes while 100k tonnes were mined in 2021. This is enough to last for hundreds of years. And the circular economy is not counted in the analysis [61].

The problem comes from new mining efforts from the private sector. Mining firms have not received enough profits in the last few years due to low material prices. Right now, with price increases, they are making more profit. Although they might take the opportunity to enjoy the high prices and not increase production in the short term, this signal to the market will introduce incentives for them to invest in new facilities. Nevertheless, there are project planning constraints in these plans as it takes around 10 years to finance and build a lithium mine. There are planned projects for 2025.

The global capacity of battery production is right now around 658 GWh in 2023, in comparison to 220.5 GWh in 2018. It is predicted that the capacity will increase up to 1102.5 GWh in 2028 [62].

4.6. Hydrogen generation and technology adoption

Hydrogen generation is an incumbent alternative method to storage energy. The main difference with batteries is the range of uses that hydrogen can have in different sectors:

chemical and industrial processes, integrated clean energy systems, and transportation [63].

In this project it will be analyzed as the capacity of hydrogen to be produced thanks to the non-generated wind power as well as the equivalent FCEV that could be put in the road. In comparison, hydrogen then can be used for different applications as commented while the energy in the BEVs can be used for driving and for electrical house application if the electricity is introduced back to the house.

4.6.1. Current state of the technology

Hydrogen is now produced using processes that release a lot of carbon dioxide, such as steam methane reforming (SMR) or coal gasification which are not largely used in Europe. In 2020, 95% of EU hydrogen production was done via SMR. The other 5 % is produced as a byproduct of chlor-alkali processes in the chemical industry using alkaline electrolyzers.

There are three types of hydrogen that can be produced:

Grey hydrogen: this is the most common type of hydrogen produced. It is generated with natural gas through a process called steam methane reforming (SMR). The process combines methane and high-temperature steam to produce hydrogen. Nevertheless, it generates large sums of carbon dioxide in the process.

Blue hydrogen: this hydrogen is produced as grey hydrogen but it includes a step where carbon is captured and stored underground. This process is less efficient than grey hydrogen but it is better for the environment.

Green hydrogen: this is the most sustainable hydrogen possible. It is produced thanks to electrolysis of water, a process which separates water into hydrogen and oxygen using electricity. If the energy to produce this hydrogen is from renewable sources, like wind, this has a low impact on the environment as the carbon dioxide produced is minimum.

In this project, it will be only considered green hydrogen, as the wind power surplus energy will generate electricity from there.

There are several methods to produce green hydrogen, which are at different stages of technological advancement, (mostly electrolytic methods) which are:

- alkaline (ALK),
- polymer electrolyte membrane (PEM),
- and solid oxide (SOEC) electrolysis.

Electrolysis is the process of using electricity to split water into hydrogen and oxygen. This reaction takes place in a unit called an electrolyzer. Electrolyzers can have different sizes, from small to large scale hydrogen production.

Hydrogen generation consists of an anode and a cathode that is separated by an electrolyte. The electrolyzers can work in different ways, that is why there are different methods to produce that electrolysis.

Alkaline:

Alkaline Electrolyzers transport hydroxide ions (OH^-) from the cathode to the anode with hydrogen being generated on the cathode side. They use a liquid alkaline solution of sodium or potassium hydroxide. They have been commercially used for several years.

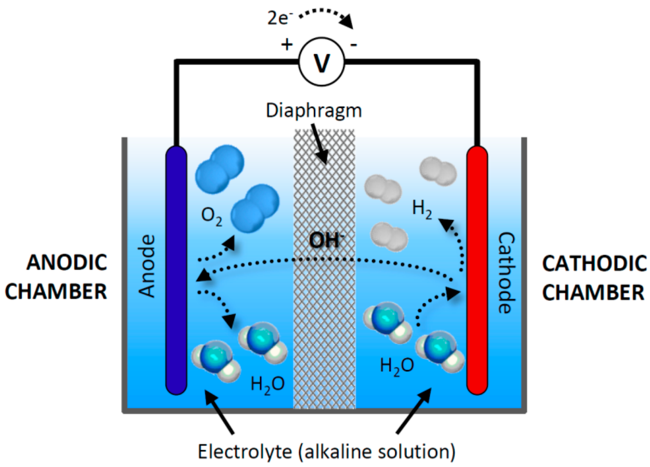

Figure 21: Operation of an Alkaline electrolysis cell [64]

$$\text{CATHODE (HER): } 2\,H_2O + 2\,e^- \rightarrow H_2 + 2\,OH^-,$$

$$\text{ANODE (OER): } 2\,OH^- \rightarrow \tfrac{1}{2}\,O_2 + H_2O + 2\,e^-,$$

Figure 22: Reaction of an Alkaline electrolysis cell [64]

Polymer Electrolyte membrane (PEM):

In this case, the electrolyte is a solid specialty plastic material.

- Water reacts at the anode to form oxygen and positively charged hydrogen ions (protons).
- The electrons flow through an external circuit and the hydrogen ions selectively move across the PEM to the cathode.
- At the cathode, hydrogen ions combine with electrons from the external circuit to

form hydrogen gas. Anode and cathode reactions are as in the following picture:

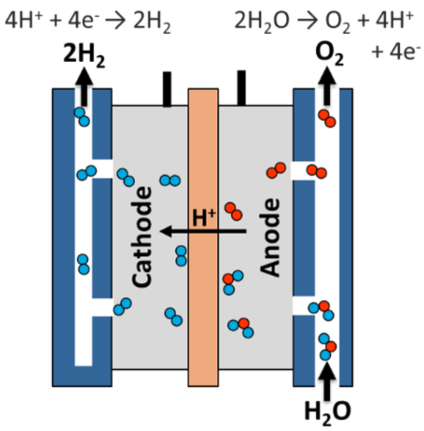

Figure 23: Operation of a PEM [65]

. Anode Reaction: $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$ Cathode Reaction: $4H^+ + 4e^- \rightarrow 2H_2$

Figure 24: Reaction of a PEM [65]

Solid Oxide Electrolyser

The last case studied are Solid Oxide Electrolyzers which use a solid ceramic material. This one generates hydrogen at elevated temperatures:

- Steam at the cathode combines with electrons from the external circuit to form hydrogen gas and negatively charged oxygen ions.
- The oxygen ions pass through a solid ceramic membrane and react at the anode to form oxygen gas and generate electrons for the external circuit.

As it will be seen later, this method is more expensive than the others as high temperatures need to be used: 700º - 800º C. In comparison, PEM electrolyzers operate at 70º - 90º C, while Alkaline electrolyzers operate at less than 100º C. Although there are current experiments to lower the temperature, this is the current state of the technology.

It is necessary now to pick one of the technologies to analyze it in this project. For that purpose, the maturity and costs will provide a better understanding on which is a better solution to analyze (although all technologies can, and probably will, coexist).

4.6.1.1. Maturity of technologies

Alkaline electrolysis is the most mature of the three technologies as it is already on

MW-scale. PEM scale-up has been realized in the last few years, largely driven by the drive to run electrolysis from VREs and to reduce plant footprint. This means that PEM might be a more feasible option for wind power in comparison to Alkaline, even if it is a more recent technology. Right now, the availability for Alkaline stacks is 6 MW and PEM is 2 MW. In the case of Solid Oxide Electrolysis it reaches 10 kW which makes it really uncertain that it can scale up [66].

4.6.1.2. Costs of hydrogen generation

The feasibility of hydrogen in comparison with batteries is determined by the cost of producing hydrogen and storing it versus storing electricity in batteries. BEVs are bought by individual consumers and there is only need to deliver the wind power electricity to households. Nevertheless, as it can be seen in the following figure, the production cost has a high cost (60% of the total cost in the low cost example and 33% in the high cost one where storage and dispensing takes a higher cost). This figure is analyzing the costs of delivering hydrogen in refilling stations [68].

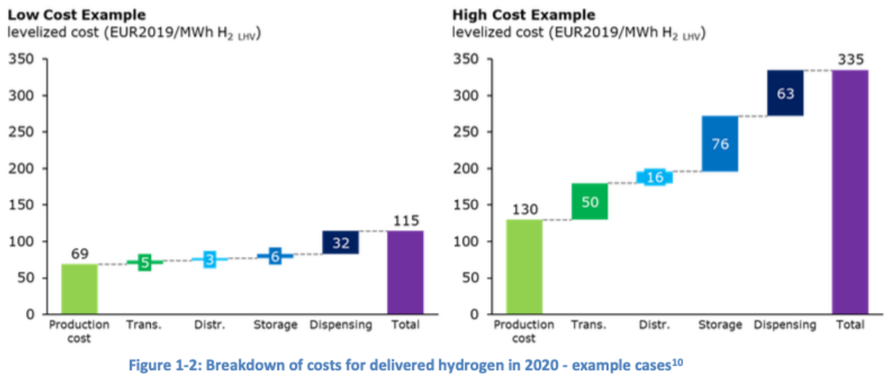

Figure 25: Cost of producing a MWh of H_2 [68]

4.6.2. Future state of the technology

The ASSET (Advanced System Studies for Energy Transition) Study on Hydrogen generation in Europe: Overview of costs and key benefits, Cihlar, Jan., et. al. [68] provides a view on how the technology is expected to be developed in the following years. It is a good study to work on as it is carried out for the European Commision.

Europe's strategic plan is to have 6 GW of renewable hydrogen electrolysers by 2024 and at least 40 GW of renewable hydrogen electrolysers by 2030 where industrial applications and mobility are the two main lead markets for hydrogen.

It is expected that the 3 different technologies for electrolyzers will improve in their lifetime and efficiency. Solid oxide is the newest technology but it could have the most efficient outcomes in hydrogen production. Nevertheless, it is still in its infancy. Alkaline versus PEM can be compared as they are currently in scale levels. In the long term (2050) it can be seen that PEM will have the same range of lifetime but Alkaline still would have a better efficiency to produce hydrogen.

	Alkaline (ALK)		Polymer Electrolyte Membrane (PEM)		Solid Oxide (SOEC)	
Year	Efficiency (LHV)	Stack lifetime (hours)	Efficiency (LHV)	Stack lifetime (hours)	Efficiency (LHV)[15]	Stack lifetime (hours)
2020	63%-70%	50,000-90,000	56%-63%	30,000-90,000	74%-81%	10,000-30,000[16]
2030	63%-72%	72,500-100,000	61%-69%	60,000-90,000	74%-84%	40,000-60,000
2050	70%-80%	100,000-150,000	67%-74%	100,000-150,000	77%-84%	75,000-100,000

Table 5: Efficiency comparison of Electrolysis technologies [68]

4.6.3 Applications of green hydrogen

One of the main advantages of FCEVs with respect to BEVs is the refueling times and the range. a Toyota Mirai (FCEV) can make even 1000 km without refilling. And when it does it only takes 5 minutes [69]. Although this might look promising for FCEVs, the advantages really take off with heavy mobility such as trucks, trains, ships, etc. as it will be seen later.

Besides, hydrogen is more energy dense than lithium batteries. A modern car can store 250 Wh energy for every kilogram of lithium-ion. A kilogram of hydrogen has 33,200 watt-hour energy for every kilogram, making it more than 100 times more energy-dense [70]. It must be pointed out that hydrogen is in gas form as for it to be liquid needs to be cryogenized. Meaning that, even if the direct comparison between hydrogen and battery energy density can be made, when applied to real life applications such as mobility, as it will be seen, the difference diminishes. This will be analyzed later in section 11.1.1.

Nevertheless, hydrogen can also be used for other applications such as steelmaking, rocket fuel, ammonia production, methanol production, concrete production and oil refining (although this last one would not be a good use for the objective of the project) [71].

4.7. New Technology adoption

This project has as an objective forecast the maximization of wind power in the future using batteries and hydrogen. Hydrogen as a storage system is considered an emerging technology with a lot of potential, but there is no general adoption of it for now. Forecasting the future technology-related is really complicated and probably will get high deviations due to several factors.

It will be presented how technology adoption can be modeled through S curves to understand which is the path forward for Hydrogen generation as it is the incumbent technology in comparison with batteries, which are in a later stage of development.

Besides, it will be done the same with batteries/BEVs. The difference between the two technologies in adoption is the maturity and efficiency of the technology and the adoption. While hydrogen generation is still at its infancy, BEVs are starting to take off as a competitive alternative to ICE vehicles as the prices of batteries drop every year while the technology and scale improves. The S-curves are applicable to this case as the BEVs are a consumer product which can be adopted widely. In the case of FCEVs it still needs to be proven that the S-curves can apply and they will not be only a niche market.

4.7.1. Modelization of technology diffusion - S curves

Adopting new technologies comes with a complicated path of uncertainties that makes it difficult to predict whether an innovation will succeed or not. Hall, B. H., & Khan, B. (2002) [2] studied how technology diffusion happens and the importance of considering it a cumulative or aggregate result of a series of individual decisions that contribute to the incremental benefits of adopting the technology versus the cost of change.

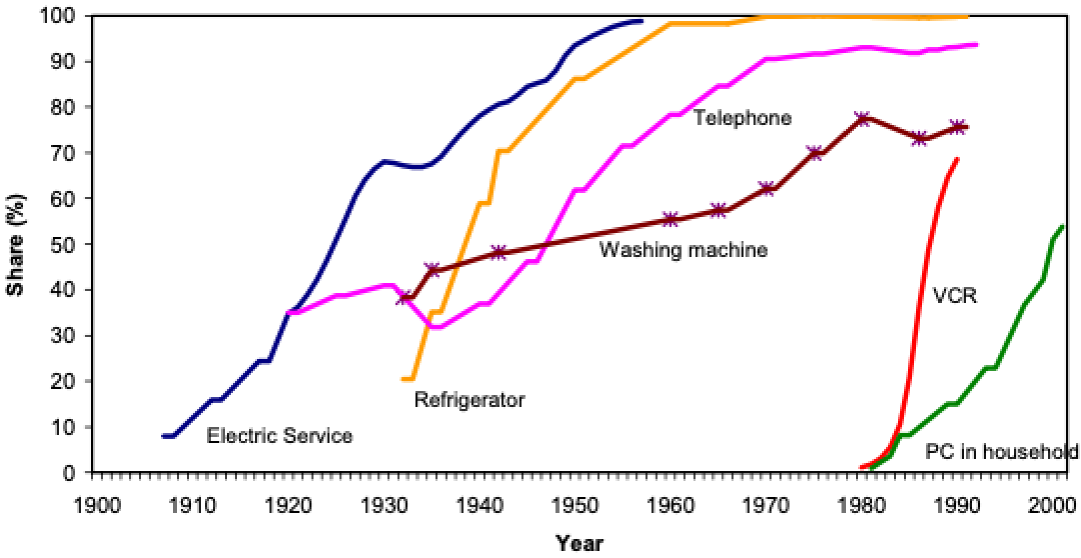

Figure 26: S curves for several US selected products [2]

Aside from benefits being higher than the costs, there are several demand determinants of a new technology being diffused successfully: Skill level of workers and state of capital goods sectors, customer commitment and relationships, and network effects.

From the supply side, the effects are: Improvements in new technology, improvements in the old technology, and complementary inputs.

Then there are other factors like Environmental and institutional factors, being the most relevant: the Market structure and firm size, government, and regulation.

In the case of energy is the government, incentivising or disincentivizing determined technologies. For example, while renewables are highly incentivized through tax cuts and subsidies, fossil fuels are taxed heavily to reduce their consumption.

5. Hypothesis

Before starting the analysis, there are some hypothesis that will be defined:

Wind farms do not operate at their maximum capacity due to low demand of electricity during the night. Introducing electric vehicles and hydrogen as storage systems will increase the power generated by a wind farm, increasing companies' revenues and profits.

The electric vehicles calculated for this study will only receive electricity from renewable energy sources, reducing their footprint as each kWh of power produced will generate close to 0 kg of CO_2.

The sleeping patterns in Europe are similar and the average sleeping time is 7 hours per day, Leaving 8 hours to charge the electric vehicles [72].

Level 2 charging (3.7 kW) will be the only type used, resulting in improved battery life due to the lower charging rate, and mitigating stress on the battery cells, thus prolonging their overall lifespan.

Hydrogen as a storage system will become feasible and play a significant role in the storage system mix between 2021 and 2030. Innovation in hydrogen production technologies and increasing demand for long duration energy storage solutions will be the driving force of hydrogen storage as a feasible alternative.

The number of electric cars found to be manufactured will be sustained by the yearly raw material extraction capacity. This will not cause significant resource shortages or supply chain disruptions.

The introduction and substitution of the number of EVs found will generate a significant positive impact on the health of European citizens.

6. Data summary

In this section of the project, all the tables and figures needed to solve the hypothesis previously stated will be displayed. With this data it will be calculated the number of vehicles needed to be charged with the unused wind energy, the amount of hydrogen needed to be produced, the health, and the carbon footprint impact of the introduction of these storage system capacities in the market.

It is necessary to know the number of wind farms in each country, separated by 4 Regional Groups (RG): RG Continental Europe, RG Baltic, RG Nordic, and the combination of RG British and RG Irish.

The data will be separated by each zone with colors, to be well-differentiated, being:

- RG Continental Europe = orange.
- RG Nordic = green.
- RG Baltic = yellow.
- RG British and RG Irish = blue.

Part of the data and analysis will come from the previous analysis. There have been some corrections on the data presented, particularly the real data coming from the United Kingdom. This will be explained in the following sections.

6.1. Wind farms in Europe

The data belonging to wind farms is taken from the previous analysis and it comes from the website *The Wind Power* [73] and it includes the country of the wind farm, the city, the position (latitude and altitude), the manufacturer, the model, the number of turbines and the total power (kW) that can be produced.

The dataset from the previous analysis [1] includes 10 randomly chosen wind farms from each country, meaning that the total energy produced by wind farms is higher than the number obtained from the table. Specifically, the dataset contains 4,676 MW capacity for onshore wind farms and 3,679 MW for offshore wind farms. This quantity extracted represents 2.34% of the total onshore energy (196.91 GW) and 14.04% of the total offshore energy.

Country	City	Latitude	Altitude	Manufacturer	Model	Number of turbines	Total power (kW)
United Kingdom	Waterbeck, Lock	55.113	-3.225	Siemens	SWT-2.3-93	16	36800
United Kingdom	Tow Law	54.761	-1.781	Nordex	N52/800	3	2400
United Kingdom	Lack, Enniskillen	54.561	-7.552	GE Energy	1.5s	13	19500
United Kingdom	Hartlepool	54.69	-1.3	Neg Micon	NM80/2750	3	8250
United Kingdom	Croeserw	51.643	-3.589	Gamesa	G80/2000	12	24000

Table 6: Partial picture of the sample of wind farms used in the project [1]

There is a high concentration of the production of wind turbines in few companies in Europe. The onshore wind turbines are mainly produced by Nordex SE, Vestas Wind Systems A/S, and Siemens Gamesa Renewable Energy S.A. while the offshore wind turbines are produced by Siemens Gamesa with 68% of the market share, Vestas in the second place with 23.9% and Senvion with 4.4% [74]. This situation leads to an oligopoly of 3 companies leading the offshore wind farm market.

6.2. Wind turbine power curves

In this section, the power curves of the different manufacturers and models have been calculated in function of speed (m/s). This information is found in appendix 2. The data has been gathered by Cristina Verdaguer, from *The Wind Power*. It represents the power values from 0 m/s to 30 m/s with 0.5 m/s intervals.

6.3. Wind speed

This section is dedicated to the study of wind during the night across Europe. The average speed of wind varies depending on the area that is analyzed. The measurement of wind is done typically at 10 meters of height. The ideal height for this study would have been 100 meters, to be close to the turbine height.

The average speed in Europe is about 3 m/s and it does not look like the trend is moving upward or downwards in the last 70 years. This means that climate change is not currently affecting the average wind speeds.

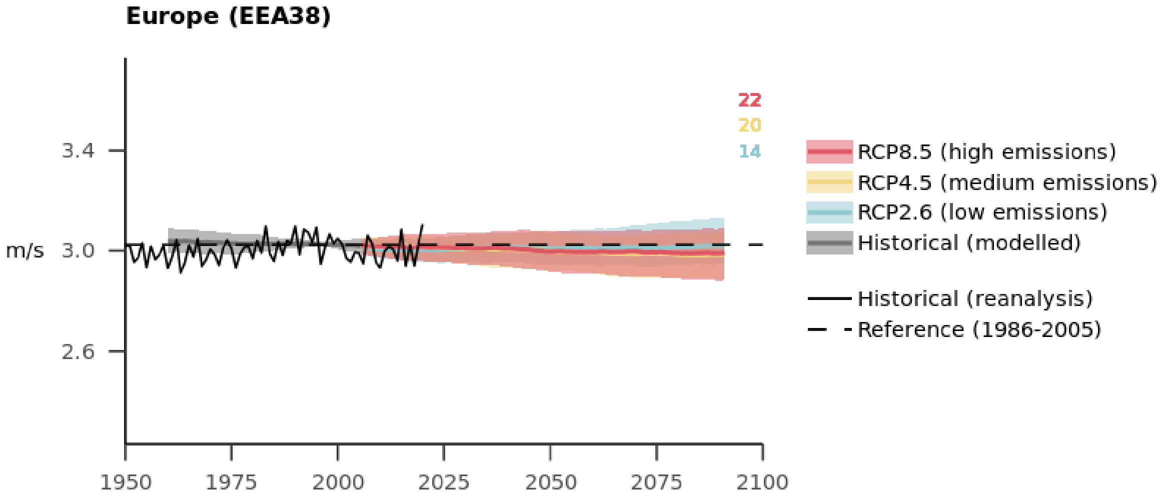

Figure 27: Average speed of wind historical [75]

The velocities in the north of Europe are higher than in the south which makes the north more feasible to install wind turbines.

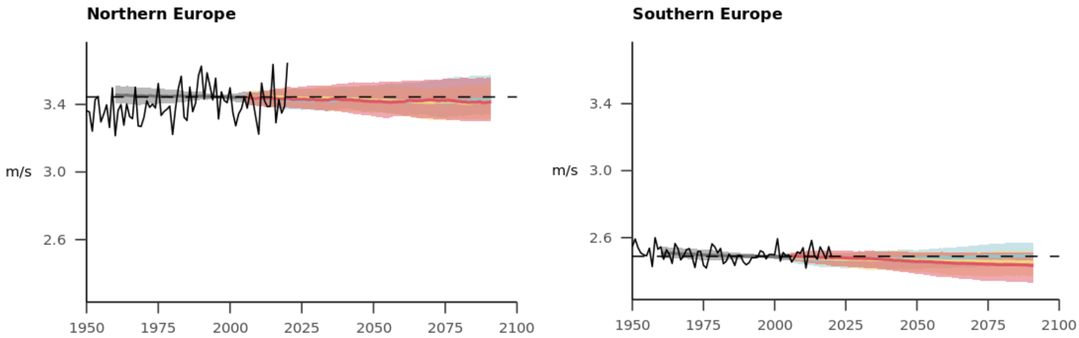

Figure 28: Average speed of wind historical, comparison between Northern and Southern Europe [75]

As it can be seen in the next heat map of wind in Europe, the north receives more wind than the south. Especially in the area of the North sea, and the Baltic sea.

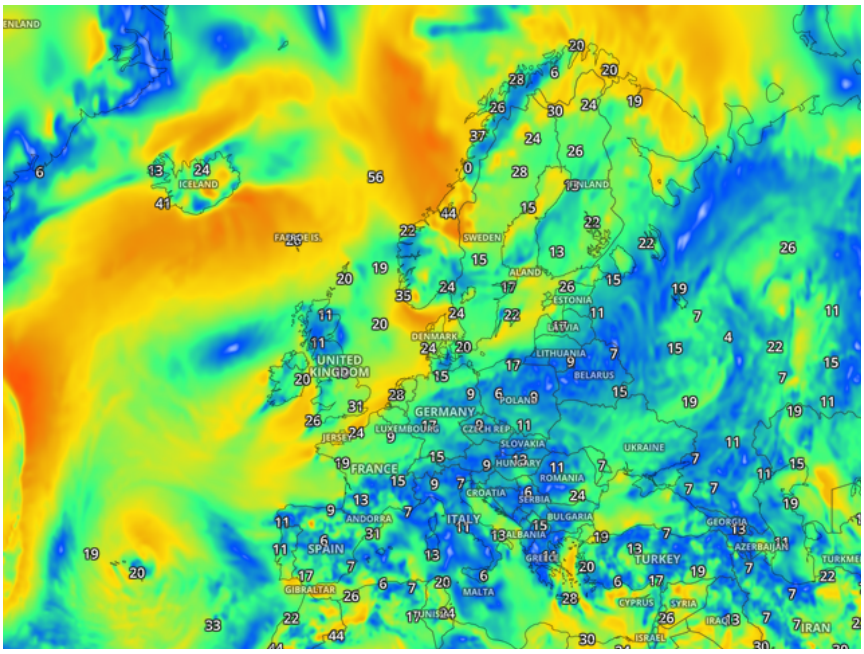

Figure 29: Heat map of Europe with wind speeds [79]

This factor plus the low deepness of the sea makes it a perfect place for offshore wind. This is one of the main reasons why the total capacity of offshore wind power is concentrated in the UK, Germany, Denmark, Netherlands and Sweden. When floating off-shore turbines are more developed, there will be other areas with offshore availability [76].

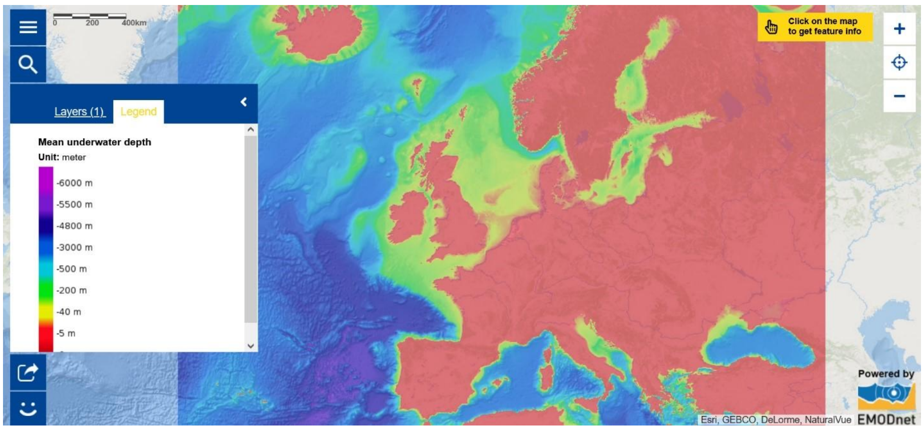

Figure 30: Heat map with the mean underwater depth of Europe [77]

From annex 3, per country, one wind farm has been chosen and the wind speed measurements have been taken (from June 16th, 2021 to June 16th, 2022) where the wind speeds are taken per hour. This data has been taken from the website *Visual*

Crossing Weather, which is specialized in weather data and forecasting globally.

The data obtained from the previous analysis by Joan Pedret consists in the maximum velocity each hour in a location without obstacles and at 10 m above the ground [78]. Data is given in kilometer per hour which is transformed in meters per second and then the formula seen in section 4.3.4.

Where z (rugosity) is equal to 100, Z0 is equal to 0.03 in onshore wind farms and 0.0024 in offshore wind farms. Using these two rugosities gives the most conservative scenario of velocities (the lowest ones).

Lastly, a correction factor has been applied using the average wind speed (V_{100_aver}) taken from appendix 3 and the average wind speed ($V_{100\_aver\_real}$) taken from *Atlas Wind [79]*. This position factor is the subtraction of the two:

$PF = V_{100\_aver\_real} - V_{100\_aver}$ (6)

Now, real velocity is calculated as the correction factor plus the velocities at height 100.

$V_{100\_real} = V_{100} + FP$ (7)

For each hour from 23h to 8h the speeds have been registered over a year and have been organized in 0.5 m/s intervals in a frequency table, making them coincide with the power curves speed values. This information is found in appendix 3, where appendix 3.1 for wind speeds and appendix 3.2. ordered and with the applied correction. Two letters have been used to differentiate each country (ES, AU,...). The average speeds and the position factors (PF) are in appendix 4, and they were found in the previous analysis by Joan Pedret.

6.4. Electric cars in Europe

Europe’s best-selling BEV models in 2021 data will be gathered for analyzing the amount of cars that can withstand the grid with the wind farm network that currently exists. The data comes from the previous analysis and originally from “EV Database” [80] and it is stored in appendix 5 from the previous analysis of Joan Pedret. It contains relevant data such as battery capacity, range, maximum power, price, weight, number of cars sold, etc.

Models with higher prices tend to also have lower sales, then a weighted average has been made to increase the relevance of basic car models in comparison with the most premium options of the models. For example, Tesla Model 3 has three options: Basic (55,865 €), Long range dual motor (62865 €), and Performance (66,165 €). The percentage of each option will come from:

$$\frac{1}{Raó} = \sum_{i=1}^{n} \frac{1}{p_i^2}$$

$$percentatge = \frac{Raó}{p_i^2} \cdot 100$$

$$\frac{1}{Rao} = \sum_{i=1}^{n} \frac{1}{p_i^2} \quad (8)$$

$$percentage = \frac{Rao}{p_i^2} 100 \quad (9)$$

Giving these percentage for each:

- Basic = 39.99 %
- Long range dual motor = 31.58 %
- Performance = 28.51 %

Using the inverse ratio above, the ponderation obtained gives more relevance to the cheaper models instead to the most expensive ones.

All the models in the top 10 have the capacity to be plugged to a Level 2 charging station (3.7 kW). Besides, charging time is stated in the dataset and the majority of them take more than 8 hours to charge. Nevertheless, it is rare that the car needs to be charged from 0 to 100% as the recommended limit is 20% to not harm the battery.

Here an example of the dataset, the Tesla Model 3:

Marca Model especificació	Tesla Model 3	Tesla Model 3 Long Range	Tesla Model 3 Performanc	Tesla Model 3 Mitjana ponderada
capacitat bateria (kWh)	57,5	75	75	68
rang ciutat fred/ideal (km)	360/555	455/700	440/665	412/632
Rang carretera fred/ideal (km)	275/360	350/460	330/430	314/411
Rang combinat fred/ideal (km)	315/445	400/560	385/530	362/505
Rang estimat (km)	380	485	460	435,9
Consum ciutat fred/ideal (Wh/km)	160/104	165/107	170/113	164/107
Consum carretera fred/ideal (Wh/km)	209/160	214/163	227/174	216/165
Consum combinat fred/ideal (Wh/km)	183/129	188/134	195/142	188/105
Consum estimat (kWh/km)	151	155	163	155,7
Potència màxima (kW)	239	324	413	315,4
Parell motor màxim (Nm)	420	493	660	511,4
Acceleració 0-100 km/h (segons)	6,1	4,4	3,3	4,8
Velocitat màxima (km/h)	225	233	261	237,8
tipus de port de càrrega	tipus 2	tipus 2	tipus 2	tipus 2
Potència màxima de càrrega (kW)	11	11	11	11
Temps de càrrega 0-100% (h:min)	6:15	8:15	8:15	7:27
Temps de càrrega 3,7 kW 0-100% (h:min)	18:30	24	24	21:48
Port de càrrega ràpida	CCS	CCS	CCS	CCS
Potència màxima (kW)	170	250	210	206,6
Temps de càrrega 10-80% (min)	27	31	30	29,1
Rodes de tracció	Posterior	AWD	AWD	-
Pes (kg)	2149	2232	2232	2198,8
Tipus de carroceria	Sedan	Sedan	Sedan	Sedan
Preu (€)	55.865	62.865	66.165	61008
Percentatge de ponderació (%)	39,96	31,55	28,49	100
Nombre de ventes 2021				141221
percentatge de ventes 2021 (%)				23,62060776

Table 6: Table with the characteristics of a Tesla Model 3 [1]

For the study it is needed the battery capacity, energy consumption, charging modes and time necessary for a complete charging cycle.

7. Available energy

Available energy during night is calculated using the maximum capacity of wind farms across Europe and the actual power of the wind farms. This information will be used to calculate the amount of power that can be used for BEVs and hydrogen generation to refuel FCEVs instead of not being produced by lack of demand. There are two data points necessary to calculate this available energy: the maximum energy that can be produced by wind farms at each moment in time and the real power produced.

7.1. Maximum available energy

The maximum available energy is the one that can be produced in case that the wind farms are producing energy during all the time. Nevertheless, producing energy with low demand of energy during the night, combined with the current lack of storage systems would mean that the energy produced during that time would be wasted.

To calculate the energy, the data of wind speeds in appendix 3 will be used along with the data on power curves of wind turbines in appendix 2. Due to lack of complete data regarding turbine types, the curve used has been the one of the models closest to the wind farm one. Those calculations are found in appendix 3.3.

With the data from the entire year and each hour of organized wind speeds in the form of a histogram, along with the energy for each velocity, the observed number of intervals of velocities is multiplied by the energy produced by the turbine model within that speed range. All values are then summed, resulting in the energy produced in one year during that specific hour by a turbine. By knowing the number of turbines in the selected power plant, this value is multiplied, and finally, it is multiplied by the percentage of energy that still needs to be covered in the country under study. This way, it is possible to predict the maximum energy that could be produced during one hour in a whole year in a specific country.

The calculations have been made in each region included in appendix 1. Finally, there is a sum of all the data per Regional Group.

7.1.1. Approximations

There are several approximations that have been made to be able to calculate the final result.

7.1.1.1. Represented countries

The countries represented are the ones that have a significant wind power capacity from the overall capacity in Europe. From *The Wind Power* all those countries that had free data available. In total 98% of the onshore wind power capacity and 90% of the offshore wind power capacity has been taken into account. Having more than 90% of the data is enough to extract results .

7.1.1.2. Wind speeds

Wind speeds come from only one location in each country. This has been made for simplicity and could lead to variability in case countries with large areas. Nevertheless, European countries tend to be rather small and the wind in different regions is not that different, taking into account that wind turbines are positioned in similar terrains and conditions.

7.1.1.3. Power curves

Power curves depend on the wind turbine model. In the case of not having that model due to the unavailability of free data (90 € to obtain all the resources), the data has been approximated with the closest power curve possible. The power curves work in the same way. In case of having used the proper models the results would have been higher as using the optimal ones would have meant extracting more energy from the wind.

7.1.1.4. Wind farms chosen

Only one wind farm per each country has been chosen. The percentage of the wind farm chosen with respect to the total capacity of the country has been used to calculate the maximum amount of power that can be generated in each country.

7.1.2. Results

The results can be found in the appendix 6, where the energy produced in a year from 23h to 8h has been calculated. The end result is the total capacity per Regional Group:

- RG British and Irish = 10,702.2 GWh
- RG Continental Europe = 19886.4 GWh
- RG Nordic = 2,579.7 GWh
- RG Baltic = 108.82 GWh

Summing a total of 33.277 TWh average power generated.

This is only an average amount while the values needed are the ones per hour separately.

7.1.2.1. Corrections

In the case of the RG British and Irish, the real energy obtained in the previous analysis is too large. The main concern comes from offshore wind representing 80% of wind power generation in the UK. Although the UK is a leading country in offshore wind power, the data shows that onshore and offshore installed power is around 50% [81]. Also the UK has 23% of offshore installations while Germany has 13% of them [82]. In comparison with the dataset, it can be seen that the average of onshore energy produced in a certain hour for a year is around 1600 GWh while offshore is around 8500 GWh. Besides, Germany produced around 1483 GWh in a certain hour during one year of offshore energy which is too low in comparison with the UKs one having just double of % installed.

The solution has been to dive deep into the data to understand which is the problem. The root of it has been using an extrapolation from the onshore maximum energy found in the UK. To find the correct results, the process followed in the previous analysis has been done for the offshore wind farm located in latitude 53.492 and altitude -3.200, with a model SWT-3.6-107. This model was not found in the annex 2. The closest found has been the Vestas V117/3600 which differ in their rotor diameter and swept area as can be seen in the “wind_farm” sheet in appendix_17.

Finally it leaves these new average results:

- RG British and Irish = 2,895.88 GWh
- RG Continental Europe = 19,886.4 GWh
- RG Nordic = 2,579.7 GWh
- RG Baltic = 108.82 GWh

7.1. Real generated energy

In the case of the real generated energy, the previous analysis points at the webpage Entso-e to obtain the datasets regarding the real power generated by wind farms. Entso-e is the entity responsible for monitoring European energy use. The data has been taken from the 1st of January of 2021 to the 31st of December of 2021. Nevertheless, in the case of the real energy generated by the United Kingdom, some discrepancies with the previous analysis have been found. UK’s data on real generation of wind power was too low in comparison with the other countries. Although this could have been due to countries regulations, it was worth it to check if the data was correct. This will be explained in corrections.

The power generation is in MW, with differentiation between Onshore and Offshore energy generated. In the columns, it appears the maximum power generated each hour, which would be in MWh in case that it was given per hour. In the appendix 7, the information of night energy produced has been organized and it has been calculated the yearly generation.

In some countries the power appeared every 15 minutes instead of 30 minutes. After separating the power in columns per each hour the generation has been summed to see the yearly quantity of power. This information is summarized in appendix 8, grouped in Regional Groups.

7.2.1. Approximations

For the analysis, no approximation has been made with the exception of some approximation due to lack of data as it will be seen in the next subsections.

7.2.1.1. Offshore wind farm lack of data

In some countries the offshore wind farm generation did not appear and it has been estimated taking the global percentage of offshore wind power versus onshore wind power. This has been applied to Sweden and the UK. Nevertheless, as it will be seen later, UK's new data will not show offshore wind either so it has been determined as 0 for simplicity.

7.2.1.2. Onshore lack of data

In this case, Ukraine had a lack of data in the first months. An average has been calculated and it has been multiplied by 365 days.

7.2.2. Results

The original results are in annex 8 and show the summary of energy generated per hour:

- RG British and Irish = 947.9 GWh
- RG Continental Europe = 13404.6 GWh
- RG Nordic = 1,952.3 GWh
- RG Baltic = 82.94 GWh

7.2.2.1. Corrections

As it can be seen, the RG British and Irish result of real data is too low in comparison with the maximum power that can be generated. This causes the non-generated energy to be extremely high, which makes the final analysis of the number of cars potentially wrong.

The correction can be found in appendix 13. In this appendix there are several sections that will provide the calculations for the final analysis.

First of all, Section 1. and Section 2. bring the maximum power and the real power generated. Section 2.1. brings the real power generated with new data.

When investigating if there was a problem with the data, Entso-e was contacted to understand why UK's data was partial or had no data at all. The response was that the data was not gathered by them anymore (Brexit) and it was monitored by Elexon [83]. In appendix appendix 14 can be seen what the process to obtain the real energy generated was made. In the sheet "cleaned_data" the hourly generation (MWh) can be found.

This leaves this average results:

- RG British and Irish = 2360.2 GWh
- RG Continental Europe = 13404.6 GWh
- RG Nordic = 1,952.3 GWh
- RG Baltic = 82.94 GWh

The RG British and Irish real energy generated goes up from 947.9 GWH to 2360.2 GWh.

7.3. Non-generated energy

Calculating the potential energy that could be generated is simply subtracting the real generated energy from the maximum power that can be generated.

$E_{surplus} = E_{max\_power} - E_{real\_power}$ (10)

Obtaining the result in appendix 13, Section 3.2. :

- RG British and Irish = 535.68 GWh
- RG Continental Europe = 6,481.83 GWh
- RG Nordic = 627.45 GWh
- RG Baltic = 25.88 GWh

The table with the full information is found below and in appendix 13 section 4.:

RG British and Irish	Maximum (GWh)	2879.9556	2882.1336	2906.6373	2859.1528	2881.5700	2833.530	2884.728	2924.432	3040.650	2865.9787	
	Real (GWh)	2424.569486	2380.388235	2353.531985	2334.776687	2318.799461	2313.137	2330.533	2349.994	2363.362	2432.86060	
	Difference (GWh)	455.38612	501.74536	553.10527	524.37611	562.77054	520.3923	554.1955	574.4386	677.2878	433.11814	455.38612
RG Continental Europe	Maximum (GWh)	19958.536	19870.558	19852.626	19885.411	19878.625	19419.93	19549.24	19673.61	20328.78	20446.559	
	Real (GWh)	13953.8984	13780.7870	13559.4614	13421.0048	13294.7472	13245.77	13198.94	12938.11	12548.35	14104.5606	
	Difference (GWh)	6004.6375	6089.7710	6293.1641	6464.4062	6583.8774	6174.166	6350.298	6735.503	7780.428	6341.9985	6004.6375
RG Nordic	Maximum (GWh)	2548.03090	2514.16170	2508.85740	2528.45420	2529.71250	2524.778	2606.680	2679.643	2783.671	2573.06770	
	Real (GWh)	2048.53527	2043.06571	2024.45534	2009.61950	1990.45069	1813.810	1907.985	1847.779	1786.896	2049.92828	
	Difference (GWh)	499.49563	471.09599	484.40206	518.83470	539.26181	710.9684	698.6951	831.8637	996.7749	523.13942	471.096
RG Baltic	Maximum (GWh)	108.685500	106.282400	107.857500	107.800000	104.875000	108.8733	106.2292	108.0052	120.6049	108.951300	
	Real (GWh)	86.829	86.393	85.912	84.959	83.865	82.368	79.857	76.712	74.802	87.658	
	Difference (GWh)	21.856500	19.889309	21.945190	22.841000	21.010000	26.50530	26.37220	31.29320	45.80290	21.293300	19.8893093

Table 7: Non-generated Energy corrected. Annex 13, section 4.

At the right of the table it can be seen that there is the minimum value in each of the hours of each RG. This is the value that will be used to calculate how much cars can be charged and how much hydrogen can be produced. The reason is that to charge all the BEVs constantly, if it is taken another value but the minimum there will be hours where some of them will not be charged.

In the case all the minimum energy is used for cars, this situation leaves extra energy that is still not produced. Nevertheless, there is extra energy for hydrogen generation: the one on all the hours except the minimum hour that will be used by cars.

With this, scenario 1 stops being just energy produced for charging cars but also includes hydrogen generation.

This brings an extra 7,198.32 GWh of energy that would not have been produced and maximizes the energy that can be produced.

Zone	Extra energy for hydrogen generation (GWh)
RG British and Irish	
	802.95465
RG Continental Europe	
	4771.8760
RG Nordic	
	1563.57191
RG Baltic	
	59.915806
Total extra energy	7198.318407

Table 8: Non-generated Energy, surplus for hydrogen production. Annex 13, section 4.

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This ideally brings the gap between the maximum power generated to the real power generated to 0 GWh.

8. Daily vehicle use

A set of data was gathered in the previous analysis to understand which is the daily range necessary. This daily range varies by different factors such as habits, country size, population, use of the car, concentration of population, etc. It is also necessary to discriminate between weekdays use and weekends use, as well as country and RG, and urban versus road use.

The data is seen in appendix 10. Here is an example of the data that can be found:

País	United Kingdom
n° of habitants	66,022,273.00
percentage of drivers	49.83
km driven per day per person (km/person)	16.25
km driven per day per driver (km/driver)	32.62
urban kilometers (%)	53.90
road kilometer (%)	46.10
work kilometers (%)	41.90
weekdays kilometers (%)	70.95
km driven during weekdays per day per habitant	32.40
km driven during weekends per day per habitant	33.17
absolute number of kilometers driven during weekdays	1,065,998,746.00
absolute number of kilometers driven during weekends	1,091,165,031.00
urban kilometers weekdays	17.46
road kilometes weekdays	14.94
urban kilometers weekends	17.88
road kilometers weekends	15.29

Table 9: Vehicle Use in the UK [1]

Using this data it will be possible to calculate the consumption of the potential EVs every day in different parts of Europe.

9. Vehicle energy consumption

Using the previous data [1] it is possible to calculate the daily consumed energy by car model and how many days it will take for the battery to go to 0%.

Having the consumption of every car depending on urban or road driving and the % of kilometers made in these 2 types of driving, it is possible to calculate the consumed energy per day. Weekends are considered.

$$Daily\ consumption\ in\ weekdays = \frac{Urban\ consumption \cdot urban\ km\ ES + road\ consumption \cdot km\ road\ ES}{1000}$$

(11)

$$Daily\ consumption\ in\ weekends = \frac{Urban\ consumption \cdot urban\ km\ CS + road\ consumption \cdot km\ road\ CS}{1000}$$

(12)

As the consumption of vehicles is in Wh/km, it is necessary to transform it to kWh/day.

For every model it has been calculated what is the time to discharge, and most importantly, how much time it takes to consume 29.6 kWh as it is the total energy that a vehicle can charge in 8 hours with a Level 2 charger of 3.7 kW of power.

To calculate the days necessary to consume the energy, it is divided 29.6 kWh by the daily consumption.

9.1. Amount of days between each charge

With the results of the total consumption of cars from the previous analysis [1] it is possible to calculate the days between each charge. This calculation is made only for each RG with a weighted average depending on the population of each RG. This has been taken from the previous analysis for the RG Continental Europe and RG Nordic as it has different countries. In the last RG it is important to know that low temperatures affect EV consumption and they will consume more than in the other RGs. In the case of a Tesla Model 3:

		Tesla Model 3	
		Days to discharge (100-0)	Days to dicharge 29,6 kWh
RG Britain and Ireland	Weekdays	15.7	6.8
	Weekends	15.3	6.7
RG Continental Europe	Weekdays	17.6	7.6
	Weekends	27.9	12.1
RG Baltic	Weekdays	16.5	7.2
	Weekends	26.5	11.5
RG Nordic	Weekdays	9.5	4.2
	Weekends	12.2	5.3

Table 10: Days to discharge a Model 3 [1]

The days obtained to discharge 29.6 kWh are pretty similar between models as they do not depend on battery capacity (all of them have one higher than 29.6 kWh) and the difference in consumption is low.

Leaving these results for each RG:

- RG British and Ireland: 6 days between charges for 83.3% of the vehicles sold.
- RG Continental Europe: 8 days between charges.
- RG Baltic: 7 days between charges.
- RG Nordic: 4 days between charges due to low temperatures.

10. Vehicle volume that the grid can withhold

Knowing the total extra energy available per night, and knowing household habits and car consumptions and charging times, it is possible to know how many cars the grid can withhold. It is considered the ideal case where the different BEVs are charged evenly so every night there is the same volume of cars and the non-generated energy is always the same.

$$V = \frac{E_{extra}}{3.7\ kW} \cdot T \ (13)$$

V represents the volume of vehicles which is calculated by multiplying the extra energy found per T, which is the number of days until a vehicle is charged and then divided by 3.7 kW is the power consumed per each vehicle.

Using this formula, it is obtained a number of vehicles that it is ideal and probably unrealistic as there are patterns of electricity consumption that have not been considered such as charging the vehicle during the day (which can happen as there are low price hours during the day too as it has been seen in the price data on UK in section 7.3.1.). The previous analysis chose to reduce the vehicle volume to half.

Following that, it is found:

RG	Surplus energy in a Year for EVs (GWh)	Surplus energy in a Year used for EVs Safety factor 0.5 (GWh)	Daily surplus energy used for EVs (MWh)	In between charges days	Vehicle volume
RG British and Ireland	455.38612	227.6930616	623.8166071	6	1011594.498
RG Continental Europe	6004.6375	3002.318725	8225.530753	8	17784931.36
RG Nordic	471.096	235.5479945	645.3369712	4	697661.5905
RG Baltic	19.8893093	9.94465465	27.24562918	6	44182.10137
Total	6951.00887	3475.504436	9521.929961		19538369.55

Table 11: Volume of vehicles per RG. Annex 13, section 6.

The most important change with respect to the previous analysis comes from the vehicle volume in RG British and Ireland.

Another important consideration in this calculation is that only half of the volume of BEVs is considered. This leaves a big amount of energy without being produced. It has been found that the extra energy that is not used because the minimum energy of all the hours is taken can be used to produce energy.

10.1. BEV increase needed with respect to 2021 figures

One of the conflicting points with the previous analysis is the need to consider or not the actual number of EVs in the market. In the previous analysis, it has been considered but in this one it will not be taken into account because they are already considered in the data (in case of the assumptions, they are already consuming electricity during the night).

10.2. Feasibility of reaching vehicle volume

One consideration taken during the previous analysis, is that the number of EVs sold per year will be constant. As it has been seen, mass-consumer technology adoption is not linear nor constant but it is exponential until one point and then it saturates, which is illustrated by S-curves. That inflection point is related to several parameters and in the case of EVs is related to price. In April 2023 Tesla dropped the price of Tesla Model Y to lower than the average price of an US car [84]. That means that the prices on EVs might be lowered to a point where a higher percentage of the mass market sees feasibility in purchasing an EV as their next vehicle. There is one data point to consider really important: Europe's target in 2030 is to have 30 million EVs on the road [85].

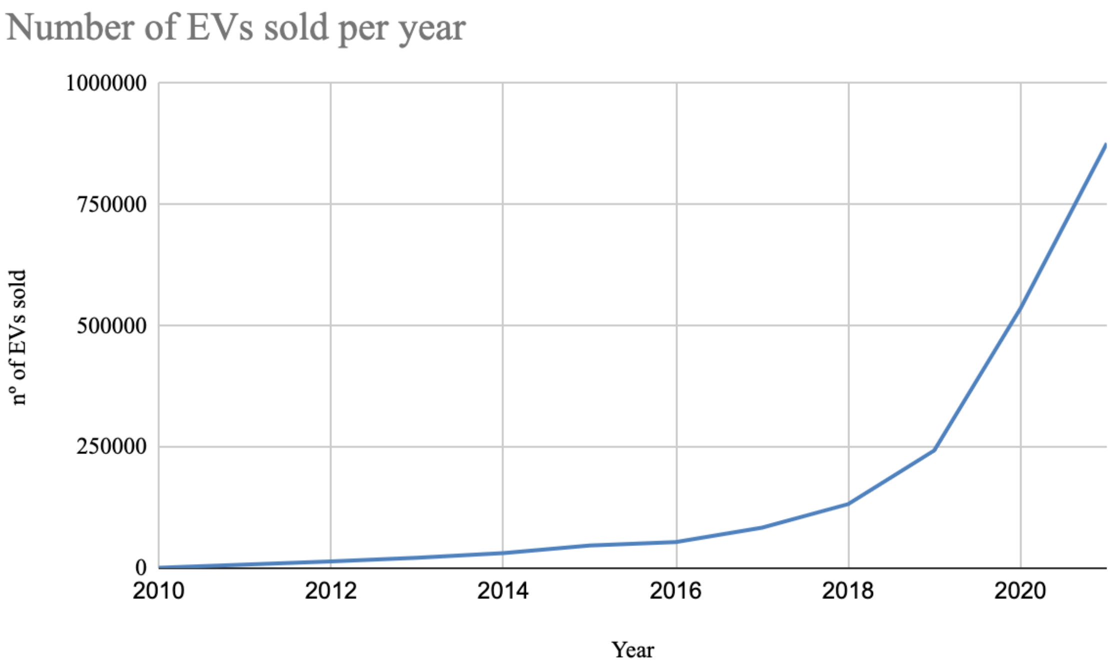


Figure 31: Number of vehicles sold per year (2010 to 2021). Annex 13, section 6.1.

It is assumed that there will be demand for all the cars (22.9 million) from 2021 to 2030. As it can be seen, the number of EVs sold is having exponential growth (hockey stick graph). The growth from 2020 to 2021 was 63.47%. It is not probable that this growth will continue at the same rate year over year until 2030. It has been calculated how much growth rate does the production of EVs need to grow to be able to add 22.9 million EVs in Europe. That can be done using a summatory formula which results in the total number of EVs through a period of time of 9 years (2022 to 2030).

$$Cars\ needed\ to\ produce\ =\ 19,538,369.55\ =\ \sum_{n=1}^{9} Cars\ in\ 2021\ (1\ +\ x)^{n} \quad (14)$$

$$Cars\ needed\ to\ produce\ =\ 19,538,369.55\ =\ \sum_{n=1}^{9} 876527\ (1\ +\ x)^{n} \quad (15)$$

Which has several complex solutions but the real one is 0.177997 (17.7997%). This means that an approximately 17.8% growth in EV production allows to produce the 19.5 million cars needed.

For instance, the battery production forecast in Europe will reach 238 GWh in 2025 [86]. This would allow it to produce 6.8 million cars considering an average of 35 kWh capacity EVs which is not a problem using the growth of 17.8% per year as the cars necessary to be produced are 1.87 million in 2025. In reality, the growth will probably be higher at the start in 2022 and lower than the 21% growth rate in 2030.

To accommodate the number of cars necessary by RGs, it will be distributed following the percentages of extra energy represented by each regional group coming from the total cars necessary.

	Year	BEV forecasted produced per year	super	BEV forecasted RG British and Ireland	BEV forecasted RG Continental Europe	BEV forecasted RG Nordic	BEV forecasted RG Baltic
Forecast	2022	1032546.176	17.80%	53459.83596	939882.0524	36869.39209	2334.895945
	2023	1216336.298	17.80%	62975.52638	1107178.238	43432.03328	2750.500419
	2024	1432840.51	17.80%	74184.98115	1304252.643	51162.8049	3240.081242
	2025	1687881.823	17.80%	87389.68524	1536405.701	60269.63069	3816.805983
	2026	1988319.723	17.80%	102944.787	1809881.306	70997.44414	4496.185997
	2027	2342234.669	17.80%	121268.6503	2132034.749	83634.77621	5296.493616
	2028	2759145.414	17.80%	142854.1063	2511530.538	98521.51547	6239.25359
	2029	3250265.02	17.80%	168281.7086	2958575.439	116058.0497	7349.822012
	2030	3828802.442	17.80%	198235.3479	3485192.992	136716.0343	8658.06828
Total (forecast)		19538372.08		1011594.629	17784933.66	697661.6807	44182.10708

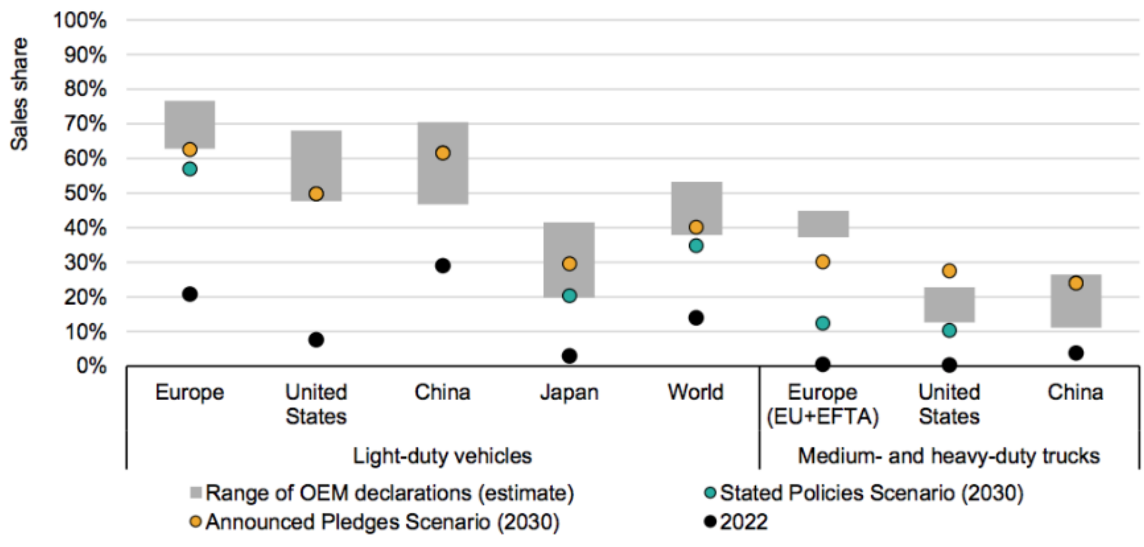
Table 12: BEVs introduced to the market each year with a high growth rate. Appendix 13, section 6.1.

Nevertheless, this growth rate is high in comparison to the reported forecast in the industry that claims that the growth in EVs will grow by 11% year-over-year until 2030. Looking at the market share that the BEVs would have with a 17.8% growth rate year-over-year, it is clearer that it is not that feasible as the total market share of BEVs would be close to 30% of cars sold in 2030.

Year	% share EV of the sold cars
2022	7.45%
2023	8.78%
2024	10.34%
2025	12.18%
2026	14.34%
2027	16.90%
2028	19.91%
2029	23.45%
2030	27.62%

Table 13: Market share of BEVs per year. Annex 13, section 6.1.

Nevertheless, the IEA is stating that the current scenario is that the sales share of EVs will be around 60% which makes the growth rate more reliable [87].



Car manufacturers' 2030 targets for electric vehicle shares of their sales in 2030 (grey area) and sales shares in the IEA's STEPS and Announced Pledges (APS) scenarios. Source: IEA.

Figure 32. Expected market share of EVs in Europe [87]

In the case the growth rate is only 11% the number of BEVs in 2030 would be 13.7 million instead, not being able to generate all the energy expected to use for the EV until 2033, three years after the studied date.

10.3. Results analysis

Against the previous analysis results, in this case, there are a lot of indicators that there is no problem regarding the capacity to produce that amount of BEVs in normal conditions (without considering macroeconomic conditions). The only question remaining is whether consumers are prepared to change their ICE vehicle to a BEV at a growth rate of 17.8% and not 11%. In any case, the difference in time to reach that volume of cars is not that high, just 3 years after 2030.

As seen, the vehicles sold from 2010 to 2030 are not separated by Regional grid. This is because the disaggregated data was not available and the production of the cars in a common market (except the UK) does not imply the consumption of that car in the same country. So it is assumed that the production of cars can be aggregated as they will be exported from the production facilities to the respective RG.

10.4. Charging stations

The other remaining problem in the BEV feasibility is whether there will be enough charging stations. As it is correctly pointed out in the previous analysis, the increase in BEVs that will be charged during the night needs to come with an increase in the charging stations. As it is assumed that the charging occurs during night, the number of charging points will be greater than what it could be in a real scenario where cars are charged at different times.

For the study, as the forecasted amount of cars from 2021 to 2030 has been calculated, it has been also calculated how many charging stations are needed to be included to the grid each year, using the high growth percentage.

Year	Necessary charging points forecast	Necessary charging points forecast	Necessary charging points forecast	Necessary charging points forecast
2022	34051.93761	102679.1807	8055.732021	340.1067926
2023	41179.9616	124172.8082	9742.022294	14806.82402
2024	49800.08061	150165.6538	11781.30034	17906.30688
2025	60224.63188	181599.5298	14247.45637	21654.59828
2026	72831.33362	219613.3962	17229.84792	26187.51203
2027	88076.97103	265584.6292	20836.53753	31669.29155
2028	106513.9472	321178.9285	25198.20825	38298.56102
2029	128810.2988	388410.6712	30472.89879	46315.5222
2030	155773.901	469715.9002	36851.72975	56010.65783
Total forecasted	737263.0633	2223120.698	174415.7333	253189.3806
Economic impact	€368,631,531.65	€1,111,560,348.92	€87,207,866.63	€126,594,690.30

Table 14. Number of charging stations needed and Economic impact. Appendix 13, section 6.2.

With a total forecasted of 3.388 million charging points that need to be installed until 2030. It has been seen in section 4.5.5. from a McKinsey study that the EU-27 will need at least 3.4 million operational public charging points by 2030 which is similar to the order of magnitude on the total charging points it has been found in this analysis. In the case of the McKinsey study, they talk about public charging points, which is different from the Level 2 charging stations which are easier to install and only cost around 500 € (but for the final consumer), having an impact of 1.7 billion euros to be spent from 2022 to 2030, far from the 240 billion that needs to be spend in McKinsey's study infrastructure. This is because McKinsey considers also the infrastructure required for fast-charging, improvement in grids and other costs.

11. Hydrogen use for non-generated wind power

11.1. Hydrogen applications analysis

The ASSET study on hydrogen found that 339 TWh of hydrogen are used per year in the EU. The use given right now could change due to the disruption of FCEVs that have several advantages in comparison to BEVs.

Consumers and industry have made it clear that BEVs are the future of light transportation. FCEVs represent less than 1% of the total market of cars. Even if they provide longer range in comparison with BEVs, they are more expensive (purchasing the vehicle and refilling it), they have less infrastructure for recharging and the energy density difference is not a relevant factor in their case.

To analyze the feasibility of hydrogen in mobility a comparison between a Tesla and a Toyota Mirai will be used. A Tesla can have 400 kg of li-ion batteries, making it have the capacity of 100,000 Wh when considering that the energy density is 250 Wh/kg. Because of hydrogen gas state, the FCEV Toyota Mirai has a capacity of 5.6 kg of Hydrogen, making it have 185,920 Wh capacity (32,200 Wh/kg). But the Tesla has around 80 - 90% efficiency in transforming the stored energy into mechanical energy [88]. The Toyota Mirai has a 58% efficiency on the highway as found by Lohse-Busch et. al. (2020) [89]. This leaves an approximately 90,000 Wh Tesla versus a 107,833 Wh useful capacity in the Toyota Mirai. Besides, hydrogen must be produced and transported. The current green hydrogen generation processes are around 60 - 70% efficiency, making the overall process much more inefficient in comparison as it consumes a lot more electricity. The following figure gives an idea on how much more efficient the electricity path is in an EV:

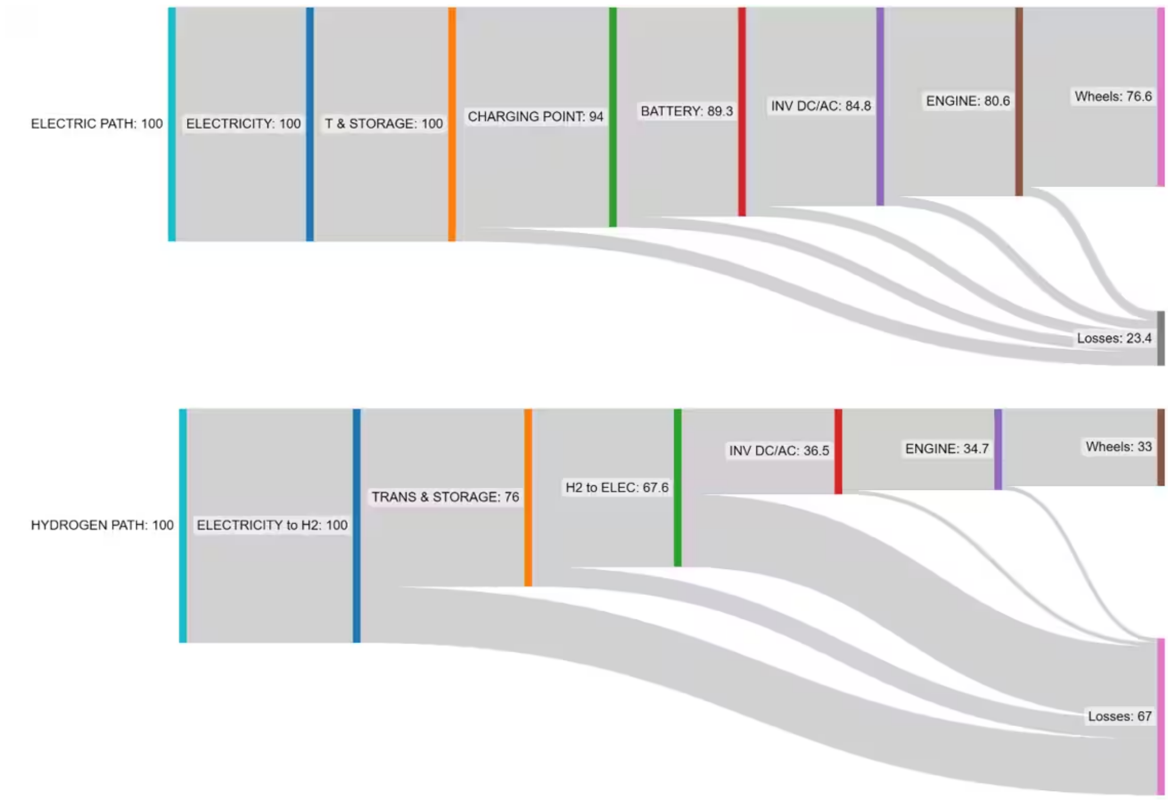


Figure 33. Breakdown of energy use of BEVs versus FCEVs [90]

Nevertheless, in heavy vehicles this starts to change as, even if both are linear, the energy density is more stepped in hydrogen. To make an idea on how the difference looks like the next figure shows a graph comparing how the energy changes normalizing the capacity with the kilograms that are inside a Toyota Mirai versus a Tesla (5.6/400) that can be found in appendix 16:

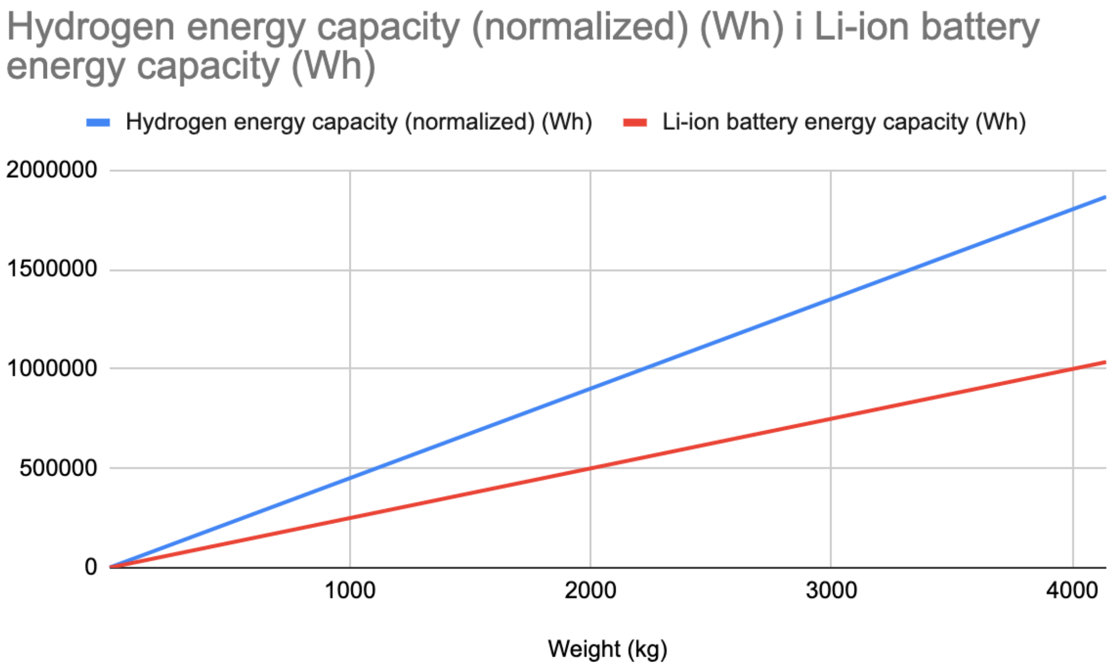


Figure 34. Hydrogen energy capacity normalized versus Li-ion battery energy capacity. Appendix 16.

But when comparing with the useful energy that both cars have, the difference shrinks:

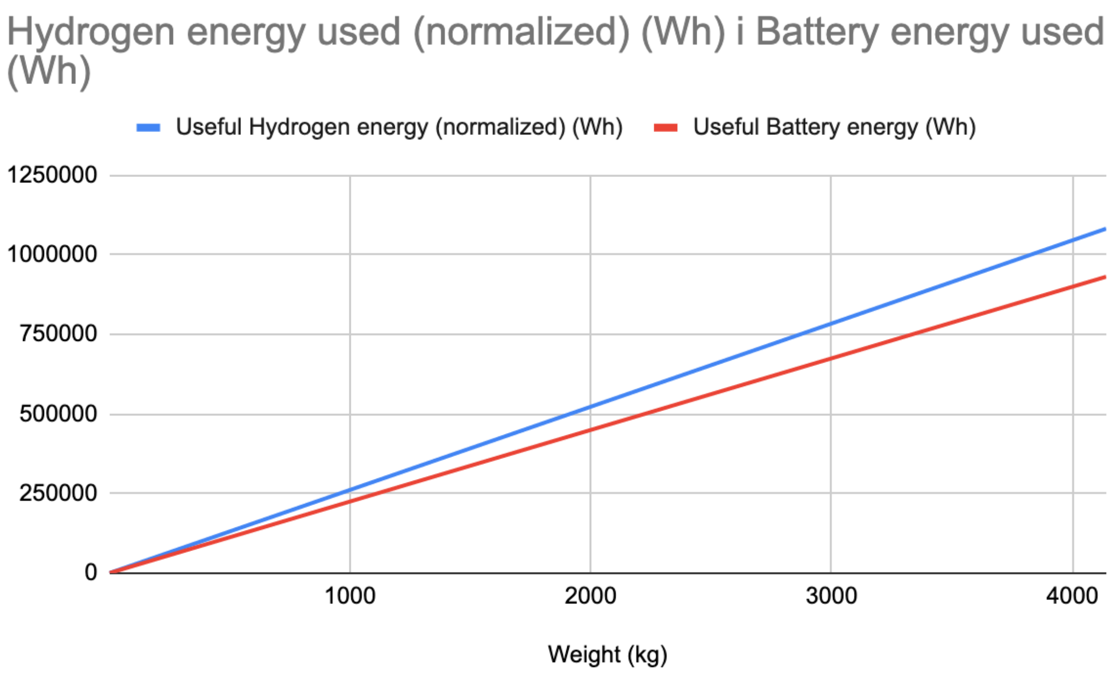


Figure 35. Hydrogen energy capacity normalized versus Li-ion battery energy capacity with efficiency

incorporated. Appendix 16.

As it is linear, the actual difference between useful hydrogen energy (normalized) and useful battery energy is 13.4% which makes it not different unless the vehicle is immense such as with trains or ships.

But these are the normalized calculations with weight. In reality, the hydrogen that a vehicle will carry will occupy a lot of volume but it will not weigh that much. In commercial transportation this is crucial.

For example, Hyundai expects to launch trucks that have 32.86 kg of hydrogen stored in eight tanks with a 400 km range. This is 1,090,952 Wh capacity. With a direct comparison, a BEV truck would require 4,363.8 kg of li-ion batteries [91]. A semi truck weighs between 5.4 tonnes to 10000 kg. The Tesla Semi truck weighs 11,000 kg with a 900,000 Wh battery pack [92].

In heavy duty vehicles, each kilogram counts. Having a more than 4000 kg battery in the BEV semi truck versus a 1,000 kg battery in a FCEV semi truck reduces the capacity of transporting around 3,000 kg of goods.

When bigger vehicles are taken into account, this is even more clear. The more kilograms you add to the vehicle, the less capacity of goods you can carry, and the less profit you will obtain per kilo transported.

At the end, the question of road hydrogen-powered transport comes not because of energy density but of weight and the time to charge the vehicle, more capacity in the battery, more time it will take, versus a FCEV that can be filled in 5 minutes for a light vehicle to 7 minutes for a heavy one (Hyundai), similar to gas or diesel. Without forgetting about the infrastructure investment needed in grid improvements for fulfilling the trucks capacity as it was seen in section 4.5.5. Most importantly for this study, the charging patterns from heavy-duty electric vehicles are totally different to the electric cars. They are constantly on the road and there is no time to charge them in Level 2 type of chargers, so supercharging is needed. This also comes with the inability to charge the heavy-duty vehicles when there would be the extra energy, while hydrogen can be generated at any point in time in electrolyzers and then it can be distributed through pipes and other transportation methods.

Another differentiation could come with ships and other types of vehicles that allow for liquid hydrogen [93]. The first ship powered by liquid hydrogen, MF HYDRA with capacity for 300 passengers and 80 cars is equipped with a 90 m^3 liquid hydrogen tank which is kept at -253º C. Nevertheless, liquid hydrogen has an energy density of 1.2 kWh per liter and compressed hydrogen has a 2.4 kWh per liter capacity. Nevertheless, DNV

(Norwegian shipping company) does not consider Hydrogen as a feasible alternative to fossil fuels and bets on biofuels and hydrogen derivatives as solutions. [94]

To conclude this section, it has been seen that hydrogen in mobility might not be the best application of all due to its low competitiveness in comparison with other technologies such as batteries for light vehicles, but heavy vehicles can be competitive in the market.

11.2 Electrolyzer technology to use

In sections 4.6.1. and 4.6.2. it has been found the different characteristics of the technology advancement to generate hydrogen. Hydrogen production is the most important step in the value chain of hydrogen as it is the one generating the most cost.

The most feasible technologies currently are either Alkaline or PEM electrolyzers as they have been tested, and most importantly, scaled. As Alkaline electrolyzers are the most mature technology, have been widely tested and have a wide range of size on the hydrogen they can generate, they will be considered as the technology to use.

11.3 Non-generated energy available for hydrogen production

After obtaining the energy that can be used for BEVs, the remaining of the non-generated energy in Scenario 1 is used. The energy left will be 54.69% of the total non-generated energy.

SCENARIO 1	RG	Total surplus energy for hydrogen generation (GWh)
	RG British and Ireland	3079.885265
	RG Continental Europe	34795.06329
	RG Nordic	3919.051857
	RG Baltic	159.3623527
	Total	41953.36276

Table 15. Extra energy available for hydrogen production. Appendix 13, section 11.

This leaves room for using hydrogen to fill heavy FCEVs. It is important to remember that the process to use hydrogen is not as efficient as the one for BEVs, having a 3 times difference in efficiency.

In this analysis, it will be used the Hyundai FCEV truck mentioned above, to understand how many of them could be filled up with hydrogen generated from the extra energy that could be generated.

Hyundai FCEV truck	
Gross Vehicle Weight (kg)	18000
Gross Vehicle Weight with trailer (kg)	34000
Driving Range (km)	400
Tank Capacity (kg H2)	32.86
Tank pressure (bar)	350
Hydrogen Refueling (min)	7
Hydrogen consumption (kg/km)	12.17285453

Table 16. Characteristics of the Hyundai FCEV truck. Appendix 13, section 11.

In the case of the technology use, the Alkaline electrolyzer will be the option chosen for this part of the analysis. As commented, it is the most mature and scaled technology from the 3 options.

Alkaline electrolyzer	2021 (same as 2020)	2030
Efficiency - low	63%	63%
Efficiency - High	70%	72%
Stack lifetime (hours) - low	50000	72500
Stack lifetime (hours) - high	90000	100000

Table 17. Characteristics of the Alkaline electrolyzer technology. Appendix 13, section 11.

Taking the extra energy that is left for hydrogen generation, it is found that it can be produced:

RG	Total surplus energy for hydrogen generation (GWh)	Total hydrogen produced low efficiency 2021 (kg)	Total hydrogen produced high efficiency 2021 (kg)	Total hydrogen produced low efficiency 2030 (kg)	Total hydrogen produced high efficiency 2030 (kg)
RG British and Ireland	3079.885265	60258624.75	66954027.5	60258624.75	68866999.71
RG Continental Europe	34795.06329	680772977.4	756414419.3	680772977.4	778026259.9
RG Nordic	3919.051857	76677101.55	85196779.5	76677101.55	87630973.2
RG Baltic	159.3623527	3117959.075	3464398.972	3117959.075	3563381.8
Total	41953.36276	820826662.8	912029625.3	820826662.8	938087614.6

Table 18. Hydrogen that can be produced with the extra energy. Appendix 13, section 11.

Now taking into consideration the driving range available from Hyundai's truck it is found that the total distance possible is around 10 to 11 billion kilometers.

RG	Total surplus energy for hydrogen generation (GWh)	Total distance possible 2021 - low efficiency (km)	Total distance possible 2021 - high efficiency (km)	Total distance possible 2030 - low efficiency (km)	Total distance possible 2030 - high efficiency (km)
RG British and Ireland	3079.885265	733519473.5	815021637.2	733519473.5	838307969.7
RG Continental Europe	34795.06329	8286950425	9207722694	8286950425	9470800486
RG Nordic	3919.051857	933379203.3	1037088004	933379203.3	1066719089
RG Baltic	159.3623527	37954462.26	42171624.73	37954462.26	43376528.3
Total	41953.36276	9991803564	11102003960	9991803564	11419204073

Table 19. Total distance possible with the extra energy. Appendix 13, section 11.

The kilometers made by a heavy duty vehicle can be found in the picture below and in appendix 13, section 11.1. It will be considered the Eurelectric data point of 14.1 years of life expectancy on heavy duty trucks for this calculation.

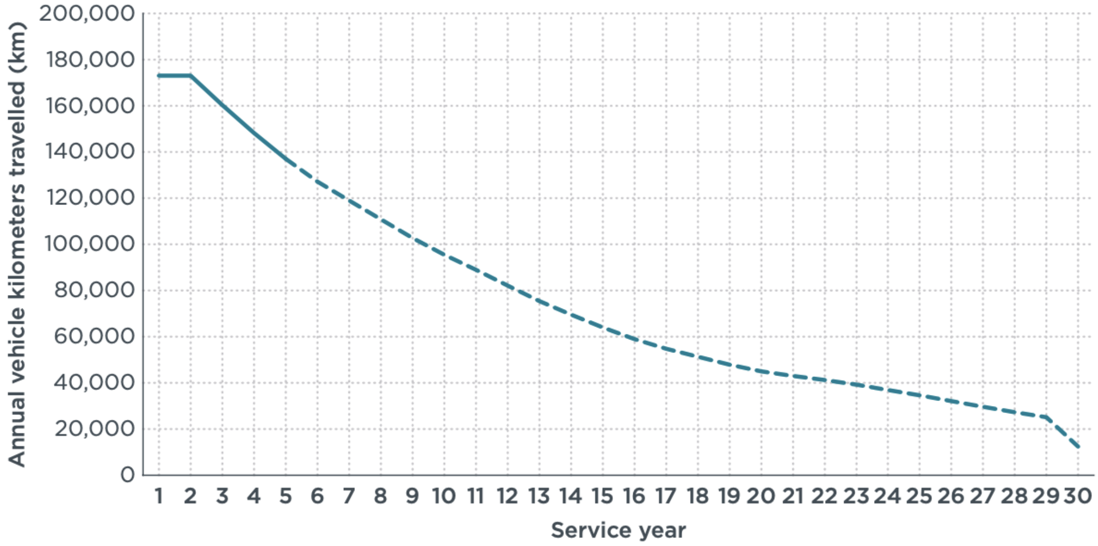


Figure 36. Average annual truck kilometers traveled each service year [95]

Which amounts to an average of 118,714.3 kilometers per year.

With the last table's number and this average kilometers per year, it can be found that it is possible to have 84,166 to 93,518 trucks in 2021 and 84,166 to 96,190.65 trucks in 3030 in Europe:

RG	Total surplus energy for hydrogen generation (GWh)	Total trucks possible 2021 - low efficiency	Total trucks possible 2021 - high efficiency	Total trucks possible 2030 - low efficiency	Total trucks possible 2030 - high efficiency
RG British and Ireland	3079.885265	6178.864398	6865.404887	6178.864398	7061.559312
RG Continental Europe	34795.06329	69805.83992	77562.04436	69805.83992	79778.10277
RG Nordic	3919.051857	7862.400028	8736.000031	7862.400028	8985.600032
RG Baltic	159.3623527	319.7126785	355.2363094	319.7126785	365.3859183
Total	41953.36276	84166.81703	93518.68558	84166.81703	96190.64803

Table 20. Total possible trucks depending on the efficiency of the alkaline electrolyzer. Appendix 13, section 11.

Averaging and considering only the efficiencies of 2021:

RG	Average total trucks possible 2021
RG British and Ireland	6522.134642
RG Continental Europe	73683.94214
RG Nordic	8299.200029
RG Baltic	337.4744939
Total	88842.7513

Table 21. Total possible trucks depending on an average of efficiency. Appendix 13, section 11.

As it can be observed, the number of trucks possible is much lower than the amount of BEVs that can be produced with a similar amount of energy. This analysis is a clear example on how electrifying heavy duty vehicles will be an even bigger challenge than cars due to the large capacity they need. Nevertheless, there is a lower amount of trucks used than cars.

For instance, the ratio in 2020 was of around 40 cars per medium and heavy duty vehicle [96].

In comparison, it is found that there will be a ratio of 219 cars per heavy duty vehicle. Only considering that the current amount of heavy duty vehicles in Europe is 1.1 million it would be possible to say that the ratio is kept, representing heavy-duty vehicles only 17.74% of the fleet of medium and heavy vehicles.

11.4. Feasibility of this capacity to be deployed in 2030

There are several constraints that will make it difficult to put in the market this quantity of heavy duty vehicles, being first the infrastructure and then the cost of each kilogram of hydrogen. Right now the price of hydrogen is 9.5 euros per kilogram and the expectation is to reduce it to 1.5 euros per kilogram. To fill a Hyundai truck it would cost 312.17 euros and 49.29 euros in the case the price can be reduced in 2050. Then the infrastructure needed for hydrogen is totally different to the one needed for BEVs. There might be technologies that makes it possible to repurpose gas stations to be able to hold hydrogen instead but to get to that point there must be demand for hydrogen and taking into account that FCEV that are light are not an option, it will be difficult to transition ICE heavy-duty vehicles to FCEV as they are specifically purposed for business, and the unit economics does not add up. Nevertheless, it is the same situation that BEV found: the BEVs were not appealing because there was no infrastructure, then demand remained low, then the infrastructure could not be built. The push in investment in Europe regarding hydrogen could change this but considering that it has taken more than 10 years to build a decent infrastructure for BEVs, it will take more than one or two decades to see if Hydrogen is a viable option for heavy-duty vehicles.

To conclude this section, even if the feasibility is low, the exercise to demonstrate how many heavy-duty vehicles can be powered by the extra energy is important to have a better view on how much energy could be unlocked with the proper storage system capacity.

12. Raw Materials capacity

A sudden increase in the raw material used for EVs can disrupt the supply chain. As it has been discussed, the new mining efforts will take time from planning to execution. For this reason, it is analyzed how much material from the total production is needed.

In the table below it is seen what are the main materials used in an EV. Although iron, aluminum and copper are the main elements found in an EV, as it has been said, other metals like lithium will be more critical in EV adoption.

Metal	BEV_622 (g)	% material
Fe	894,671.17	73.15%
Al	161,464.68	13.20%
Cu	59,517.26	4.87%
Ni	37,600.61	3.07%
Mn	17,959.34	1.47%
Co	12,324.36	1.01%
Pb	11,561.68	0.95%
Li	7,211.57	0.59%
Cr	6,534.84	0.53%
Zn	5,921.35	0.48%
Mg	2,339.42	0.19%

Table 22. Principal raw materials in a BEV and the percentage they represent [98]

This data comes from a raw material study by Iglesias-Émbil, et. al. (2020) [98]. In appendix 13 it is found the complete table with the analyzed amounts needed for the required EVs as well as the following analysis to understand the potentiality of supply chain disruptions due to the increase in EVs that have been calculated.

In the analysis there are 3 different EVs that are studied, and for simplicity the BEV_622 has been chosen for the analysis which has a total weight of 1,738.65 kg while the weight analyzed is of 1,223.06 kg, so 70.35% of the weight has been analyzed.

The data regarding the amount of material extracted yearly comes from the World Economic forum and it contains several of the materials inside the raw material study of EVs discussed above [98]. The data has been gathered in appendix 13, section 8.

There is a gap in the data between the analysis for a BEV and the total yearly production as not all the materials from the yearly material production have been found, representing only 0.23% of the weight analyzed. Some of those materials are rare and that is the reason why they are not counted, and they might represent a problem in the future.

From the total analysis, using Scenario 1, it is found that the most critical materials are Cobalt, Lithium and Nickel:

			Scenario 1						
Metal	BEV_622 (g)	% material	Total material needed for 2021 (g)	Total material needed for 2030 (g)	Material production yearly (tonnes) - 2019	Material production yearly in g	% of the total material production 2021	% of the total material production 2030
Co	12,324.36	1.01%	10802636927	50877510932	123,000	123000000000	8.78263%	41.36383%
Li	7,211.57	0.59%	6321133188	29770835124	97,500	97500000000	6.48321%	30.53419%
Ni	37,600.61	3.07%	32957949881	155223068839	2,702,000	2702000000000	1.21976%	5.74475%

Table 23. Critical raw materials in a BEV due to the volume of BEVs that are required. Appendix 13, section 8.

Cobalt use in EVs in 2021 is already 8.78% of the total global production in 2021 while it could reach 41.36% of production in case of keeping the extraction capacity constant during this decade.

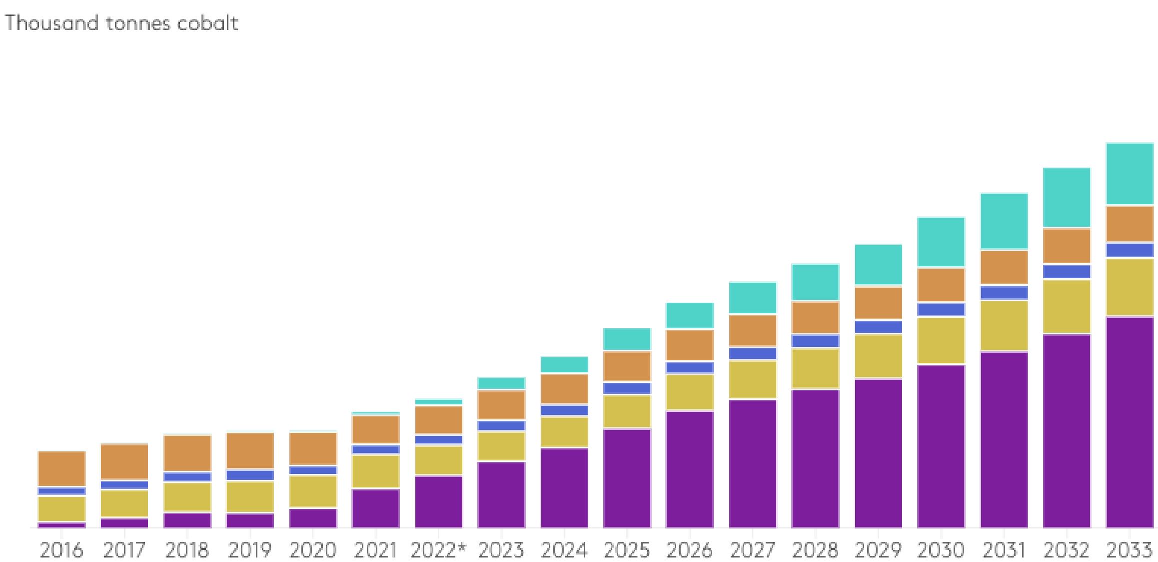


Figure 37: Cobalt growth from 2016 to 2033 [99]

Cobalt has been a concern during these last years, as 70% of it comes from the Democratic Republic of the Congo. There have been high concerns of chill labor, illegal mining and other human right violations [100]. Besides, the high increase found in cobalt demand can be a problem for EV production in the next few years. Nevertheless, some EV automakers and battery producers want to move away from Cobalt, using Lithium iron Phosphate (LFP) batteries [101].

In the case of Lithium, there have already been problems with the supply chain because of the increase of EVs. Considering production constant, 30.54% of the total material being used for EVs will certainly become a problem for the industry. Nevertheless, there are 300 lithium projects in the pipeline. There will be delays on it due to regulatory frameworks and ESG requirements and there will be a deficit of Lithium until 2026, which will increase the price but will boost the demand for new projects for the next few years [102]. Due to the opacity of the market it has been difficult to find a reliable forecasted growth of lithium production and the only data point is the one obtained from World Economic Forum.

In the case of Niquel, there should not be a problem to have 5.74% of the production dedicated to EVs in 2030.

Now, in the case of the FCEVs, the range of materials changes. There is less information about the components of the FCEV trucks, but the most critical metals for the technology are iridium and platinum.

Iridium demand is small as only 7 tonnes were extracted in 2020. Besides it is a rare material, which makes it even more possible that there will be constraints in the supply chain [103].

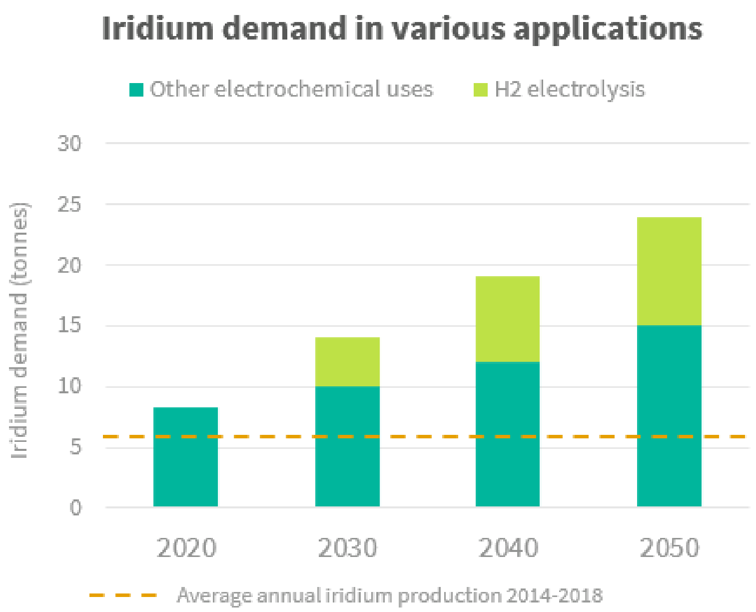


Figure 38: Iridium demand growth from 2020 to 2050 [103]

Platinum is another critical material but the current tendency is to reduce the material use for fuel cells and even substitute it. The supply chains will probably be disrupted when the technology of FCEV reaches the mass market even as the platinum needed will be low in comparison to actual technologies. The actual mining of platinum is about 457 tonnes, which is lower than the 3,350 tonnes of produced gold and the technology of fuel cells still is at its infancy.

The current Toyota Mirai uses 30 grams of platinum. This car has a range of 500 km to 1000 km while having a capacity of 5.6 kg of hydrogen. The Hyundai truck has a capacity of 32.86 kg H_2 with a 400 km range. It can be assumed that a truck, by extrapolating the capacity of hydrogen, would need 176 grams of platinum. That would mean that to produce all the FCEV trucks needed, it would require 15.64 tonnes of platinum, a quantity that represents 3.42% of annual production of platinum. This is not as critical as the lithium or cobalt needed for the BEV cars. And the prospect of reducing the platinum use per car makes it more feasible when it comes to raw materials.

13. Emission calculation

Introducing BEVs will save carbon dioxide emissions in the long term. In this section of the project, it is calculated what is the positive impact of the BEVs that will be produced in comparison with ICE vehicles. There are two types of emissions, the ones of ICE vehicle substitution and the one regarding energy use.

13.1. ICE Vehicle substitution

The total number of vehicles sold in Europe has been decreasing since 2020 while BEVs were growing at a rate of more than 50%. In the case the tendency continues and considering that the peak of cars sold was in 2007, it can be considered that BEVs will be fully substituting ICE vehicles and not both of them growing [104], which would not make that much of a difference in case the market for vehicles would grow constantly. In this case, it is going to be considered that the vehicle market will stagnate, that is, will not grow anymore nor decrease (2020-2022 can be considered an anomaly due to the COVID situation and the chip crisis). This means that the BEVs will take more and more stake on the vehicle market while the ICE vehicle market shrinks.

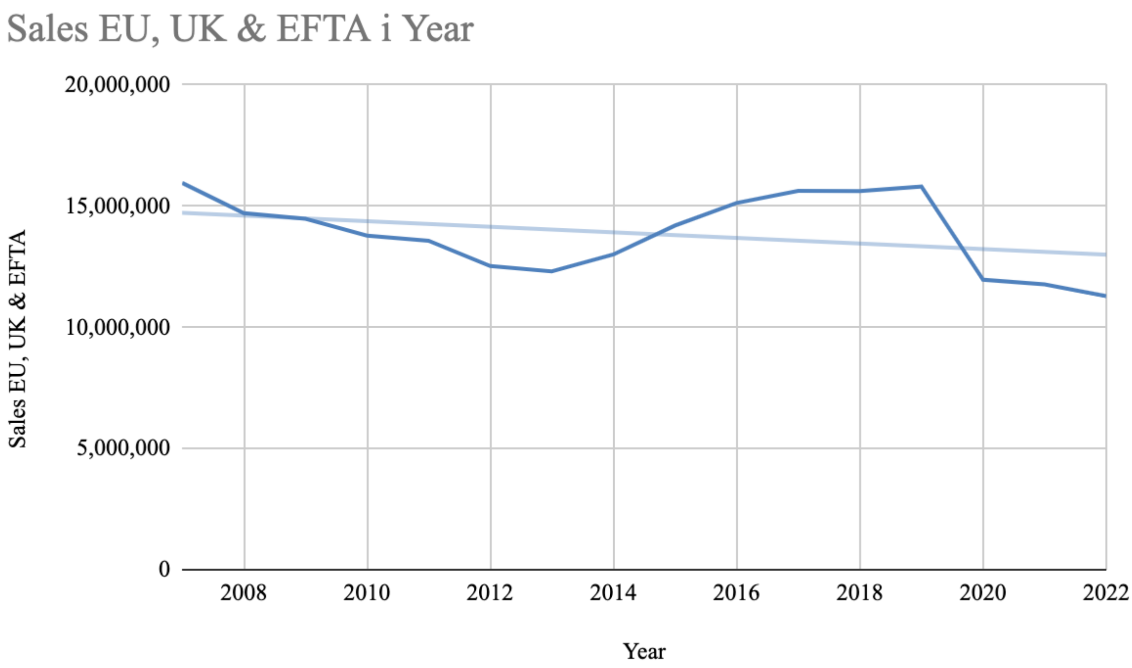


Figure 39: Sales of cars from 2007 to 2022. Appendix 13, section 9.1.

In Section 4.5.6., a comparison on the impact of an ICE vehicle with an BEV from the previous analysis has been shown. It has been seen that the majority of the impact on the environment from an BEV comes from the battery (6903 kg CO_2) while the energy is the most offender in the ICE (48216.3 kg CO_2). The final result is that BEVs are less polluting in the long term considering a useful life of 13 years.

In the end, the reduction on CO_2 from an BEV is around 60% with respect to an ICE vehicle, considering that these vehicles will be powered with wind power.

13.1.1. EVs emission break even

As seen in the previous analysis, BEVs will pollute more than ICE vehicles when manufactured but will have minimum pollution after in comparison with ICE vehicles.

The emission break even will be calculated as it was calculated in the previous analysis. The calculation will have a different result because of how the growth in BEVs is calculated this time (linear growth, year over year).

First, it is calculated the total amount of BEVs CO_2 in manufacturing, from Section 4.5.6. it is found that

$$N_n = N_{total} \cdot \%_{sales} \quad (16)$$

$$Emissions = \sum_{1}^{n} N_n \cdot C_n \cdot 0.177 + N_{total} \cdot 5.93 \quad (17)$$

Where N_n is the number of BEVs introduced from model n, C_n is the capacity of the battery of model n and N_{total} is the total number of vehicles.

The emissions calculations can be found in appendix 13, section 9 and they amount for 119,320,131.2 kg of CO_2.

In the case of the saved emissions for not driving ICE vehicles it is by first finding the number of daily kilometers in Europe and then calculating the emissions with that number.

$$dailykm_{Europe} = \frac{\sum_{1}^{n} dailykm_{n} \cdot H_{n}}{H_{Europe}} \quad (18)$$

$$emissions = \frac{dailykm_{Eurioe} \cdot 365 \cdot 215.395}{1000000} \quad (19)$$

From the previous analysis it is found that the daily kilometers are 29.015 per day, which the total savings amounts to 44,45 million kg CO_2 saved in a year. The break even for an BEV produced would be 2.68 years.

Nevertheless, the BEVs will not be produced at the same time. Using the high growth numbers from appendix 13, section 6.1., it is found that the break even is in between the 3rd and the 4th year (2024 and 2025).

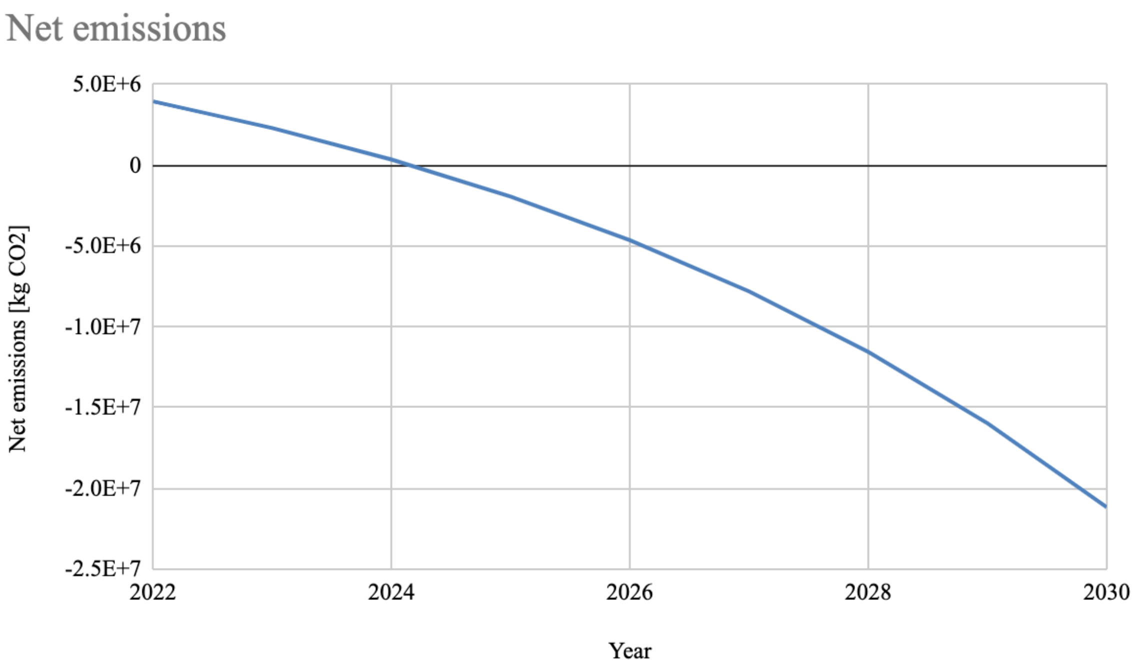


Figure 40: Net emissions of the BEVs introduced. Appendix 13, section 9.2.

In the case of the FCEV there is little information about the trucks, the only assumption that it can be made to calculate the CO_2 saved is that as more than half the energy (54.7%) is used in for FCEVs and they would have similar CO_2 savings, it could be think that the CO_2 saved in total is more than the double of the amount of the total savings that has been found. It would be in total 96.63 million kg of CO_2 of yearly savings while the amount of CO_2 required to produce the EVs would be 239.83 million kg of CO_2.

13.2. Electricity generation substitution

Contrary to the analysis on electricity generation substitution, in this project, it will not take into account the electricity generation substitution. In the previous analysis it is considered that because the energy stops coming from combined cycle power plants and it is changed by wind power, then there are savings in CO_2.

Nevertheless, this is double counting of CO_2. Double counting refers to a situation where two parties claim the same carbon removal or emission reduction in a case of carbon credits [105]. 1 tonne of CO_2 emissions reduced or removed from the atmosphere by an offsetting project creates one carbon credit. In this case, the double counting would come from counting 1 credit carbon for every 1 tonne of CO_2 of ICE vehicle substitution and 1 credit carbon for every 1 tonne of CO_2 of electricity generation substitution .

It might look that they are separated, but if the BEV would not have been built, then the extra energy from wind power would not have been generated. That means that the only credit carbon that can be counted is the one from the vehicle substitution and not by electricity substitution.

In the case of the previous analysis, the CO_2 saved was either 1.555 million tonnes of CO_2 saved in the case of gas combined cycle versus the 3.992 million tonnes of CO_2 of a coal power plant.

In this analysis, to not double count CO_2 emissions, it must be considered that there will be 0 savings from this energy generation.

14. Health improvements

One of the most important benefits of Electric Vehicles is health improvements as it has been discussed previously. The data has been taken from the study Buekers J. et al. (2014) [58] did about health and CO_2 reduction benefits thanks to BEVs.

Calculating health cost as an externality, or the social cost that is avoided allows one to have a well understood reference on the value of the negative externality of continuing to use ICE vehicles instead.

In appendix 13 section 10, the health impact is evaluated with the BEVs that will be on European roads in 2030.

What has been done is to separate the health benefit by RG and calculate an average of the health benefit for the countries that were taken into consideration. With this health benefit per ICE vehicle substitution for an BEV, it has been multiplied by the number of cars found in Scenario 1:

RG	Health 2010 (euro cents)	CO2 2010 (euro cents)	Total 2010 (euro cents)	Health 2021 (euro cents)	CO2 2021 (euro cents)	Total 2021 (euro cents)	Health 2030 (euro cents)	CO2 2030 (euro cents)	Total 2030 (euro cents)	Health benefit 2030 with cars calculated (euros)
RG British and Ireland	-0.75	-0.45	-1.2	-0.75	-0.45	-1.2	-0.85	-0.7	-1.55	-859855.3233
RG Continental Europe	-0.70625	-0.575	-1.28125	-0.70625	-0.575	-1.28125	-0.7375	-0.6875	-1.425	-13116386.88
RG Nordic	-0.7	-1	-1.7	-0.7	-1	-1.7	-0.75	-1.1	-1.85	-523246.1929
RG Baltic	-0.45	-0.15	-0.6	-0.45	-0.15	-0.6	-0.55	-0.5	-1.05	-24300.15575
Total										-14523788.55

Table 24. Health benefits of introducing the volume of BEVs. Appendix 13, section 10.

It is found that the yearly benefit in 2030 from the BEVs introduced in the road is about 14.523 million euros. Note that the health benefits come in negative numbers in the tables. This is because it is counted as a negative cost.

The problem with this number is that it is really small for the European Union to be able to take action and decide to change policies based on it at least in comparison with the benefits from EVs introduction and extra energy used as well as savings on oil as it will be seen in the next section.

15. Economic implications of the use of the non generated energy

In the new Scenario 1, the new amount of energy that is produced will have a cost and a profit for the wind farm owners. The extra amount of energy produced will generate more revenue for them.

As seen in section 7.3. in Scenario 1 there are an extra 12,582.69 GWh for charging EVs and a total of 9256.41 GWh per night to generate hydrogen.

Understanding the European electricity market is important in this part of the analysis to be able to obtain the economic impact of the increase in efficiency in wind turbines.

The data has been found in the webpage Ember Climate and it includes all the prices from the countries from 2015 onwards. It is a cleaned compilation of data coming from Entso-e. As it comes with a great amount of data, this could cause a problem when uploaded to Excel or Google Sheets (around 2 million rows). To take only the data belonging to 2021, it has been used the terminal of the computer, using these commands:

```
Unset
(base) MacBook-Pro-de-Marc:european_wholesale_electricity_price_data_hourly marcmacia$ awk -F, '$3 ~ /2021/ {print}' all_countries.csv > all_countries_filtered.csv

(base) MacBook-Pro-de-Marc:european_wholesale_electricity_price_data_hourly marcmacia$
```

Obtaining the information necessary except for United Kingdom data. In this case the data from the UK was lacking in ENTSO-E and in ELEXON. After some research, it has not been possible to find hourly data on the British energy prices in other webpages. To estimate the prices from 2021, several steps have been taken.

First of all, there has been found the Electricity's average monthly price on EUR/MWh for the UK, which can be found in section 2.1. in appendix 15. The data was in pounds. To transform it to Euros, the Google Sheets function GOOGLEFINANCE() [106] has been used which allows it to retrieve financial data from Google Finance with data coming from official financial exchanges, particularly from Morningstar in the case of currency [107]. The final average value from all the year is 109.57 €.

Then, as 2021 UK data is not available, a different approach has been taken to estimate the price which requires an assumption. It has been assumed that the demand on electricity intraday is constant through time, meaning that if in 2021 there was an average valley on demand during night, in 2022 and 2023 it would happen the same. Following this assumption, data samples from ELEXON in 2023 in appendix 15 section 2.2. for February 1st to 7th, March 1st to 7th, and May 1st to 7th have been taken. After aggregating the data, and transforming it from pounds to euros, the average price during the day has been found, which is 137.96 € which is almost 30 € more expensive than in 2021. With this data point, it has been calculated the average price each hour in 2023 with respect to the average in 2023 in a day. Now it is possible to observe the price variation each hour, regardless of the price during those days.

Finally, these prices have been multiplied by the average price in 2021 to give the final estimate on 2021 prices each hour and included into the other european price data directly in appendix 13 section 4.1.

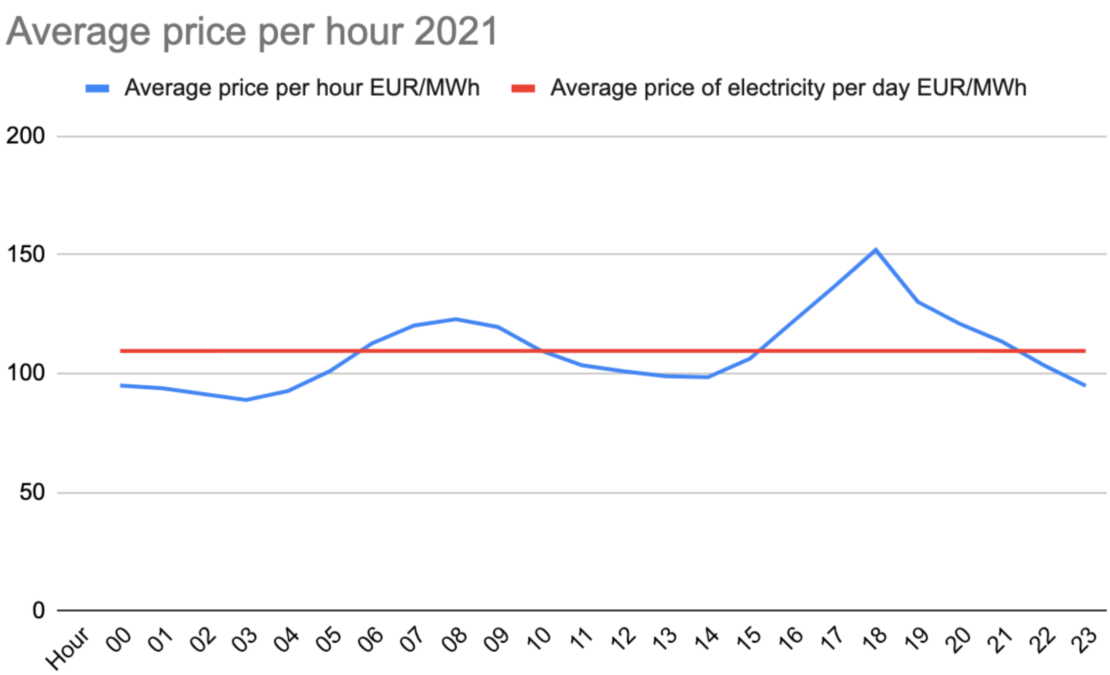


Figure 41: UK electricity average price per hour in 2021. Appendix 15, section 2.3.

With the data cleaned, it is then calculated the average price per hour in appendix 13, section 4.1. and then it is multiplied by the potential energy generated in case of combining batteries and hydrogen in section 4.2. In section 4.3. It is found that the yearly monetary value generated from this extra energy is 6.9 billion euros for the whole European market yearly.

Zone	Monetary generation	Total value
RG British and Irish	Monetary value (€)	€247,124,406.82
RG Continental Europe	Monetary value (€)	€6,235,550,968.40
RG Nordic	Monetary value (€)	€398,400,676.45
RG Baltic	Monetary value (€)	€22,566,437.88
Total yearly (€)		€6,903,642,489.55

Table 25. Revenue generated from the non-generated energy. Appendix 13, section 4.3.

The implication of these results are key in the study as it sends a message to the market telling them that the potential future profits of the energy market regarding wind power are higher than what it is expected.

The wind power business not only grows in revenue by new installed capacity but also because of new BEV purchase and generated green hydrogen for FCEVs. There is then a new metric that must be taken into account to forecast the growth in potential returns of the energy market: the storage capacity of the countries which includes: batteries, hydrogen generation and gravitational systems (water or solid).

Not only that, the change of ICE vehicles by EVs has another economic implication as it creates savings for the European economy. Except for Norway, there is no significant oil producer in Europe. This increases the exposure of Europe to price fluctuations of the price of the barrel of oil.

One of the reasons why Europe is investing heavily in renewables is because it is important to reduce the energetic dependency on countries that can use their power to bend policy decision-making towards their goals. Increasing the share of renewables decreases this power and the money is kept in the local economy which makes the economy more stable from price shocks on oil prices.

Then, it is worth analyzing which are the yearly savings from not consuming oil in the EVs that are incorporated.

First of all, it is found that a barrel of oil amounts to 119 liters, the average consumption of an ICE car in Europe is 6 liters per 100 kilometers [108] while the average consumption of an ICE truck is 33.1 liters per 100 kilometers [109]. All the calculations can be found in appendix 13, section 12.

From the analysis made in section 11. in the same appendix, it was found the distance that the FCEV trucks travel with the amount of hydrogen produced, then using the data of the price per barrel during the year 2021 it is possible to obtain the yearly savings in gas in liters and in Euros.

In the case of the BEVs, the data regarding the distance traveled per day is found in the annex 10 from the previous analysis and then the calculation can be made for the cars.

RG	Total yearly savings in gas (EUR)
RG British and Ireland	449073894.2
RG Continental Europe	6337711676
RG Nordic	368279891.8
RG Baltic	18737924.78
Total	7,173,803,387.0

Table 26. Savings in oil due to the incorporation of the volume of EVs. Appendix 13, section 4.3.

The savings that can be made from not consuming oil amounts 7.17 billion Euros, a similar order of magnitude as the value of the non-generated energy. In this case, it is not double counting savings because the price of the oil as a commodity is pre-tax and governments need to import that oil while the energy produced is local.

16. Gender perspective

There are several parts of the projects that could relate with gender perspective, coming first about the gender gap between men and women when it comes to EVs drivers.

In the UK, it has been found that 76% of EV drivers are male while only 23% are women [110].

There is more data regarding this issue in the US. For instance, there is a high underrepresentation to appeal to women in the EV sector even if at the start of the century EVs were associated with conservatism and femininity, as they were easy to operate while men mocked EVs' lack of power. Besides, the marketing efforts towards women in the industry of EVs have been minimal until not so long ago [111].

Nevertheless, there is a gap that is closing, which is the proportion of women scientists and engineers with respect to men, as they represent the 41% of the total population in these disciplines, having areas of Spain, Portugal, Norway, Poland, Sweden, Lithuania, Bulgaria and Denmark with more than 50% of the population of scientist and engineers being women [112].

Nevertheless, only 20% in 2021 of the automotive workforce in Europe were women, growing from 16% in 2019, which is a big increase in a short amount of time [113].

A Deloitte's article has found several reasons why women might be underrepresented in the industry [114].

The top 3 issues found by Deloitte can be related to imbalance of power for women with respect to men. It shows that there is a high change that the industry has cultural norms that affect women's promotion inside the industry.

When it comes to leadership representation, polls says that there is an industry bias towards men as well as organizational cultural norms affecting them to not be promoted.

In the energy industry, it does not look more promising but the percentage of women in the renewable energy sector is higher than in the energy sector as they represent 32% and 22% respectively [115].

In this analysis, there has been a lack of perspective on non-binary genders as the representation of the population is so low that statistically it has been difficult to obtain data. Part of it is how the surveys are constructed, which does not let understand in a more granular way the representation of this population, for example by using: I prefer not to answer as the third gender response instead of non-binary.

To summarize this section, it is really concerning the gap between men and women in this sector although it is improving with time. Several measures such as mentorship for women in the industry and marketing efforts to attract underrepresented groups for EV purchasing could change this.

17. Budget of the project

The initial budget of the project was 0 € as it was not expected to spend anything in a resource given the free use of information on the internet and of the accessibility that having two universities (UPC and UPF) gives privileged access to papers and databases. Nevertheless, it has been necessary to spend 0.84 € in the access of a database for obtaining the offshore data on wind of the UK from Visual Crossing.

In the case of this project being developed as a professional there could have been a larger budget for this business case. Due to the student being a full time intern in Amazon Luxembourg, the time spent in the project has been condensed through the evenings on weekdays with a dedication of 2 hours per day from mid February to June of 2023 and full time on the weekends in sessions of 9 hours from mid April to June. That amounts to 280 hours not taking into account the time spent in meeting sessions which can reach 285 hours to 290 hours. Considering that a junior engineer in Europe can be paid around 16 €/hour, the total amount of money for this project would have been 4640 €.

18. Emissions of the project

The work has been carried out more than 90% in the offices where the student has been working in and the transport to go to the office has been by walk, then no spending related to transport has been needed. In case some transport was used,it was public and it is free in Luxembourg.

The use of Google Suite as a way to store data means that the net emissions in regard to data is equal to 0 kg of CO_2 as the company has been carbon neutral since 2007 due to carbon offsetting. It could be argued that the carbon offsetting projects are not as effective in execution than in paper but in this project it will be assumed that they are.

In the case of the computer used, a Macbook Pro of 13 inch screen has a power of 69.1 W. As the time spent in the project has been 290 hours, the amount of energy used has been 20,039 W [117].

Considering that the Carbon intensity of energy production is 0.2 kg of CO_2 per kWh, the amount of CO_2 consumed from the usage of the student computer is 4 kg of CO_2 taking into consideration that the Amazon HQ is connected to the grid and no there are no photovoltaic solar cells on the ceiling of the building [118].

Summarizing, the total CO_2 consumption of the project has been 4 kg of CO_2

19. Project planning

The hours dedicated to the project have been unevenly distributed throughout the time of the project. This has been partly attributed to the nature of the student moving from Spain to Luxembourg and having to start a new job and adapt to a completely new environment and routines. The approach for the project changed in mid March. Firstly, the student thought that the approach to follow would be to start from where the previous analysis left and build new information from there. The problem with that approach was that there was a lot of understanding to be made about the project and the technology. Then, in mid March, the approach was changed to firstly understand end-to-end the analysis made by Joan, write the base of the project improving the sources and introducing the new ideas to improve the analysis and then restart again with the analysis. The writing of the base of the project has been continuous since March but at the beginning of May it was partially completed with 19,000 words. The analysis was slowly made until that point and from May to delivery on the corrections it was completed with the full picture of the necessary steps to be done.

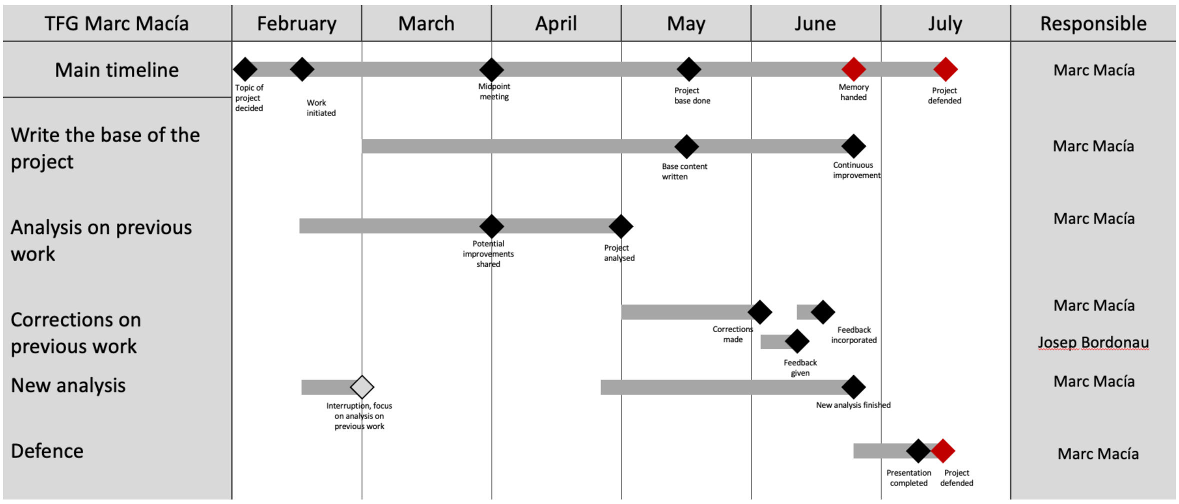


Figure 42: Gantt chart of the project plan.

Conclusions

This project is the continuation of an analysis made where there was already a quantity of vehicles given. In this new analysis, it has been demonstrated that the previous analysis was correct in the conclusions of being able to extract more energy from wind power in the valley hours of low demand. It has been corrected data on UK ideal and real energy that gives more robustness to the final results of the number of EVs found.

More importantly, the analysis of hydrogen as a storage system has allowed breaking the limitations of using only partly of the potential energy due to the simultaneity charging problem of BEVs, taking advantage of 100% of all potential energy available for the study.

The number of vehicles amounted to 19,538,369 light BEVs and 88,842 heavy-duty FCEVs. The total amount of CO_2 saved by these vehicles is 96.63 million kilograms of CO_2 while the manufacturing requires extracting 239.83 million kilograms of CO_2, totalling in a break even of 2.68 years per every car. The BEVs have a positive externality of 14,52 million euros yearly in Europe.

One important aspect to be corrected from the previous analysis is the double counting of CO_2 from the electricity generation substitution.

One of the most important analyses made is the economic analysis of the project as the revenue generated for the wind power value chain is of 6,903,642,489.55 euros and the savings on oil is of 7,173,803,387.00 euros. This demonstrates that the increase in EVs will not only provide a singular value for decreasing the CO_2 used in the future but it will create a flywheel effect where companies want to invest more money in renewable energy as it is more profitable and governments want to support it even further as they reduce exposure to oil prices.

Nevertheless, it must be noted that there is still high uncertainty about the development of the hydrogen as a realistic alternative to heavy duty BEVs or heavy duty ICE vehicles. It remains a job for engineers to find innovative ways to improve the fuel cell technology and reduce prices on hydrogen generation, storage, transport, and usage in FCEVs. The scalability of these technologies will determine if they are a viable option to scale or just a niche market.

There are several parts of the project that could be improved to increase the robustness of the calculations made and to comprehend the feasibility of the better use of wind power capacity in Europe. For instance, it would be necessary a deeper assessment on the infrastructure requirements for distributing the energy produced to all the cars while simultaneously connected to the grid, its cost as well as the infrastructure and investment needed to generate all the necessary hydrogen for the FCEV heavy duty vehicles. Also, it would be interesting to analyze which are the regulator limitations on the wind production as there might be other reasons why some of the energy is not used aside from low demand during the valley hours in the night. This last idea of improvement could constitute a standalone new project, where another student takes care of contacting the regulators and understanding which are the policies involved in the energy market. This could have a positive impact on the network that the student would have as they would be meeting important people in different countries in a key sector for Europe's future. This project would provide understanding on how much of that extra energy could be really used.

Besides, qualitative research could be made to assess the reduction of costs in the technologies that have been described during the project, notably in batteries and Hydrogen, where a potential student could search expert knowledge on how the costs could be reduced, in a similar fashion of the research paper on the lithium market presented in section 4.5.7. This could provide a better understanding on what are the limitations of these technologies and how fast the market will shift to electrification.

Another interesting next step would be understanding potential policies, regulations and frameworks that the government could apply to motivate more introduction of EVs and hydrogen based on the benefits of unlocking the non-generated wind power energy and reduction of the CO_2 consumption.

Acknowledgements

I would like to thanks first of all Josep Bordonau firstly for accepting being my project advisor and secondly for understanding my situation with work and not being bothered for my emails during the weekends. Not everybody would have been that empathetic and I really appreciate that as well as his motivation for proving that we will be able to make a big impact in reducing pollution in the future thanks to the introduction of these EVs.

Secondly, I would like to appreciate the amazing job that Joan Pedret Botey did in his project “Model per a l’anàlisi de l’impacte del número de vehicles elèctrics en el sistema energètic Europeu" as it has been the base of this project to work further. His research has been fundamental for contributing further in understanding the positive impact that introducing a large amount of EVs and FCEVs in the market could have. Working on such a great project has been an honor for me.

I would also like to thank the both schools (UPC and UPF) that I have attended during these 5 years. I have become much more resilient since 2018 and learned to accept failure, something that I had not seen in my first 18 years of life. Everytime I face a challenge now, in work for example, or in balancing both work and writing this project, I remember that I went through more difficult challenges and I continue moving forward.

Inside the school I would particularly like to thank Joaquim Minguella Canela as he has been the major promoter and responsible of executing the Bachelor’s degree in Industrial Technologies and Economic Analysis. I do not believe in destiny but learning about this program, which seems made for me personally, 6 months before my selectivity exam erased my fears of not finding my ideal studies.

Professionally, I would like to thank my manager at Amazon who has been really supportive of my project and has tried to give me freedom and ease my workload when needed for the project.

In the personal aspect, I would like to really appreciate the support of my family and friends who have been there through this changing period of my life and have helped me stay motivated during my work and project.

ETSEIB

Annex index

From previous analysis:

Annex 1: Wind power plants in Europe. There is information on 10 power plants per country, their location, the model of the turbines, etc.

Annex 2: Power curves of a series of wind turbines of different power and different manufacturers.

Annex 3: Information on wind speeds from different countries, one file for each location. It is separated into 3 parts:

Annex 3.1: Wind speeds throughout a year for each hour in km/h.

Annex 3.2: Wind speeds ordered by each hour of the night, converted to m/s, at 100 meters high and organized in the form of a histogram.

Annex 3.3: Based on wind speeds in a year, the power they produce.

Annex 4: Calculation of the position factors of each location

Appendix 5: Information on the 10 most popular electric vehicles in Europe and their specifications.

Annex 6: Results of the maximum potential energy for each synchronous zone and for each hour of the night.

Annex 7: Actual wind generation data for each country during 2021 in the night hours and the calculation of the total and the daily average.

Annex 8: Results of the real energy generated in each synchronous zone during a separate year in the night hours.

Annex 9: Calculation of the remaining energy during the night.

Annex 10: Data and calculations of driving habits in European countries.

Annex 11: Calculation of volume of electric vehicles and calculation of registrations by country.

Annex 12: Calculation of the volume of vehicles supported by the current electricity network.

The archive divided in different countries have distinction of 2 letters to differentiate them:

Shortening	Country (catalan)	Country (English)		Shortening	Country (catalan)	Country (English)
AL	Alemanya	Germany		BE	Bèlgica	Belgium
DN	Dinamarca	Denmark		ET	Estònia	Estonia
FR	França	France		HU	Hongria	Hungary
IT	Itàlia	Italy		MB	Mar Bàltic	Baltic Sea
NO	Noruega	Norway		OI	Polònia	Poland
RO	Romania	Romania		RX	República Txeca	Czech Republic
UC	Ucraïna	Ukraine		BU	Bulgària	Bulgaria
AU	Àustria	Austria		FI	Finlàndia	Finland
ES	Espanya	Spain		IR	Irlanda	Ireland
GR	Grècia	Greece		MN	Mar del Nord	North Sea
LI	Lituània	Lithuania		PR	Portugal	Portugal
PB	Països Baixos	Netherlands		SU	Suècia	Sweden
RU	Regne Unit	United Kingdom				

From this analysis:

The analysis has been made in Google Sheets as it provides important advantages with respect to Excel.

- It has real time collaboration, which has been really useful in the calls to coordinate and change information when necessary. Having this visibility at any point in time has been important for transparency in the calculation made.
- There are formulas that do not exist in Excel and make calculations more quickly. For example the googlefinance() formula allows to have real time data on prices of currencies, stocks, and other securities and commodities. Another more important formula is the query() formula, which uses a pseudo-SQL language to retrieve and transform data from tables. Lastly, the formula arrayformula() allows to use only one cell to propagate formulas along a table. This is not as useful as in other cases, but it improves the efficiency of the calculations necessary when data changes.

- In case it would have been necessary, there exists the possibility to connect several sheets and retrieve information from them, having all the analysis connected and easy to fix if there is a problem with data or corrections are needed.

Annex 13: The document annex_13 contains the main information of the analysis made and is divided in sections:

Section 1. maximum-energy_NOT_corrected: it is the Annex 6 of the previous analysis and it is used as having the reference for future corrections.

- Section 1.1. maximum-energy_check: calculates the % offshore in UK
- Section 1.2. maximum-energy_corrected: it corrects the offshore UK's maximum offshore energy with the data calculated in Annex 17.

Section 2. real-energy-generated: annex 8 from the previous analysis to have a reference when correcting it.

- Section 2.1. real-energy-generated_corrected: it corrects annex 7 UK's real energy generated with the data obtained from ELEXON instead of ENTSO-E. The data of the correction is found in Annex 14.

Section 3. difference: annex 9 from the previous analysis to have a reference when correcting it.

- Section 3.1. difference_corrected: it contains the clean data from the difference between section 1.2. and 2.1.

Section 4. minimum-surplus_corrected: it contains the information of the surplus energy that can be used for car charging and the extra energy that can be used for hydrogen generation.

- Section 4.1. average_price_per_country: it contains the prices of electricity in 2021 for every country except Ukraine. The data in the UK has been extrapolated from partial data on the prices in 2023 and recalculated for prices in 2021.
- Section 4.2. economic_value_surplus_per-country: it calculates the revenue generated with the extra energy that could be produced, using the prices in section 4.1.
- Section 4.3. economic-value_surplus_per-RG: it calculates the total economic value of the extra energy in the Regional Group level.

Section 5. EVs-charging-requirements: annex 10 used as a reference for calculation on the volume of BEVs possible.

Section 6. extra-energy-applied: 2 scenarios are calculated (only scenario 1 is finally used) where there are the volumes of BEVs possible with a safety factor of 2 (half the vehicles possible), and scenario 2 without a safety factor.

Section 6.1. time-to-reach-volume: calculates how much time it will take to reach the volume of BEVs with a high growth scenario and an expected scenario. It has a sense check with the % of share of EVs using the section 9.1. of the same annex.

Section 6.2. charging-stations: calculates the Level 2 charging stations necessary with the volume of BEVs in scenario 1.

Section 7. forecast-wind-capacity: non-used data for forecasting wind capacity.

Section 8. car_raw-materials: it calculates the material necessary for the volume of BEVs found and the % it represents of the total yearly production capacity.

Section 9. environmental-impact_comparison: it compares the environmental impact of a BEV and an ICE vehicle.

- Section 9.1. cars-sold_europe: it gathers the data of the last years sales of cars in Europe (2007 to 2022).
- Section 9.2. BEV_emission_break-even: it calculates the number of years necessary to break even the pollution of BEVs.

Section 10. health-impact_EVs: it calculates the positive externality of introducing the volume of BEVs to circulation.

Section 11. hydrogen-use: it calculates how many heavy duty FCEVs can be put on the road thanks to the hydrogen produced with the remaining energy from Scenario 1.

- Section 11.1. distance-traveled-truck: it gives the distance traveled of a truck since purchase year to year 14.

Section 12. savings_oil: it calculates the amount of oil and money saved on purchasing oil made thanks to introducing the volume of EVs into the market.

Annex 14: it calculates the real power of the UK using the data of ELEXON. It has several sections to go through the calculation process. Section 3. cleaned_data_real-power is the final data.

Annex 15: it calculates the prices of energy of each country. The final data section is 3. final_data_sorted.

Annex 16: it analyzes the differences in light BEVs and light FCEVs when it comes to energy capacity normalized.

Annex 17: it calculates the offshore power of the UK with a new database of wind with the location of an offshore wind farm. Section energy_produced is the one to look for the final data.

Here are the appendixes online:

Annex 13:

https://docs.google.com/spreadsheets/d/1jzMpgdiMrnf3dIGWywX8YqqBOf_r77mgEzw5AKZr-jQ/edit?usp=sharing

Annex 14:

https://docs.google.com/spreadsheets/d/17jUBoIvGowAd2G0e_LmQYs9YoMBcasETyeZFvTC09Io/edit?usp=sharing

Annex 15:

https://docs.google.com/spreadsheets/d/1B700bQ1CLHeyTyahHg2spnBqkTcYqUYVBfWUAyNvkQE/edit?usp=sharing

Annex 16:

https://docs.google.com/spreadsheets/d/1eTJ7OtBmNIOr8KxWIMkaz8NqTOhuUDyjUr4Gfihj770/edit?usp=sharing

Annex 17:

https://docs.google.com/spreadsheets/d/1sTG1KFo5EVHesOi_g1CV7Ad-ffgMMzngoqB4CWMTSFU/edit?usp=sharing

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