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Raw critical materials in energy transition

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Abstract

To achieve the Net Zero Emission scenario allowing to keep the temperature rise under 1.5 °C, it becomes urgent to accelerate the energy transition aiming at replacing the limited and highly carbonated energy sources by renewable energies. The challenge related to the increasing electricity intermittence must be compensated by the deployment of energy storage technologies. This thesis analyses the effect on material availability of the soaring wind and solar markets as energy sources, together with the deployment of batteries and the green hydrogen production as storage alternatives.

The cumulative solar capacity is expected to exponentially increase to reach 15 TW of power by 2050. It is boosted by the continuous increase of the efficiency of cells and the development of huge solar farms. The leading technology will likely stay the c-Si which could be used in tandem configuration with perovskite in the future. Critical risk of materials shortage exists for silver and copper due to a tremendous demand compared to the annual production. In addition, the fact that China accounts for more than 95% of the polysilicon and silicon wafers fabrication represents a considerable vulnerability.

The wind industry is expected to reach 8 TW of power by 2050 arising from both onshore and offshore turbines. The turbine dimensions increase leading to better capacity factors, together with the economy of scale, enable the wind energy to be cost competitive in certain parts of the world where it was previously subsidiary driven. In the coming years, the onshore industry will be dominated by the GB-DFIG technology, while the offshore industry is mostly covered by the DD-PMSG turbines. Critical risk of materials shortage is attributed to the rare earth elements (neodymium, praseodynium, dysprosium, and terbium) which are highly concentrated in China and also much needed to produce electrical motors. Besides, the wind industry also requires a huge quantity of copper for the electrical cables into the sea.

The batteries industry previously driven by electronics is switching to ensure the demand of both the electrical vehicle and the stationary storage rising markets. Despite the announcement of revolutionary solid state batteries, the conventional lithium ions technology will likely stay the dominant player. Consequently, the critical risk of supply chain perturbation comes from lithium, nickel and copper while the cobalt use should be reduced due to ethical concerns.

In the hydrogen industry, the critical materials will depend on the intense competition between the different electrolysis technologies. PEMs containing very limited PGM might dominate the future market taking the advantage over alkaline electrolysers. In this situation, a critical risk regarding the PGMs (iridium, platinum, palladium) supply chain exists as those elements are geographically concentrated and limited on the earth's crust.

This work has demonstrated that for all selected technologies there are critical raw materials risks regarding the supply chains. Solutions to reduce the materials supply pressure and hence mitigate the risk to see the energy transition slowed down exist and include the technological improvement, the eco-design, and the recycling increase providing secondary materials sources. However, the energy sobriety stays the best way to fight the global warming as the greenest energy is the one which has not been consumed.

Keywords: Energy transition, emergent technologies, raw materials, risk of shortage.

Acknowledgment

First of all, I would like to express my deep and sincere gratitude to my supervisor, Alexandre Thys, who offered me the possibility to work on this fascinating topics. Besides, he has a lot of knowledge on this subject, he was always available to answer my questions and gave me some interesting feedback.

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Contents

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Acronyms

AEL	Alkaline ELectrolyser
a-Si	Amorphous Silicon
ASSB	All Sold State Battery
BOS	Balance Of System
BEV	Battery Electrical Vehicle
CCGT	Combined Cycle Gas Turbine
CdTE	Cadmium Telluride
CIGS	Copper Indium Gallium Selenide
DD-EESG	Direct Drive Electrically Excited Synchronous Generator
DD-EESG	Direct Drive Permanent Magnet Synchronous Generator
GaAs	Galium Arsenide
GB-DFIG	Gearbox Double Fed Induction Generator
GB-PMSG	Gearbox Permanent Magnet Synchronous Generator
HDV	High Duty Vehicle
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRENA	International RENewable Energy Agency
LCO	Lithium Cobalt Oxide
LCOE	Levelized Cost Of Electricity
LCOS	Levelized Cost Of Storage
LDV	Light Duty Vehicle
LFP	Lithium iron Phosphate
LMO	Lithium Manganese Oxide
LSM	Lanthanum Strontium Manganese
NCA	lithium Nickel Cobalt Aluminium oxide
NMC	lithium Nickel Manganese Cobalt oxide
NZE	Net Zero Emission
PEM	Polymer Electrolyte Membrane
PGM	Platinum Group Metal
PV	PhotoVoltaic
REE	Rare Earth Element
DRC	Democratic Republic Congo
SOEC	Solid Oxide Electrolysis Cell
SMR	Steam Methane Reforming
VFB	Vanadium Flow Battery
YSZ	Yttrium Stabilized Zirconia

Introduction

Recently, the Intergovernmental Panel on Climate Change (IPCC) has published the third part of its 6^{th} edition report, gathering the most advanced scientific knowledge over the climate change and the global warming [1]. Results are alarming and show that greenhouse gases emissions released during this decade have never been higher in the entire human history. Temperature has already risen by 1.1 °C compared to the pre-industrial period and climate change is already observable everywhere through floodings, droughts, or hurricanes. According to the IPCC, crossing the 1.5 °C limit would lead to disastrous irreversible consequences. Time is running short to act for our planet.

The energy sector is the most efficient way to combat the global warming as it is responsible for around 75% of the world greenhouse gases emissions while the other contributions are mainly the agriculture and some industries [2]. In this context, the International Energy Agency (IEA) has developed a Net Zero Emission scenario (NZE) which would bring the global energy-related carbon dioxide emissions to net zero by 2050, which would limit the global temperature rise to 1.5 °C [3].

The energy transition has already started, as proved by the emergence of wind turbines, solar panels, or electrical cars all around us. However, green energies including solar, wind, hydraulic, or biomass currently only accounts for a small percentage of our energy mix meaning that the transition must be drastically accelerated. Among the keys, large scale solar and wind farms must be deployed to help the nuclear and hydroelectric energies which must be the foundations of our new energy system. Those low-emission energy sources must be coupled with storage solutions as large batteries or hydrogen power plants to deal with the energy intermittence and store the excess, in foresight of lower production periods. On the other hand, usage of high emission fossil fuels and the manufacturing of thermal engine cars among others must be drastically reduced.

Although essential, the wide development of renewable energies and storage systems raises concerns over the availability and sustainability of required raw materials. These green technologies do not consume fuels, but are much more material intensive. Figure 1 highlights the quantity of minerals contained in common power generation sources (kg/MW), together with the comparison between the thermal and electrical cars (kg/vehicle).

A typical Battery Electrical Vehicle (BEV) demands six times more minerals than a conventional one, while the production of wind energy requires nine times more minerals than a similar quantity produced with gas. Given the limited amount of those materials on the earth's crust, the geographical concentration of their reserves, the energy cost of their extraction, the human ethical issues, and the geopolitical tensions, the supplies of raw materials is one of the biggest challenge related to the energy transition.

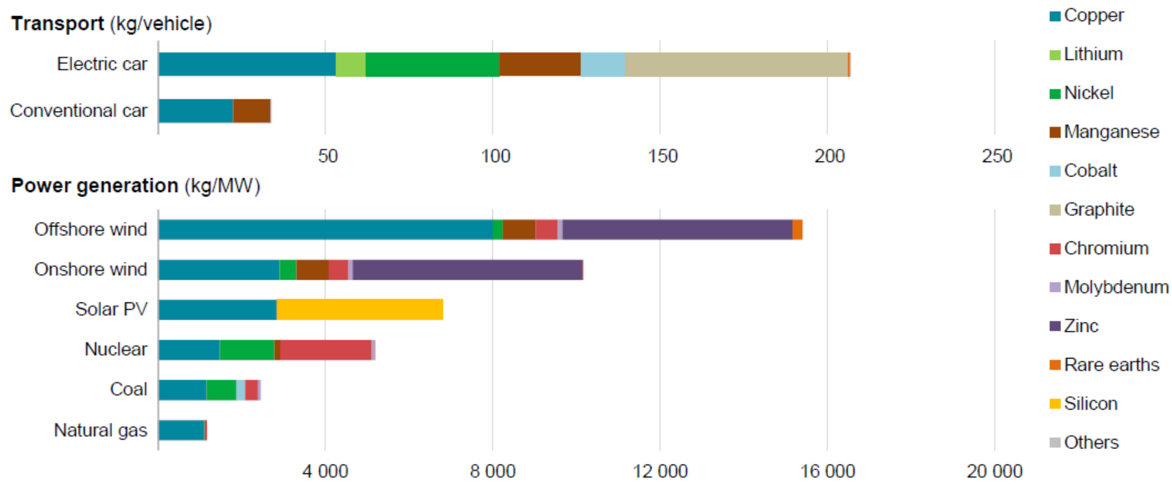

Figure 1: *Minerals used in essential technologies related to the energy transition. Battery electrical vehicles demand six times more minerals than conventional cars, while offshore wind energy consumes nine times more minerals than gas [4].*

This thesis aims to evaluate whether the quantity and availability of raw materials is sufficient to ensure a good energy transition based on the assumption that the NZE scenario will be followed. It only focuses on the solar and wind energy, together with the batteries and hydrogen as energy storage solution[1]. Raw materials are then classified into three categories based on their strategic importance in the energy transition, their availability, and the risk related to the supply chain either limited, moderate, or critical. Thanks to a technological overview of each selected industry, the expected market growth and future dominant technologies are assessed. Besides, the impact of recycling as solution to reduce the pressure on raw materials access is studied. This analysis relies on interviews of energy experts from Laborelec (expertise center of ENGIE group) and a literature review.

In this work, Chapter 1 gives an overview of the current energy market and its theoretical evolution to guarantee the NZE. Chapter 2 is dedicated to the presentation of the selected green technologies, as well as the recent advancements influencing the market. Chapter 3 discusses the risk related to the raw material supplies which could slow down the energy transition deployment and gives a level of impact. In addition, it describes some solutions helping to mitigate the risk of shortage and reduce the supply chains pressure.

[1] It has been chosen to only analyse those industries because they are expected to drastically increase in the coming years and have a significant importance in the energy transition. Besides they all have a large demand in minerals

Chapter 1

Energy market overview

This chapter aims to give an overview over the current energy market while investigating the sectors of end-consumption. It also presents the scenario to be followed to maintain the temperature rise under 1.5 °C.

1.1 Current energy mix

Figure 1.1 exhibits the worldwide primary energy consumption. In 2019, it climbed to 173 000 TWh of energy, what is comparable to more or less 226 times the annual consumption of Belgium. Since the beginning of the industrial period, the demand for energy has continuously increased, except during the exceptional COVID year. In the past few years, it has been approximately distributed into 80% of fuel energy and 20% of electricity [5].

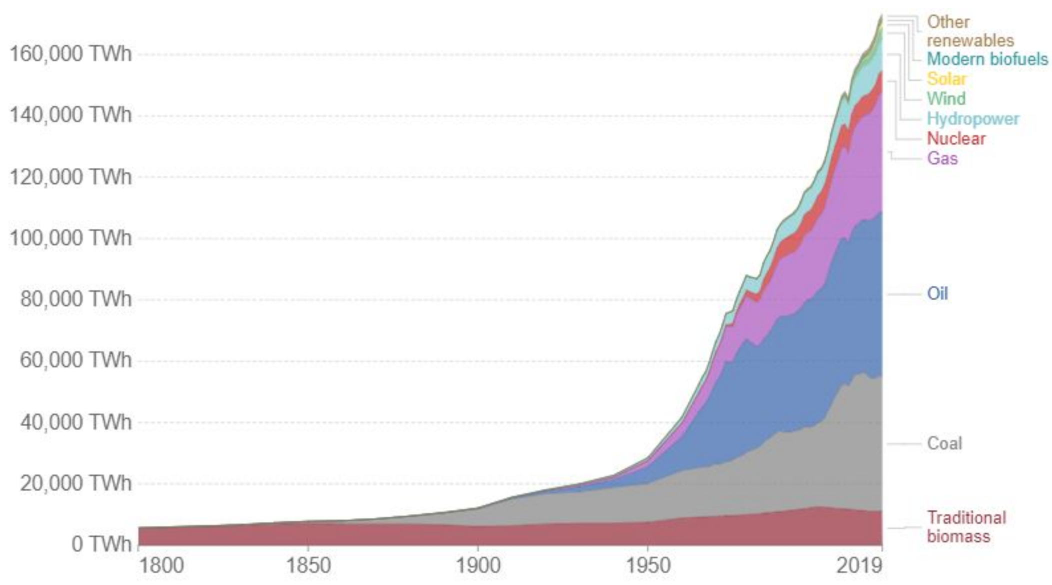

Figure 1.1: *Historical evolution of the worldwide primary energy consumption up to 2020 [6]. Since the industrial revolution, demand for energy has continuously climbed.*

Sources of energy can be classed in three categories depending on their CO_2 emissions, and their sustainability. Fossil fuels are the first category including energy arising from coal, gas, and oil, which are raw materials extracted directly from the ground. They are historically the conventional energy sources and are still accounting to respectively 27%, 25%, and 31% of the current energy mix as illustrated Figure 1.2. Although those sources are reliable in terms of energy production, fossil fuel resources are limited on earth and generate large quantity of carbon dioxide emission (going from 469 to 1001 gCO_2/kWh) when burned. In addition, recent tragic events in Ukraine prove the danger to rely on geographically concentrated raw materials.

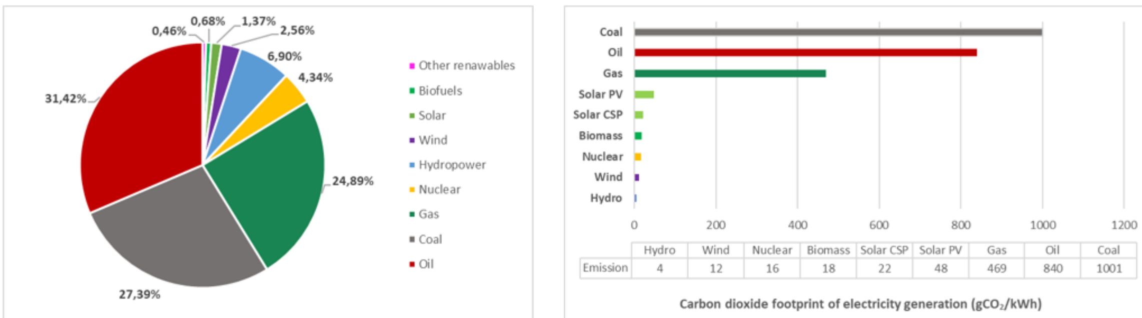

Figure 1.2: *Market shares (%) of the different energy sources in 2020 & ranking of carbon dioxide emissions (gCO_2/kWh) by energy sources. Data from [6][7]*

The nuclear energy which uses the radioactive fission of uranium to provide huge amount of energy represents the second energy source category. Numerous countries as France, China, or US operate nuclear power plants to produce cheap electricity. Despite the good reliability, the low carbon dioxide emission (16 gCO_2/kWh), and its relatively low cost, the nuclear energy is eternally debated due to the risk of accident and the management of the nuclear wastes. In 2020, nuclear energy accounted for 4% of the energy mix.

Renewable energies are the last category including among others the solar energy, the wind energy, the hydro energy, or the biomass. They are characterized by very low carbon dioxide emissions and are infinite resources. They account however for only 12% together, with the hydroelectric power being the main current contributor. Individually, wind and solar energy provided respectively 2.6% and 1.4% what is already much larger than the 0.06% and 0.65% produced in 2010. The main issue related to the renewable energies is their intermittence, meaning that the electricity production is unstable and depend on the environmental conditions.

Figure 1.3 illustrates the distribution of the energy consumption by sectors, as well as the percentage produced through renewable energies. Hence, the three main sectors of consumption are the heating and cooling (51%), the transports (32%), and the electricity generation (17%). Energy sources are however not all well adapted to the same final application. Transports are mainly fed by oil since it provides a high energy density, easily transportable in a tank. The current automotive market electrification is however opening the doors to a more sustainable way of displacement, at least if the electricity is produced with renewable technologies. Nonetheless, for long distance transports such as planes, trucks, or freights it seems more challenging due to the large amount of energy which need to be carried. Heating and cooling is also primarily based on fossil fuels, with natural gas and oil meeting the bulk demand [8]. Finally, the renewable energies account for approximately 28% of the electricity generation which has the potential to become relatively easily clean through the direct production of green energies.

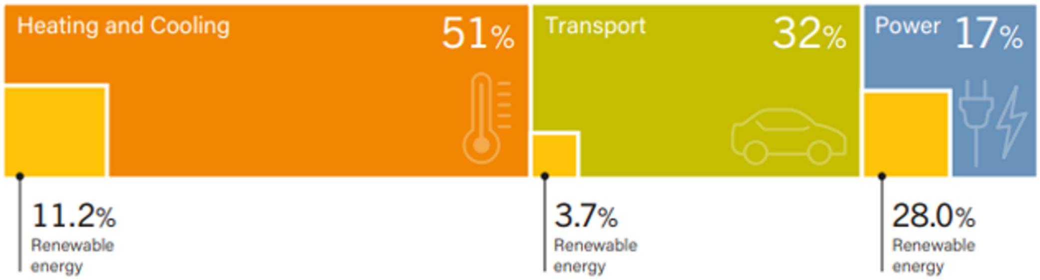

Figure 1.3: *Distribution of the energy consumption by sectors, including the share produced with renewable energies [9]. While the power generation can be relatively easily turned clean, it is more challenging for long way transport such as planes, trucks, and freights.*

1.2 Projection of future energy mix

Numerous scenarios and predictions are developed by experts to forecast the future energy market, but the outcomes can change a lot depending on the assumptions. Figure 1.4 exhibits the NZE scenario which is considered to be the reference as it would give us a chance of limiting the global temperature rise to 1.5 °C [1]. In this model, the energy market in 2050 is much more complex and diverse than today. Thanks to a better energy efficiency, the total energy supply is close to the level of 2010 despite a population increase of nearly 3 billion people and a global economy being three-times larger than in that period.

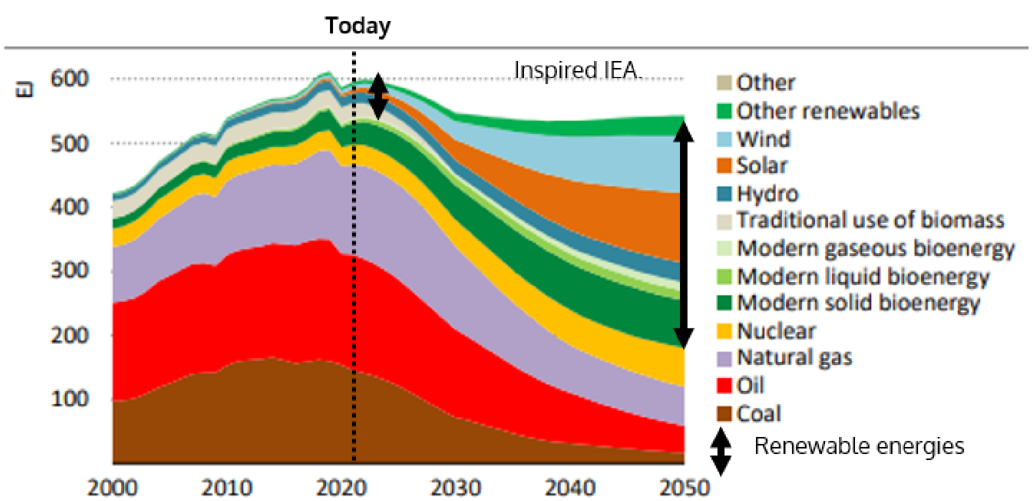

Figure 1.4: *Evolution of the energy market by sources to respect the NZE scenario developed by IEA [3]. It is expected to be much more complex and diverse than today*

[1]Net zero emission does not mean that there is no more emission, but they are compensated by the carbon absorption of forests and oceans

In 2050, fossil fuels energy represents only 20% of the total primary energy due to sectors as heavy industries or long way transports where alternatives are difficult to implement. On the other hand, there is a large renewable capacity deployment which more than triple up to 2030, and is even multiplied by nine to 2050. This is enabled thanks to the huge investments of advanced countries and the drastic reduction of their Levelized Cost Of Electricity (LCOE) [2] while this industry was mainly subsidiary driven up to now. Figure 1.5 shows the LCOE historical evolution and demonstrates that green energies became cost competitive to classical energies, what can be explained by the increased competition, the improved technologies and the reduction of the supply chain costs. While largely used in the past, this metrics lost in reliability because it does not integrate the costs related to the grid adaptation required with the renewable energies and the costs to store the energy excess coming from the production peaks of large solar and wind farms.

Figure 1.5: *Historical evolution of the unsubsidized Levelized Cost Of Electricity ($/MWh) for the main energy generation sources [10]. Renewable energies are now cost competitive.*

1.3 Energy storage capacity to deal with energy intermittence

This leads us to another pillar of the energy transition, the energy storage. While hydropower is currently the main source of storage, it goes out of the scope of this thesis, as the capacity should not drastically increase in the future. The continuous increase of renewable energies on the grid is really difficult to handle due to the large production variations depending on the environmental conditions. Figure 1.6 compares expected electricity supplies during winter and spring in a theoretical 100% renewable market in France. It shows that the instability on the grid is compensated by various storage technologies to balance the load and supply. In winter, synthetic gas and batteries allow meeting the demand during low wind period (4^{th}- 7^{th} February). The load is mainly increased during solar hours by charging the batteries and exporting energy to foreign countries. In the summer, batteries are the main source of flexibility. Besides, wind and solar energy are complementary energies, since the wind blows stronger in the winter in the European countries.

[2] The LCOE measures the average net present cost of electricity generation for a generator over its lifetime

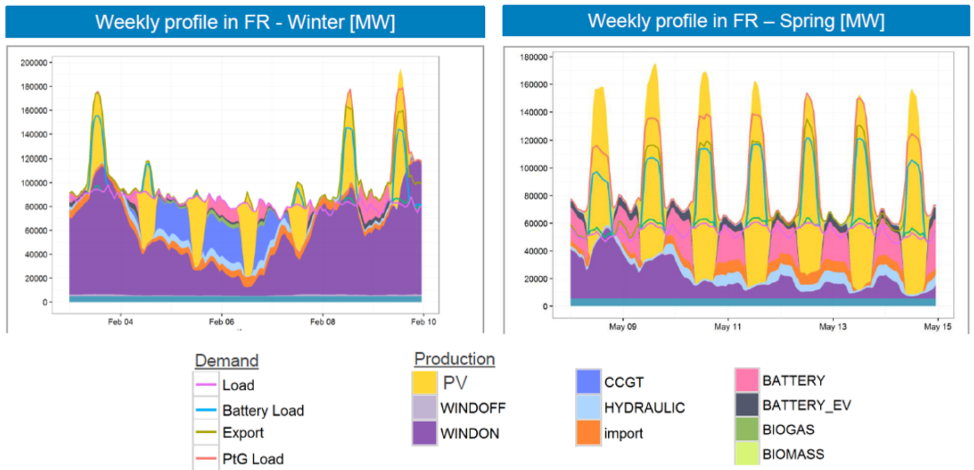

Figure 1.6: *Weekly energy profile in France for winter and spring season [11]. The optimal system uses batteries and synthetic gas to balance load and supply. CCGT = Combined Cycle Gas Turbine, WINDOFF/WINDON = wind offshore/onshore, PtG=Power To Gas*

In such system, 19% of the European electricity demand is supplied by batteries. This market can be split into individual-use batteries as in electric cars, or large scale batteries directly connected to the grid. Today, Germany is the leader in the large battery storage ranking with a total capacity of approximately 2000 MW thanks to huge investments dedicated to the energy transition [12, 13]. Far further, it is followed by UK having 1300 MW and France which owns 800 MW but plan to install 200 additional MW in 2022 [14, 15]. This market is expected to take off in the coming years to ensure the market electrification. The same trend is observed with the electrical car market, which is soaring in Europe, as shown in Figure 1.7.

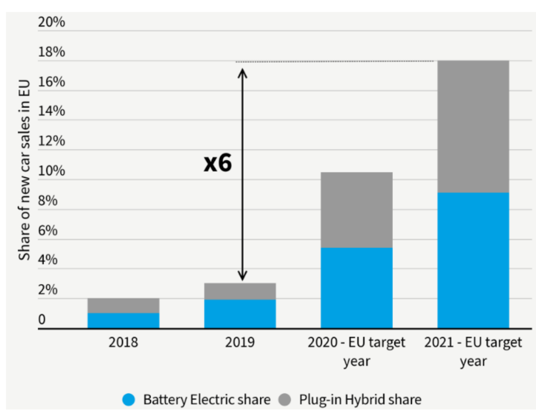

Figure 1.7: *Battery electric car sales evolution in European Union [16]. Driven by the EU objectives, the sales of BEV climbed to 9% of market share in 2021.*

This evolution should accelerate since recently the European Union launched a 20 billion euro package to stimulate the sales of clean vehicles and the development of charging stations with the objective to reach at least 30 million BEV on the road by the end of this decade [17]. Besides, the related technology is also evolving fast, as demonstrated by the development of the vehicle-to-grid project called SMATCH. In this technology, the battery of BEV is in direct interaction with the power grid, meaning that depending on the demand, it can either return electricity to the grid or throttling their charging rate [18].

As already explained, batteries are not adapted for all applications as long transports (trucks, freights, airplanes) and some heavy industries (metallurgy or chemistry) due to the low energy density. Besides, they only allow to store energy on short-term. Use of hydrogen as energy vector allows filling those gaps without generating undesired by-products. It enables to store large quantity of energy, while being light and taking small space. In addition, as all fuels, it offers the possibility to refuel in only a few minutes. Nevertheless, producing hydrogen requires a large amount of energy due to the low conversion efficiency. It is considered that the path from power to hydrogen and back to power has a round-trip efficiency between 18-46%, what is far behind technology as pumped-storage hydropower 70-85% [19]. Besides, to get green hydrogen the electrolysis process must be performed with low carbon emissions energies, while today it is produced at 95% from natural gas and coal.

Figure 1.8 describes the nomenclature as defined by the International RENewable Energy Agency (IRENA) attributing a colour to the hydrogen based on the energy sources used to produce it[3].

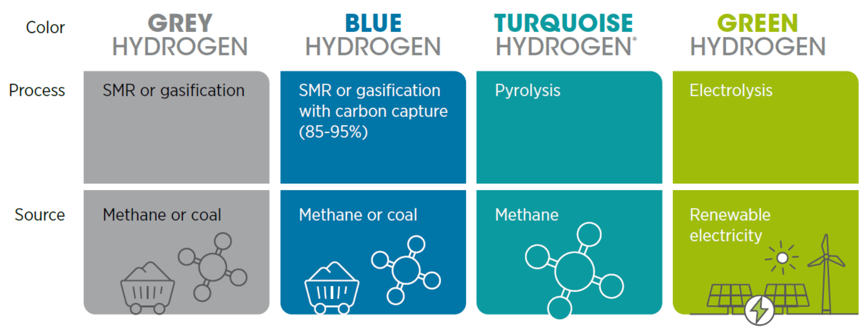

Figure 1.8: *Nomenclature attributing a colour to the hydrogen based on the energy sources used to produce it [20]. Currently, 95% of the volume comes from fossil fuels energy, while it must be produced with peak periods of low emission energies to be sustainable.*

- **Grey hydrogen**: it is produced with natural gas or methane using reformation and is therefore responsible for large CO_2 emissions. Such production way must be avoided to achieve the net-zero emissions objectives.
- **Blue hydrogen**: it is produced similarly to grey hydrogen with an additional system to capture the carbon emission, having a maximum theoretical efficiency around 85-95% which is though not yet reached. This is a good solution for industries requiring a continuous flow of hydrogen, as steel industry. It can be seen as a short term solution to produce hydrogen with low green house gases emissions, reduce the pressure on renewable energies, and facilitate the transition towards this new energy carrier.
- **Turquoise hydrogen**: it is produced through a pyrolysis process converting natural gas as feedstock without any CO_2 production. Wastes are under carbon black form and can be easily stored in comparison to gaseous CO_2.
- **Green hydrogen**: it is the only viable source of production for a sustainable energy transition. It transforms the excess of electricity produced by low emissions sources during the peak periods and converts it into hydrogen through water electrolysis.

[3] Other classifications can also be found in the literature including pink (nuclear), yellow (solar), black (coal), brown (oil) and white (natural) colours

Chapter 2

Green emerging technologies overview

Now that the current energy market has been briefly presented, this chapter enters more into the details of the existing technologies with a strong focus on the expected industry growth as it is a determinant factor to analyse the material's criticality.

2.1 Solar energy state of the art

Figure 2.1 shows the historical evolution of the cumulative PhotoVoltaic (PV) capacity, which has exponentially grown in all regions of the world during the last decade.

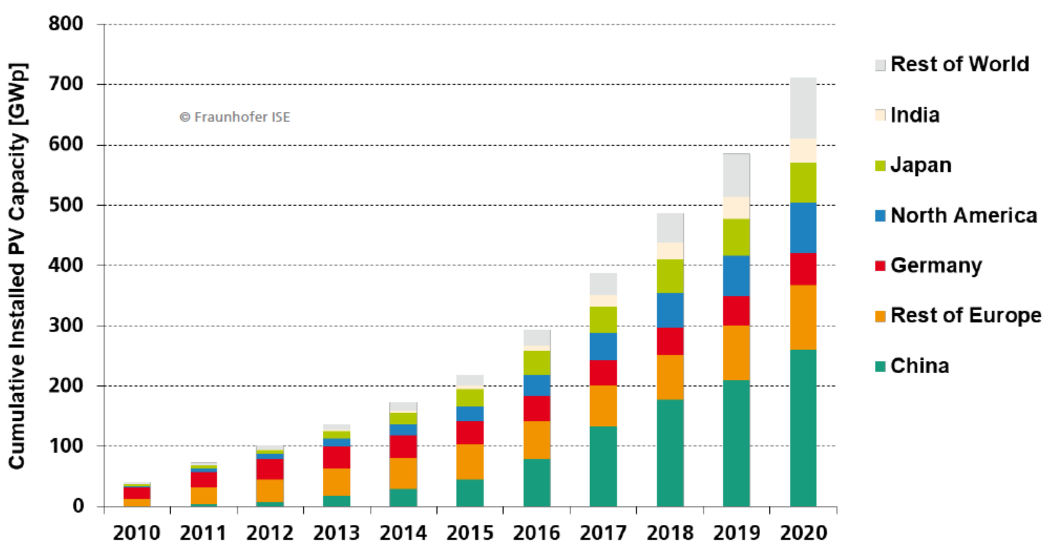

Figure 2.1: *Historical evolution of the cumulative photovoltaic panels capacity[21]. The solar capacity has exponentially grown in all the region of the world during the last decade.*

Very recently (March 2022), the world has installed enough solar capacity to generate 1 TW of electricity directly from the sun thanks to the development of huge solar farms [22]. This exponential growth tendency is expected to continue, with yearly additional capacity of at least 300 GW from 2022 [23]. In addition, Figure 2.2 describes the required capacity evolution to keep the NZE scenario on tracks. It would imply an average capacity addition of 600 GW between 2030-2050 to reach a total value of 15 TW in 2050.

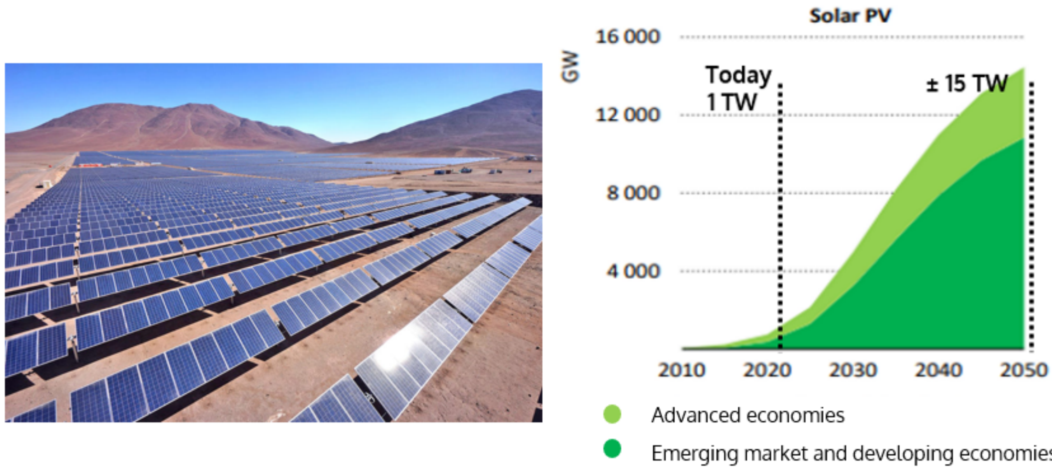

Figure 2.2: *200 MW solar farm built in Chile (left). Cumulative solar capacity as described in the NZE scenario (right). It must continuously rise to reach 15 TW in 2050.*

The main factors driving this continuous expansion are both the drastic price decrease of the cells and the constant race towards a better efficiency. Today, the cells market is widely dominated by the silicon wafer-based technology (either monocrystalline or polycrystalline) which represents around 95% of the market share. This can be attributed to the affordability of this technology resulting from economy of scale of its main ingredient, silicon, generated in mass in the booming semiconductor industry. Figure 2.3 illustrates this large price decrease all along the years for both the modules and the Balance Of System (BOS) encompassing all the components which are not directly part of the panels.

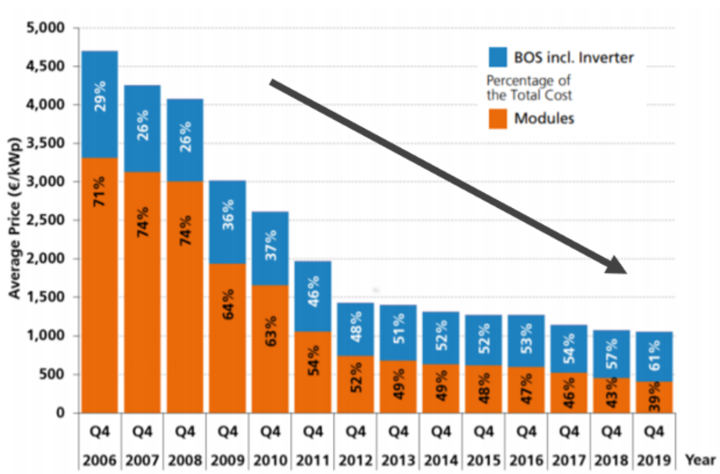

Figure 2.3: *Average price of solar energy (€/kW) including both the modules and the balance of system contribution [21]. The average price has drastically decreased during the past few years, mainly driven by the economy of scale made on the silicon wafer.*

It then became particularly difficult for other technologies to compete, despite the fact that they could theoretically reach a better efficiency. Thin film technology gathers the second generation of solar cells and includes amorphous silicon (a-Si) having an easy fabrication process but a low efficiency, Cadmium Telluride (CdTe) absorbing light of smaller wavelengths, but the presence of toxic cadmium is an issue, III-V Galium Arsenide (GaAs) mainly used in aerospace due to its very good efficiency but at high price or Copper Indium Gallium Selenide (CIGS) having good resilience to heat [24]. Other technologies as nanocrystal based solar cell, organic solar cell[1], or perovskite technologies are still under development [25]. Although they should not be commercialized before 2026, perovskite cells are promise to a bright future due to the high achievable efficiency, in particular when use in tandem with Si [26].

Together with the price, the efficiency improvement is the second factor driving the exceptional solar growth[2]. Figure 2.4 gives the efficiency at lab-scale and industrial scale for typical solar technologies. It can be seen that the efficiency of Si technology is stable for the past few years, while the efficiency of perovskite cells has impressively risen and is expected to be further improved in the coming years.

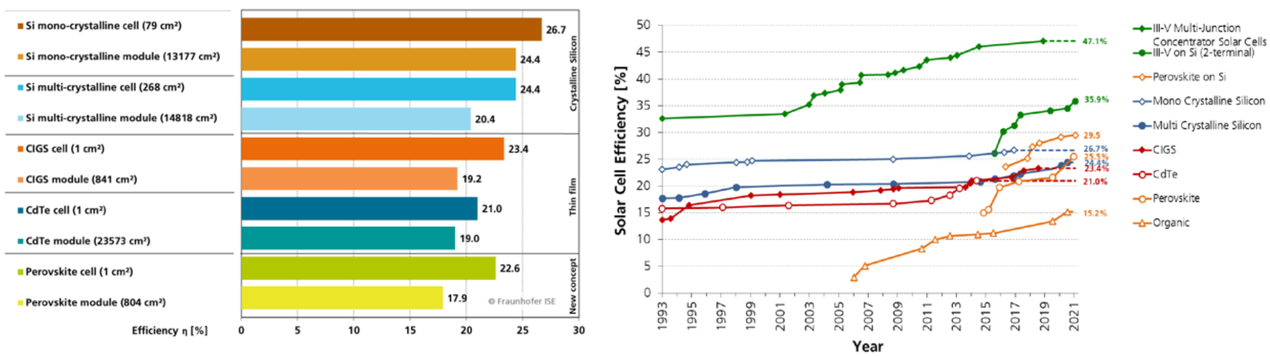

Figure 2.4: *Maximal lab-scale and industrial scale efficiency for various solar cell technologies (left), together with the historical evolution (right) [21].*

This positive market evolution made the installation of solar panels on various locations economically profitable. Figure 2.5 illustrates the fact that recently solar panels have started to be placed on windows, water, or even fields taking part to the development of the solar industry.

- **vehicle integrated PV** consists of solar cells integrated into vehicles and connected to electric loads or vehicle batteries.
- **floating PV** consists of solar cells mounted on a structure that floats on a body of water.
- **agri PV** consists of partially transparent solar panels placed on crops. In summer, it protects crops during a very sunny day while producing electricity.
- **building integrated PV** is used to replace conventional building materials in part of the building envelope such as roofs, skylights, or facades.
- **infrastructure integrated PV** It refers to embedding solar power in infrastructure such as noise barriers, carports, or streetlights.

[1]Those PV modules are light and flexible what allows installing them in various locations
[2]When the price is a function of the energy capacity, it already takes the efficiency improvement into account

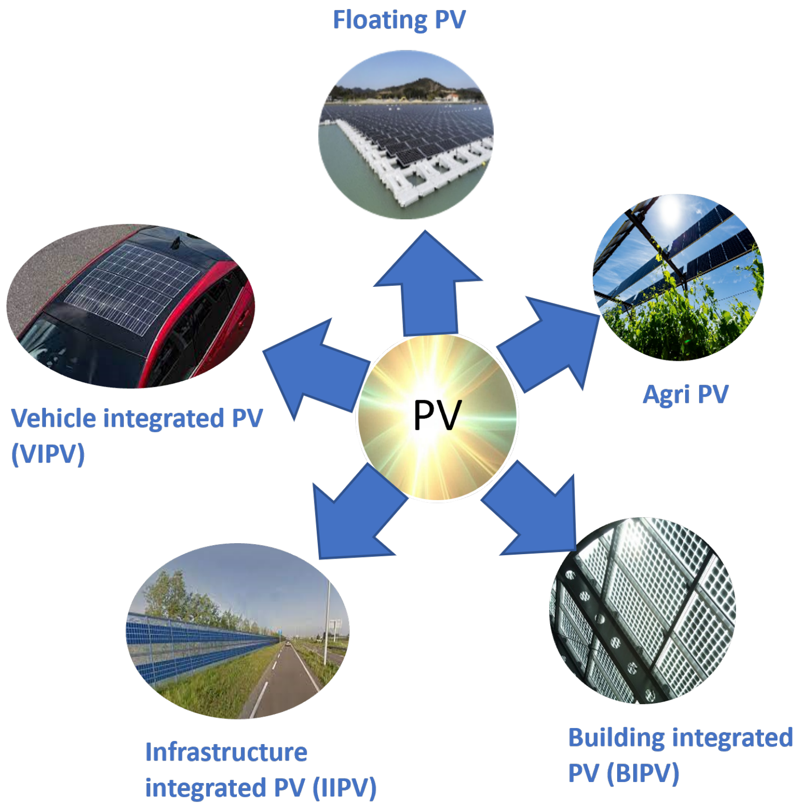

Figure 2.5: *Installation of solar panels everywhere: on windows, water, infrastructure or even fields. It has been made possible thanks to the improved profitability.*

2.2 Wind energy state of the art

Similarly to the sun, the wind energy must be a pillar of the NZE scenario with both contribution of onshore and offshore turbines.

Figure 2.6 shows the worldwide evolution of wind capacity which has been nearly multiplied by four during the last decade. In 2021, around 94 GW of wind turbines were commissioned, bringing the cumulative capacity to 847 GW of power. Contribution mainly came from onshore projects 87 GW, while offshore accounted for 7 GW [27].

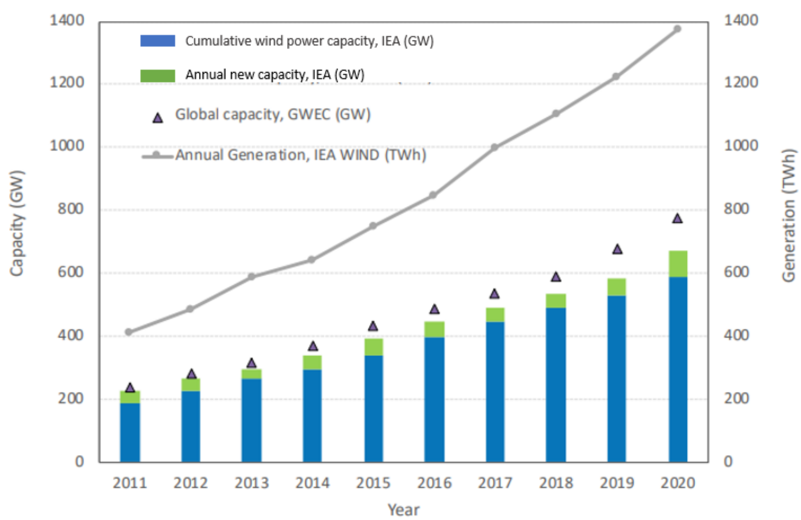

Figure 2.6: *Wind turbines historical capacity evolution [28]. During the last decade, the total cumulative capacity has nearly been multiplied by four, with the main contribution coming from onshore projects.*

This evolution has mainly been allowed by the development of large wind farms and the technological development of the turbines. Figure 2.7 describes the required capacity evolution to keep the NZE scenario on tracks.

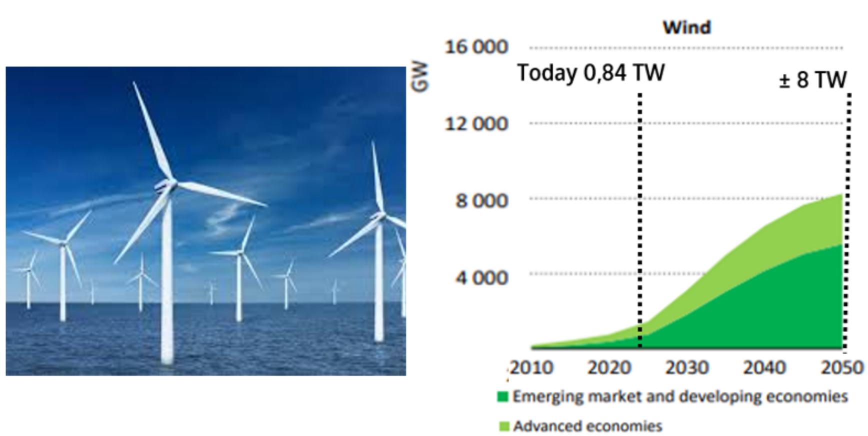

Figure 2.7: *Wind farm in North Sea (left). Cumulative wind capacity as described in the NZE scenario (right). It must continuously rise to reach approximately 8 TW in 2050 [3]*

Although smoother than for the solar energy, the wind capacity should continue to drastically increase to reach a total of 8 TW up to 2050 with annual capacity addition close to 160 GW in 2040. While today the dominant markets are located in China, Europe, and USA, the wind industry is expected to expand to new markets such as Latin America, Middle East, and Southeast Asia.

This growth will be partially driven by the offshore industry, which should be a soaring market in the future, despite the higher manufacturing and maintenance costs compared to the onshore industry. This is explained by the faster and more constant winds coming from the sea and the possibility to get larger turbines, optimizing the production, as illustrated in Figure 2.8. Currently, the average rotor measures around 164 m, the average turbine height reaches 125 m, while the hub height is situated at 90 m leading to capacity factors around 40% [29]. Those dimensions are still expected to grow leading to a better capacity output, which has already been multiplied by 7.5 during the last two decades and an improved capacity factor. Turbine prototype of 20 MW are currently under design phase and should arrive on the market in the coming years. At a slower pace, the onshore turbines size also increased, reaching capacity of 5 MW in 2021.

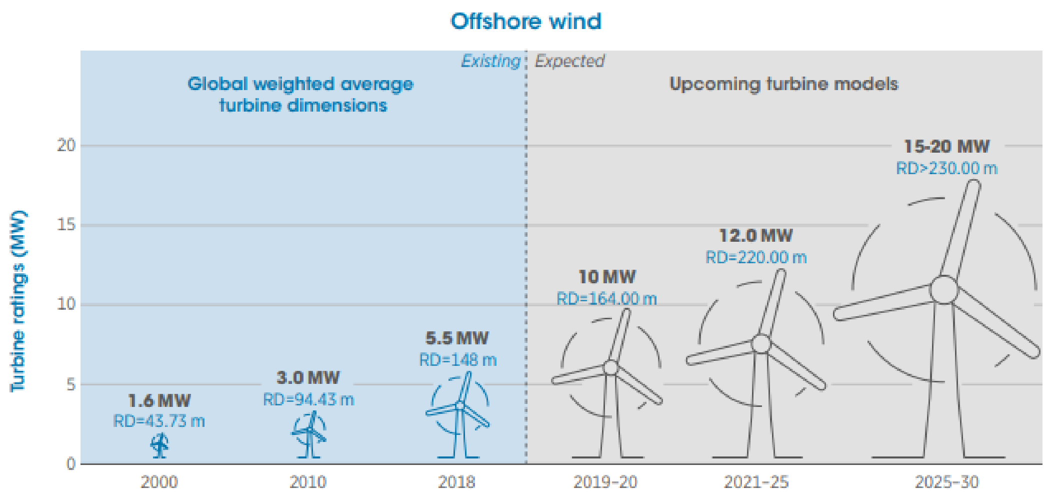

Figure 2.8: *Evolution of wind turbine dimensions all along the years, together with the resulting power output [30]. Larger rotor diameter as well as increased turbine height, and hub height lead to bigger output capacity which should reach up to 20 MW in the coming years.*

Resulting from the ongoing innovation, the technical development, the economy of scale, and the production learning, the onshore wind energy is already cost competitive compared to the fossil fuels. Regarding the offshore energy, it has already widely dropped in price and start to be competitive in certain countries as Germany. Table 2.9 shows that the cost should continue to decline in the coming years, allowing a faster deployment.

	On-shore			Off-shore		
	2018	2030	2050	2018	2030	2050
Installation cost $/kW	1497	800-1350	650-1000	4350	1700-3200	1400-2800
LCOE $/kWh	0,06	0,03-0,05	0,02-0,03	0,127	0,05-0,09	0,03-0,07

Figure 2.9: *Installation costs ($/kW) and LCOE ($/kWh) for wind turbines onshore and offshore together with the predictions for 2030 and 2050.* Data from [27]

Wind turbines can be grouped in four technologies having specific characteristics. The Gearbox Double-Fed Induction Generator (GB-DFIG) is a popular system containing a gearbox and using a power electronic interface to control the rotor currents. It allows adapting the speed, maximizing the energy produced in variable winds [31]. Gearbox Permanent-Magnet Synchronous Generator (GB-PMSG) is a technology in which the excitation is created by a permanent magnet instead of a coil. The term synchronous refers to the fact that the rotor and magnetic field rotate with the same speed. Direct Drive Permanent Magnet Synchronous Generator (DD-PMSG) uses a permanent magnet. It gives a good efficiency, while the absence of gearbox allows reducing the maintenance cost so that it is well adapted for the offshore industry. This type of generator is however more expensive. Finally, Direct-Drive Electrically Excited Synchronous Generator (DD-EESG) is also a technology adapted for offshore wind turbines because turning without a gearbox. Compared to the permanent magnet generators, it works with a coil, bringing a better controlability but a lower efficiency [32].

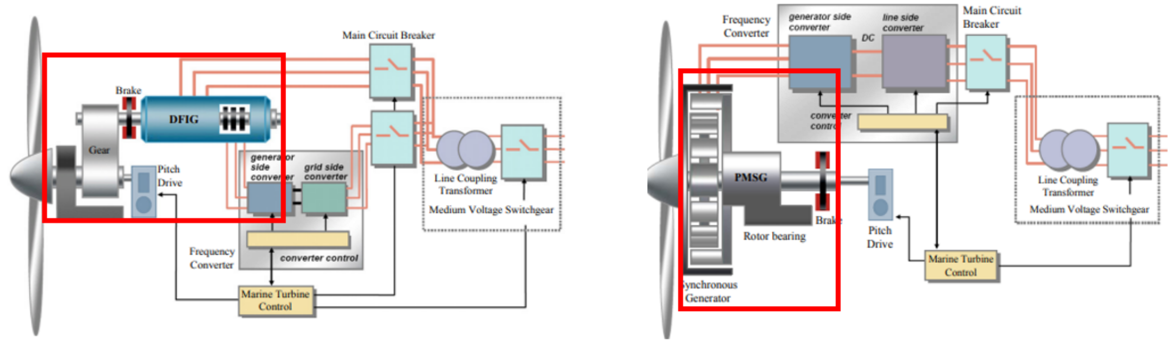

Figure 2.10: *Design of DFIG and PMSG generator technologies [33]. Despite the higher initial cost, the absence of gearbox makes the PMSG an ideal candidate for the offshore industry due to the reduce maintenance cost.*

Figure 2.10 shows the design of the leader technologies, while Figure 2.11 gives their market shares. Currently, the onshore industry is dominated at 70% by the GB-DFIG having a good efficiency while being relatively cheap to install. On the other hand, DD-PMSG have doubled their market shares over the last decade. In the offshore industry, this technology even became the dominant player with more than 60% of the market as it requires taller and larger turbines while keeping them light and without much maintenance.

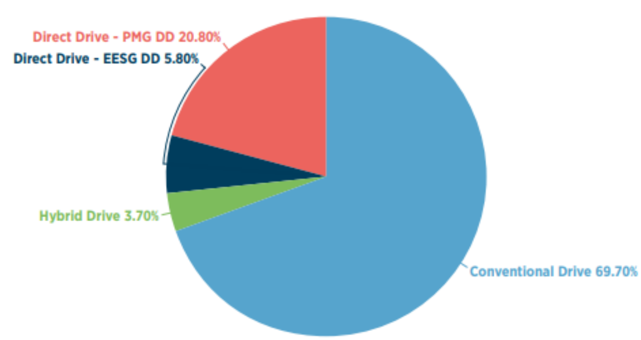

Figure 2.11: *Wind turbines market shares by technologies. The GB-DFIG is the leading onshore technology, while the DD-PMSG mainly driven by the offshore industry development [34]*

One of the main challenge faced by the emergent offshore industry is the limitation of available space in optimal wind conditions, as foundations can be placed at maximum 60 m of water depth. Floating wind turbines is however an innovative technology unlocking new areas of deep water situated close to big city centers, notably in Japan and the US, where the energy demand is high [30]. In addition, this technology is more environment respective as it reduces the huge invasive movements in the seabed during the installation. The first floating wind turbine project started in 2017 in Scotland and shows positive results. Figure 2.12 illustrates the different designs under development for this technology, which is expected to largely penetrate the market.

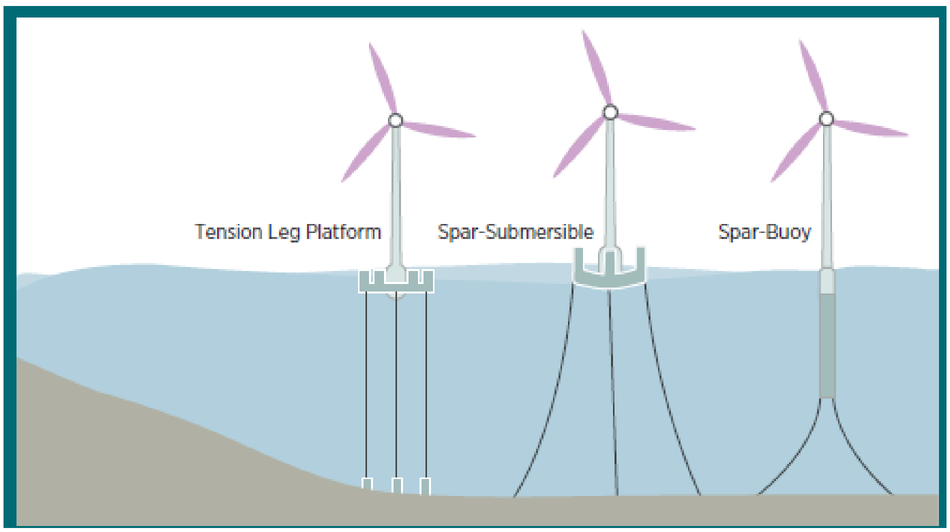

Figure 2.12: *Floating wind turbines designs [30]. This innovative technology allows unlocking new sea locations with ideal wind conditions but where the water depth was previously a limiting factor to install turbines.*

2.3 Batteries for electrical vehicles and stationary storage

A battery is a system able to store chemical energy, and return it into electrical energy. Figure 2.13 describes the working principle exhibiting both the charge and discharge phase. During the charging time, electrons coming from the charger flow from the cathode to the anode through the external circuit. To compensate this flux of charges, positive ions diffuse in the same direction through the electrolyte and accumulate at the anode, creating a chemical potential. In discharging configuration, the electrons and ions take the opposite direction to create a current alimenting an electrical device.

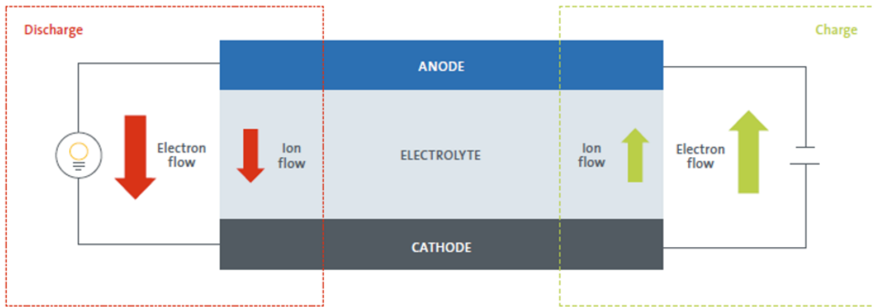

Figure 2.13: *Working principle of batteries, allowing to store chemical energy and return it into electrical energy after having accumulated charges during the charging time [35].*

Figure 2.14 shows the large panel of existing battery types having each various chemistry resulting in specific properties. Among all, the main categories are lithium ions and lead batteries which are mature and commercialized technologies, while the Redox Flow and Solid state batteries are expected to enter the market in the coming years.

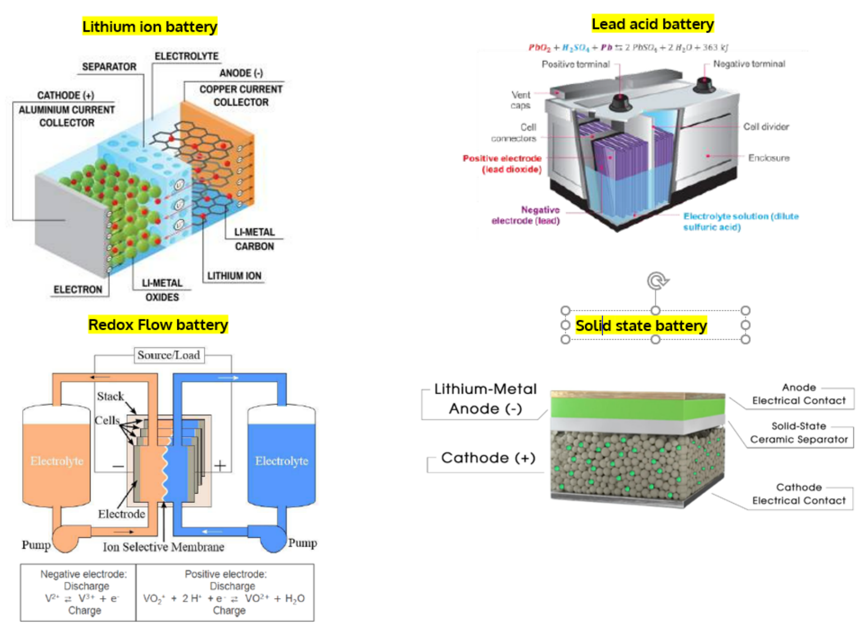

Figure 2.14: *The four main batteries technologies: lithium-ion, lead acid, redox flow, and solid state [36, 37]. They have all a different chemistry, leading to specific properties. While lithium and lead acid are relatively mature technologies, redox flow and solid state are expected to be the future challengers of lithium.*

Lithium ions battery is the dominant technology on the market. Its fundamental advantage over competitors like lead acid and nickel cadmium is its much higher energy density allowing to store a large quantity of energy (90-260 Wh/kg) in relatively light packs. It makes it the ideal candidate for all the portative applications justifying its tremendous dominance in the BEV market. In addition, its long cycle life (1000-10000 cycles) and its high round trip efficiency are non-negligible positive points. However, such energy quantity stored in a highly inflammable liquid raises safety concerns, and many examples of explosive accidents were reported [38]. Other limitations of this technology are its high cost, its small lifetime (less than 10 years) and its irreversible degradation when subjected to temperatures higher than 70°C.

Lead acid battery is a more declining technology, which was mainly used for its good reliability and its historical low cost (150-300 €/kWh). This technology has also a simple manufacturing process, is easily recyclable, and offers a low self-discharge. Nonetheless, its low energy density (35-40 Wh/kg), its small life cycle (500-2000) and the dangers related to both the overheating and the toxic components make this technology difficult to compete with the emerging ones.

Redox flow battery is a technology relying on porous electrodes instead of solid or immobilized electrodes, which are more conventional. In this system, active materials are flown in the form of positive and negative liquid solutions containing redox-active species. Those solutions are stored in two tanks, each related to one electrode [35]. Among the benefits, one can cite the low sensitivity to temperature, the possibility to scale the energy and the power independently, the high life cycle (20000 cycles), and the expectancy to get a very good calendar life for vanadium redox flow[3]. Although this technology is very promising for large scale energy storage, the low power and energy density (10-50 Wh/kg) make necessary to lead further research and development before seeing the the redox flow flooding the market. Besides, the needs for pumps, valves, and sensors maintenance make this technology expensive, while there is always a risk of leakage.

Solid state battery relies on the same technology than lithium ions batteries, except that the electrolyte is a polymer or a ceramic under a solid state, instead of a liquid. The absence of very flammable solvent drastically reduces the risk of accident and the undesired reactions with the lithium salt resulting in capacity fading and ageing [39]. It also brings the outlooks to achieve higher energy density, hence lithium metal solid state batteries of 320 Wh/kg have already been produced, while theoretical maximum potential could reach 480 Wh/kg [40]. This would rise the energy volumetric density by 70% compared to current lithium ions technology, leading to important weight and cost reduction making it the ideal candidate for the BEV industry. Other benefits arising from this technology are the possibility to get various cells size and shape and the avoidance of internal short-circuits due to the reduced lithium dendrites growth in the solid electrolyte. The greatest challenges are the development of electrolytes with sufficient ionic conductivity, the high self-discharge, but overall the production scaling-up to make it commercially viable what is not yet the case.

Many other technologies exist such as: cadmium nickel, lithium-oxygen, lithium-sulfur, sodium-ion, zinc-air, aluminium-ion, aluminium-air or potassium-ion. Although, redox flow and solid state batteries are expected to be the main challengers of lithium-ion in the coming years, progresses in those technologies could lead to different industry landscape [41].

[3]Calendar life is the time for which a battery can be stored, as inactive or with minimal use, such that its capacity remains above 80% of its initial capacity

Historically, batteries were mainly dedicated to electronics applications accounting for more than 90% of the market shares in 2013, however, requirements from the energy transition redesigned the market. Nowadays, demand for electrical vehicles became the biggest batteries consumer, representing around 65% of the final uses in 2019. Beyond that, the rising of small and large scale stationary storage batteries to accommodate the higher share of intermittent renewable sources in the energy mix is pushing up the demand.

Figure 2.15 shows the past, the current, and the future demand for batteries across key applications. In the NZE scenario, the electronics consumption should moderately increase, while the huge rising should come from the adoption of electrical mobility and the development of stationary batteries. In 2020, the BEV market climbed by 40% to account for only 4% of the automotive market, while a target objective of 40% is stated for 2040. Regarding the stationary storage, the total capacity connected to the electricity network was 15.5 GW, but need to 25-fold increase between 2020 and 2040.

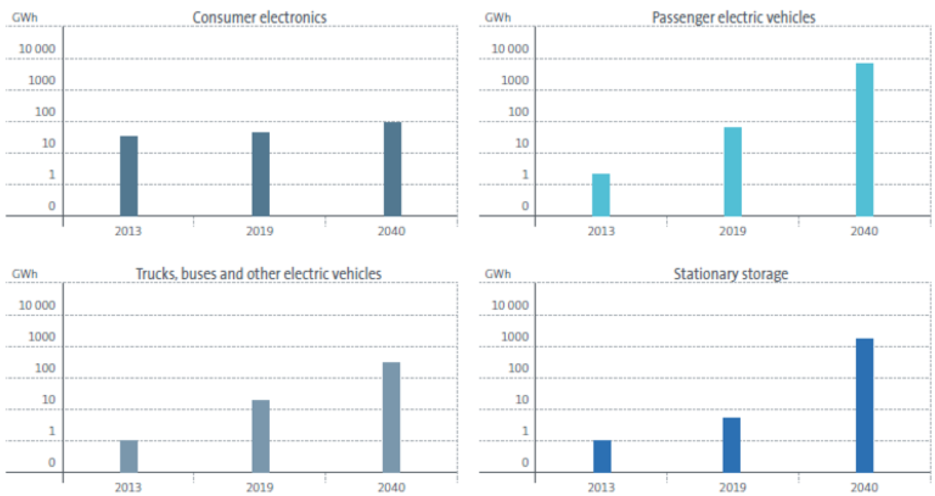

Figure 2.15: *Evolution of batteries final-uses: electronics, electric vehicles, trucks and buses, and stationary storage [35]. Historically, the main demand of battery was attributed to electronics but stationary storage and electric mobility are expected to soar in the coming years.*

The rapid cost reduction will continue to play an essential role in the large deployment of batteries. Last decade, the average cost of lithium ion batteries has been decreased by 90%, falling from around 1370\$/kWh to 137\$/kWh. Such decline has been made possible by the significant research and development investments following the penetration of BEV in the automotive market. Costs are moreover expected to further decrease below 100 \$/kWh by mid-2020s what is considered as a milestone to establish the cost parity between electrical and thermal engine. This tendency has also been observable for the stationary storage were the price was cut by two-thirds during the same period [42]. Efforts are still on the way, for example Tesla through the development of gigafactories has slashed the costs thanks to the economy of scale [43]. Today, possible additional savings could arise from the optimization of cells energy density, the enhancing of the pack assembly efficiency, and the reduction of the manufacturing costs [44].

2.4 Hydrogen as energy vector

Back in 1800, English scientists William Nicholson and Sir Anthony Carlisle discovered that applying an electrical current to water could generate almost pure hydrogen and oxygen. Few decades later the first hydrogen fuel cell was developed, able to recombine hydrogen and oxygen to produce electricity, while generating water as by product and a small amount of heat. During a long time, the generation of hydrogen only served for chemical industries as ammonia, polymers and resins or refining industry as hydrocracking and hydrotreating, or in general industry as iron, steel, glass, semiconductors [45]. Following the industrial growth, its historical demand exhibited Figure 2.16 has continuously increased for decades. However, today most of the people know the hydrogen as having a significant importance in the energy transition.

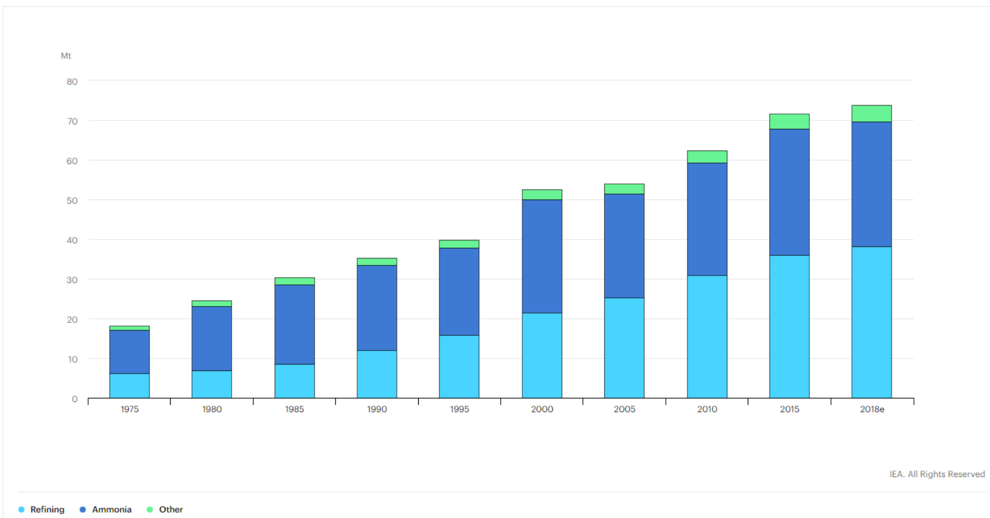

Figure 2.16: *Historical evolution of hydrogen demand [46]. The continuous increase has mainly been driven by the development of chemical, refining, and materials production industries.*

As previously explained, hydrogen can be produced by different processes depending on the initial energy source. It can either be gasification or Steam Methane Reforming (SMR) from methane or coal, pyrolysis from methane, or electrolysis from electricity. Figure 2.17 exhibits the 2019 global production market by energy sources.
It highlights than more than 95% of hydrogen was produced from fossil fuels. All of those processes are also very energy intensive so that they are responsible for large production of CO_2 emissions. It then becomes essential to start producing only green hydrogen from renewable electricity.

More and more projects are currently developed to install electrolysers next to solar and wind farms to transform the energy excess during peak of production into hydrogen. Figure 2.18 shows that this hydrogen can subsequently be transported, transferred in refuelling station, or stored, to feed end-use applications. Currently, the development of infrastructures to refuel cars and trucks would however require huge investments and incentive policies. It is also complicated to transport it by road or ship due to the need of cryogenic liquid tanker. Nevertheless, hydrogen flows three times faster in pipelines than methane and could be a relatively cost effective option for long distance transport, opening the possibility to import renewable energies from locations having better conditions of production. It would tough require huge

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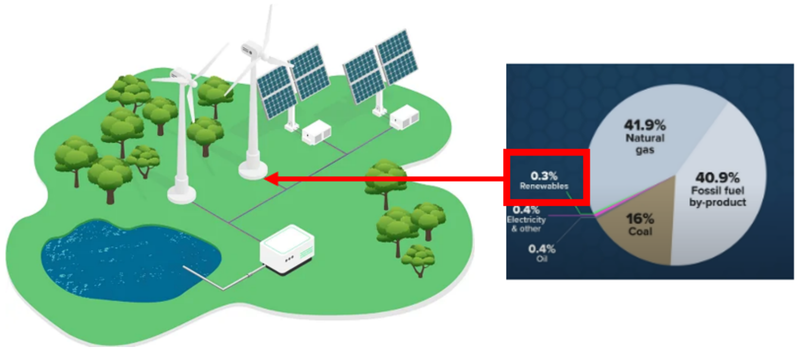

Figure 2.17: *Worldwide H_2 production by energy type and zoom over the production of hydrogen from renewable energies [47]. The excess of energy coming from the renewable sources if converted into hydrogen thanks to an electrolyser and store in a tank for later reuse.*

upgrades of pipelines system to make it compatible with hydrogen.

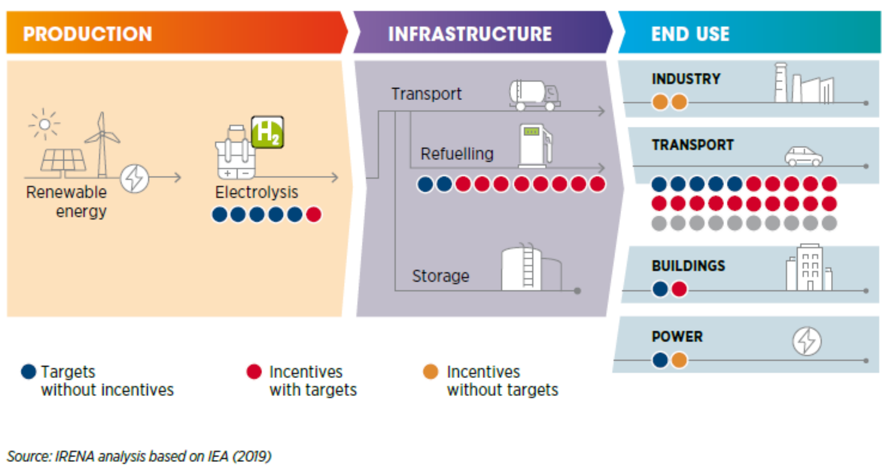

Figure 2.18: *Scheme of end-uses and required infrastructures following the production of hydrogen with related incentives needed [20]*

Storing large quantities of hydrogen is also one of the challenges faced by this industry despite the numerous possibilities. Conclusions drawn by a Bloomberg study highlighted that the current best way of storing hydrogen are the salt caverns which can contain the hydrogen fuel under gaseous state. It allows to store large volumes during long periods while being a cheap solution with a Levelized Cost Of Storage (LCOS) of 0.23$/kg. Such caverns are however geographically limited. Pressurized containers are another viable option as they can be installed everywhere without limitation. Besides, they are the cheapest alternative with a LCOS of 0.17$/kg but can only contain a restricted volume. Hydrogen can also be stored in other gaseous states (depleted gas fields, rock caverns), liquid state (liquid hydrogen, ammonia, organic liquid), or solid state (metal hydrides). Although interesting, those solutions are often more expensive than the hydrogen production what is a limitation for industrial development [48].

Chapter 3

Raw materials criticality in energy transition technologies

The rapid development of all those technologies demanding a lot of raw materials raises concerns regarding the availability of materials to ensure a reliable supply chain. This chapter aims at analysing the situation based on the expected industries growth.

3.1 Solar panels materials analysis

The large development of solar farms containing million of modules, inverters, trackers, or mounting structures leads to the consumption of a huge amount of materials. Figure 3.1 shows the expected market shares evolution of the PV cells types. The technologies based on silicon wafer are likely to stay the dominant market players thanks to the relatively good efficiency at low price. In addition, recent breakthroughs also predicted a promising future to the perovskite technology which is also mainly used in tandem with silicon (perovskites/c-Si). This analysis then assumes that the silicon cells stay dominant in this industry.

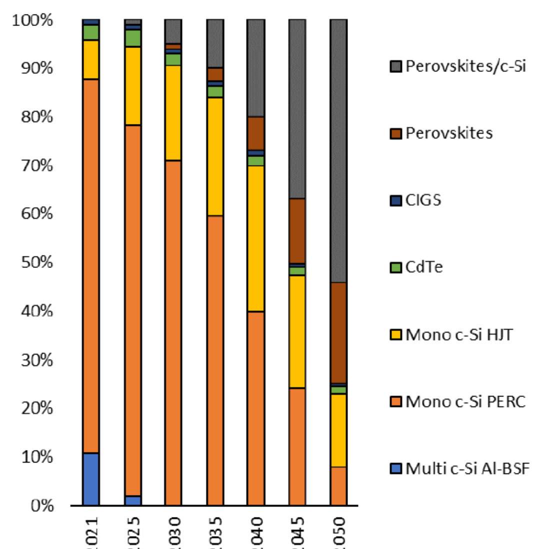

Figure 3.1: *Evolution of the PV technology market share [21]. The silicon based technologies are expected to stay the dominant market players.*

Figure 3.2 exhibits the typical structure of silicon solar panels installed at industrial scale. The silicon (Si) layer is the core of the cell and allows the creation of an electrical current resulting from a photon excitation. This wafer is placed between two encapsulant polymer layers protecting the fragile cells against environmental stresses, prolonged periods of high temperature, humidity, and UV radiations. On top of it, a glass layer inserted into an aluminium (Al) frame allows to prevent the chipping and other damages. The junction box houses all the electric bits, containing then some copper (Cu), while the back sheet provides the internal circuit isolation. Presence of silver (Ag) and aluminium pastes applied during the metallization process are vital since they provide the necessary conductive contacts on the frontside and backside respectively. Finally, antimony (Sb) reduces the UV long term impact on the glass, lead (Pb) and tin (Sn) are part of the soldering paste and ribbon coating while zinc (Zn) serves as galvanized steel in mounting structure.

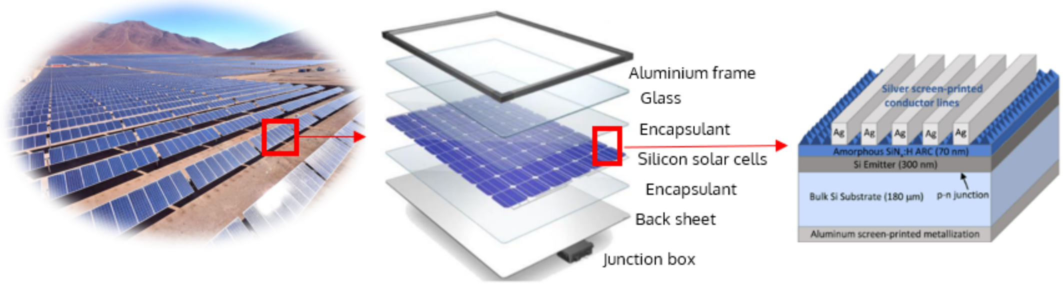

Figure 3.2: *From left to right: solar farms, solar module, and silicon wafer [49, 50]*

Figure 3.3 illustrates the weighted and the value based composition of a typical c-Si cell. It shows that glass, aluminium, and polymers have the larger material intensity. In term of value, crystalline silicon, silver, and glass are the most valuable materials. In particular, silver accounts for less than 0.1% of the panel mass while it costs up to 23% of the price. It should be noticed that this composition does not take into account the steel and concrete contained in the panel structure.

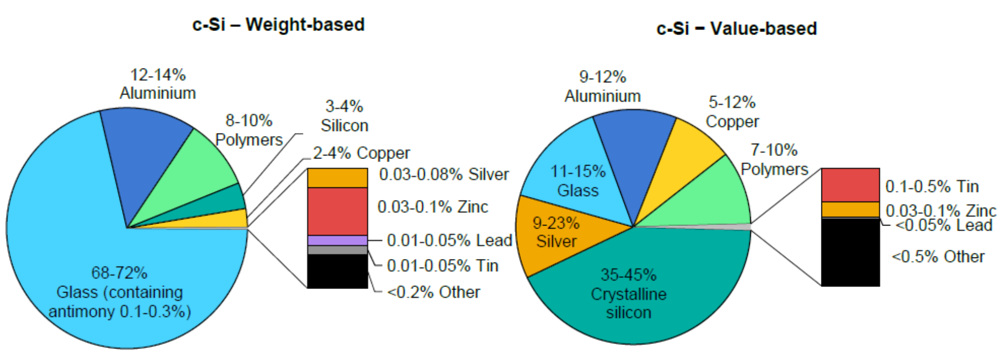

Figure 3.3: *Typical c-Si cell composition [51]. Top three in term of mass includes glass, aluminium, and polymer materials while the value ranking is led by the crystalline silicon, silver, and glass.*

Some raw materials contained in PV are scare resources since they are limited on earth's crust and their extraction is concentrated in certain areas of the globe. Their demand could therefore be drastically impacted by the rapid solar capacity growth or the geopolitical tensions. Figure 3.4 describes the annual production distribution for some strategic minerals of the PV supply chain, together with the larger existing solar farms of the world. It can be seen that silicon and aluminium extraction is widely concentrated in China, as silver in Mexico and copper in Chile. Besides, an additional risk arises when considering the entire value chain because China exceeds 80% of the production capacity in all the key manufacturing steps. This is even set to rise to more than 95% for polysillicon and wafers production in the coming years. Today, one out of every seven panels produced worldwide is manufactured by a single facility in China. Such level of concentration represents a considerable vulnerability for the entire industry which might slow down the energy transition.

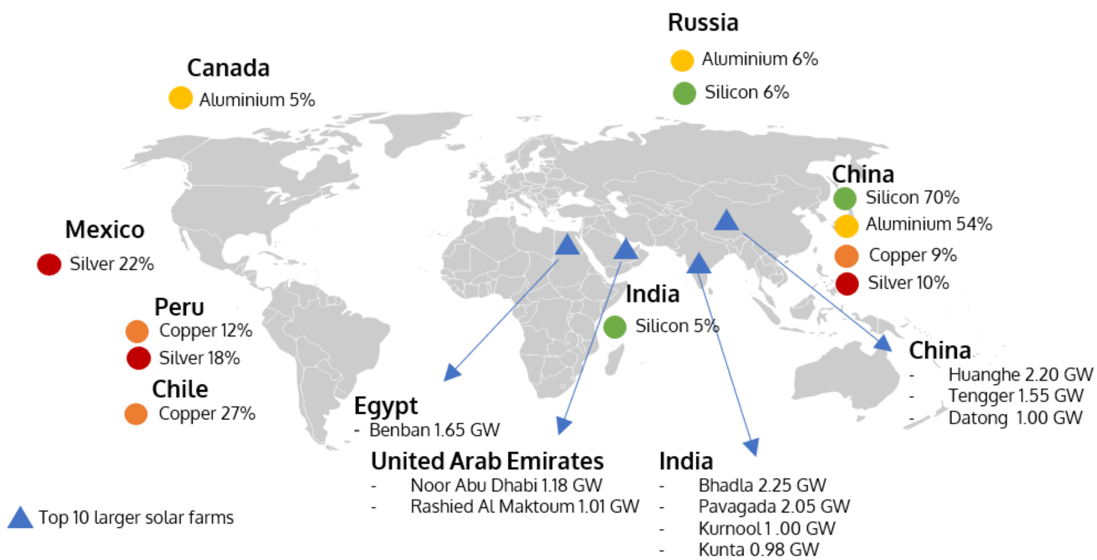

Figure 3.4: *Map indicating the distribution of annual production for some strategic minerals in the PV industry, together with worldwide biggest solar farms (2017). It shows that extraction of silicon and aluminium is highly concentrated in China as copper in Chile, and silver in Mexico. Data from [52–55].*

Based on the fact that it is theoretically possible to install annually 1 TW of solar capacity in the very long term, the impact on the raw materials was evaluated. Figure 3.5 highlights the resulting quantities which were computed from two sources giving the material quantities demand (kg/kW) and knowing the annual production of each element.

Impact of the installation of such solar capacity would be limited for steel and concrete as it would be equivalent to less than 5% of the annual worldwide production. Silicon and glass would also be in that category despite the higher required percentage of yearly production as Si is the second most abundant element in the earth's crust[1]. Therefore, no fundamental barriers exist to scale up the production facilities for both forms [2]. Impact on aluminium is

[1] The main element in glass production is silicon

[2] It should be noticed that the geopolitical risk of the concentrated extraction of Si in China was not taken into account in this analysis

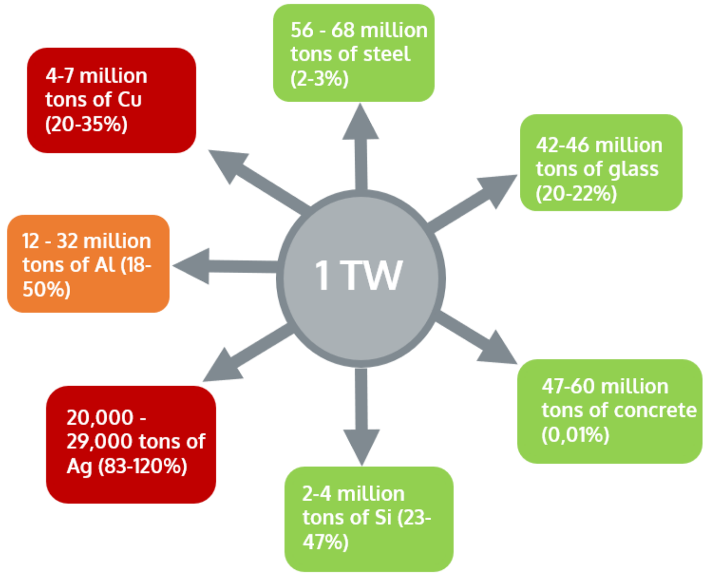

Figure 3.5: *Raw materials demand to install 1 TW of additional solar panels capacity. The impact is limited for steel, glass, silicon and concrete. The impact is moderate for aluminium, while it is critical for silver and copper. Data from [56–58]*

moderate due to the high fraction demand of the solar industry but the high recycling rate of panel frames (and other industries) what reduces the supply pressure. Impact on silver and copper is considered critical. Ag is very limited on earth with an annual production in 2021 around 24 000 tons. Without any changes, roughly all the production would be required to ensure such a solar capacity. Regarding Cu, it has a superior electrical conductivity. It is then widely used in the cabling, the solar key power electronics components (inverters, junction boxes and transformers), and more generally in all the growing markets such as electrical cars, off/onshore wind or the electricity network development.

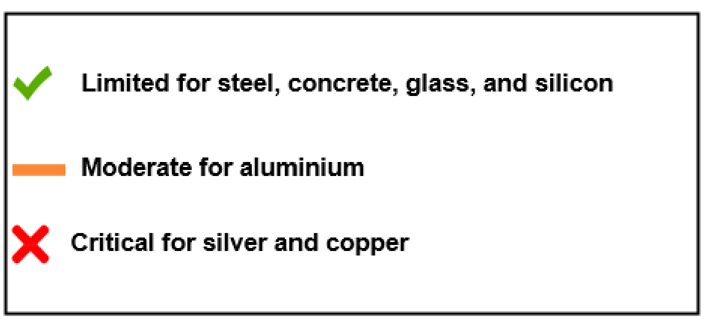

Figure 3.6: *Results of the raw materials analysis on PV industry*

However, several solutions exist to mitigate the material scarcity and hence reduce the risk of shortage:

Reduce the raw materials quantity in the solar panels. Since 2008, the silver quantity per cell (mg/cell) has felt by 80% due to better metallization pastes and is expected to be further reduced by 25% in 2030. Regarding Si, it has been decreased by three over the last decade as exhibited Figure 3.7 (a) [21].

Recycle to reduce the supply chain pressure and the energy impact related to the mineral's extraction Figure 3.7 (b). Currently, recycling processes can achieve high recovery of glass and aluminum (around 80%), moderate recovery of copper (around 40%), but most often do not recover silver and high-purity silicon which are though the most valuable materials. While it is technically feasible, it would require a costly and difficult thermal treatment to remove the polymer encapsulants. However, numerous projects and researches are on going to improve this recycling industry which will benefit of large economy of scale in the future. Among them, Veolia built a plant allowing to reach 95% of recycling efficiency while recovering both silicon and silver [59][3]. Other recycling projects are: PV Cycle, SolarWorld, or NPC Incorporated [60, 61].

Eco-design consists of developing improved design which will be more sustainable all along the system life cycle. Figure 3.7 (c) shows a new module technology (N.I.C.E) which was developed without encapsulant, soldering or lamination allowing an increased robustness and a theoretically 100% recyclable panel [62].

Substitution is the principle to find an alternative material to replace a critical one. Figure 3.7 (d) illustrates a recent hot topic aiming at replacing silver by copper during the metallization process. It would lead to direct financial savings and reduce the scarcity, assuming no impact on the cell efficiency [63]. Despite the criticality of copper and assuming a similar required quantity, it would not be an issue due to the different scale of annual production (24 000 tons of Ag and 28 M tons of Cu).

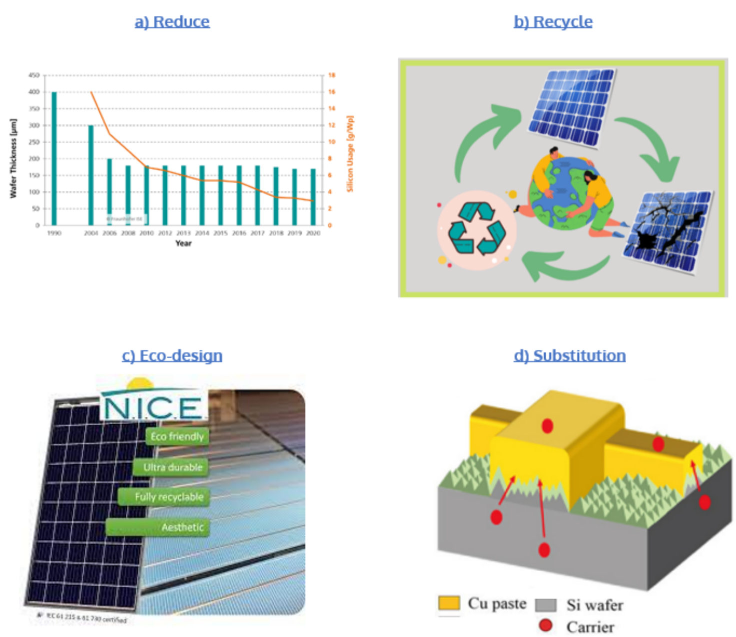

Figure 3.7: *Four solutions to mitigate the material scarcity on PV and then reduce the risk of shortage [21, 62, 63]. Reducing the quantity of silver and silicon during the fabrication, improve the panels collect and recycling, find new eco-design leading to easier recycling process, find alternative to critical materials.*

[3]Interesting video about this topics can be seen: https://www.youtube.com/watch?v=PaUlSZ2biI8

3.2 Wind turbines materials analysis

Figure 3.8 shows the wind turbines market projections for the coming years. The onshore industry should be dominated by the GB-DFIG technology accounting for at least 70% of the market shares, while the DD-PMSG technology should reach more than 80% of the offshore market in 2040.

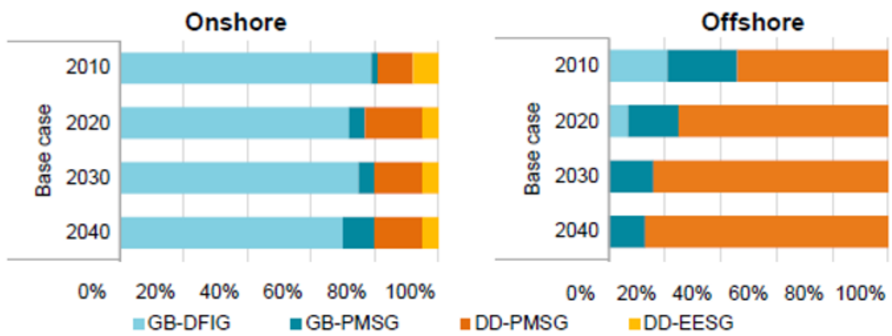

Figure 3.8: *Turbine shares for wind power capacity addition in the NZE scenario [4]. The onshore industry is dominated by the GB-DFIG technology while DD-PMSG are mostly used in the offshore industry.*

The materials used in the wind turbines structure are essential as they allow to improve the production performances, but also to resist to harsh environments as highly corrosive waters or deserts. It is however, very difficult to dress a standard material composition as it drastically depends on the used technology, the size of the turbines, the geographical location,and the various manufacturers. Figure 3.9 describes the design of a classical wind turbine.

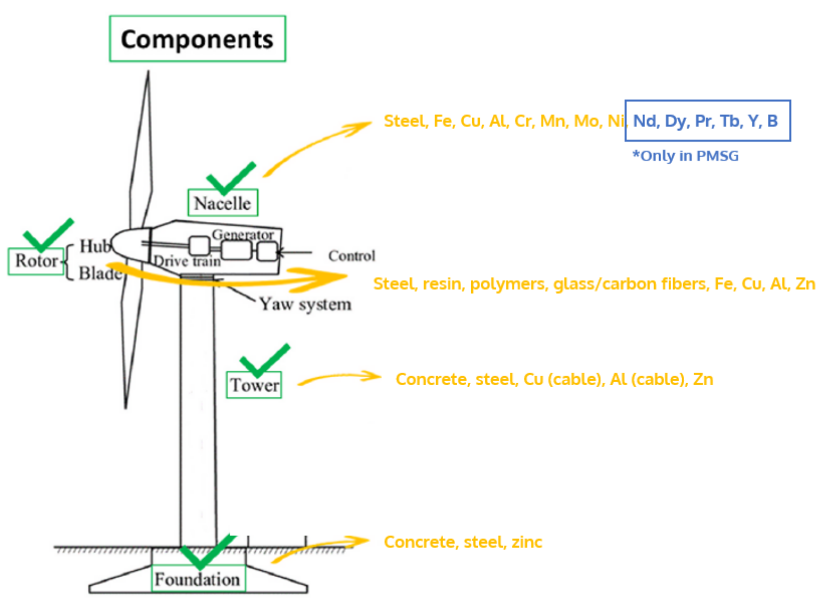

Figure 3.9: *Wind turbine design with the different components and their respective composition [64]. Foundations and tower are mainly made of concrete and steel, blades are made of a complex composite while the nacelle is made of specific alloys and materials contained in the generator. Rare earths are mainly found in the PMSG technology.*

Most of the time, the foundations are made of concrete, steel and can also contain some zinc to protect from corrosion. The tower provides a structural support to the nacelle and the rotor so that robust materials as concrete and steel must also be employed. Besides, it can also contain some aluminium, copper, or zinc for respectively the electrical cables and the corrosion resistance. While the hub is generally made of steel and cast iron, the blades must resist to aerodynamic, inertial, and gyroscopic loads while being also light. In addition to their very complex design, the composite materials used in the fabrication must achieve very good mechanical properties. It is therefore considered that blades are glass fiber-reinforced polymer which can be combined to a core material such as balsa wood in sandwich construction [65]. Typically, a thermoset is used as matrix and the glass fiber is used for longitudinal reinforcement. As alternative to glass fiber, carbon fiber can also be used.

Located on top of the tower, the nacelle houses the turbine drive-train including the generator, the low and high speed shaft, and the gearbox if any. The biggest part of the turbine is generally made of cast iron and various alloy steels hence it can contain elements such as nickel (Ni), chromium (Cr), molybdenum (Mo), and manganese (Mn) giving specific properties to alloys. For example, Mo increases the hardness, the strength and the toughness, reducing the probability of drive train issue [90]. Regarding the generators, the DFIG technology mostly demands magnetic steel and copper. In addition to those two raw materials, the PGMG technology uses expensive Rare Earth Element (REE) including neodynium (Nd) , praseodynium (Pr), dysprosium (Dy), and terbium (Tb).

Figure 3.10 assesses the projected demand for raw materials in 2040, based on the an annual capacity installation of 160 GW corresponding respectively to 32 GW of offshore wind assumed to use the DD-PMSG technology and 128 GW of onshore assumed to use the GB-DFIG technology.

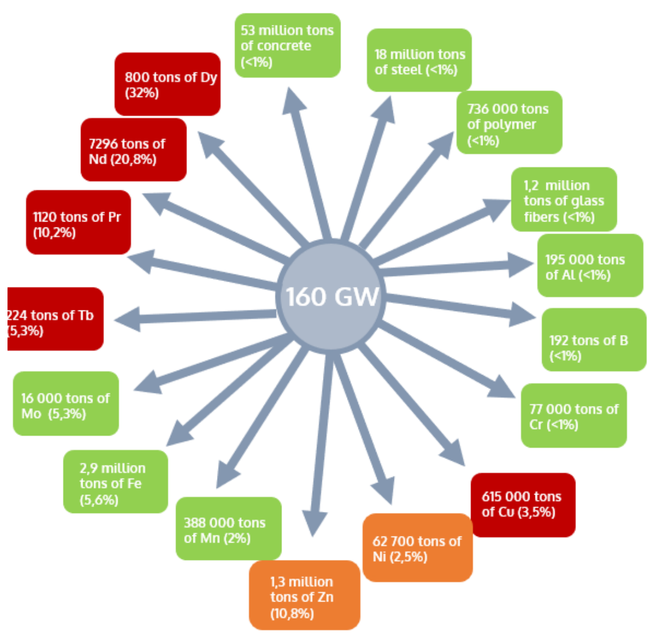

Figure 3.10: *Raw materials demand to install 160 GW of additional wind capacity. The impact is limited for concrete, steel, polymer, glass, aluminium, boron, chromium manganese, iron, and molybdenum. The impact is moderate for zinc and nickel while the impact on REE and copper is critical. Data from [34, 64]*

Impact on concrete, steel, polymer, glass fibers, aluminium, boron, chromium is limited as it corresponds to less than 1% of the annual production. Also for manganese, iron, and molybdenum which are not of strategic importance in the energetic transition or are easily recyclable in large quantity. The decision to let the aluminium in the limited impact while it is set in moderate impact in the solar analysis comes from the difference in demand for each industry. However, an imbalance in the supply chain coming from the solar demand would have negative knock on effects.

Impact on zinc is moderate since the wind industry should account for around 11% of its annual production in 2040. Although this fraction is smaller for nickel, it has been placed in this category due to the very high demand of the battery industry and the risk related to the Ukrainian war as Russia is one of the main nickel producer.

Impact on copper is critical as the development of offshore industry will require huge quantities of cables. This demand can even be accelerated in case of floating wind turbines emergence and the possibility to install them farther in the water. However, the biggest challenge faced by the wind industry is definitely the availability of REE including neodymium, praseodynium, dysprosium, and terbium. Despite their names, those materials are not necessarily rare as they can be abundant on the earth's crust and present in various location on earth. Nonetheless, they are never found in high concentrations and are usually mixed with radioactive products. Their chemical properties make them difficult to separate from the other elements, so that their extraction in high purity is cost and energy intensive. Besides, Figure 3.11 demonstrates the fragility of the supply chain due to the omnipresence of China in all the permanent magnets manufacturing steps. Few years ago, it was even stated that China use to produce more than 95% of REE. Since then it has fallen a bit above 60% in 2019 thanks to the boosted production of US and Australia.

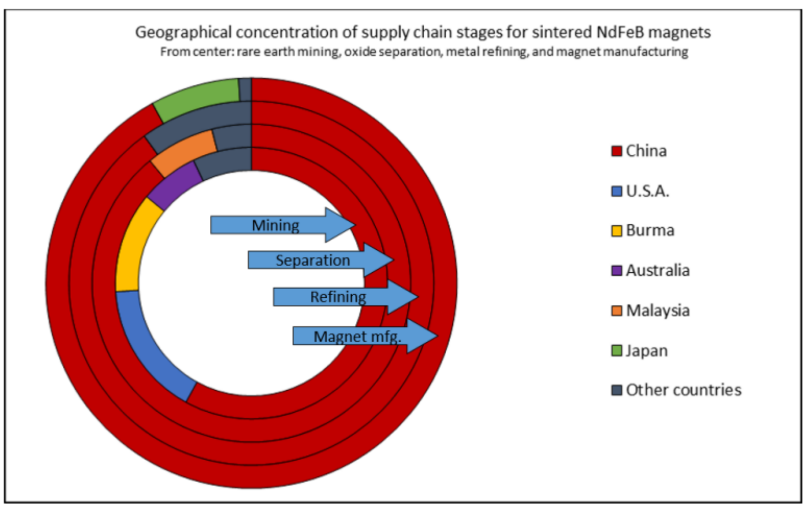

Figure 3.11: *Geographical concentration of supply chain for the fabrication of permanent magnets from REE [66]. China dominates all the steps entailing a supply risk.*

Figure 3.12 highlights the results of the raw materials criticality analysis for the wind industry.

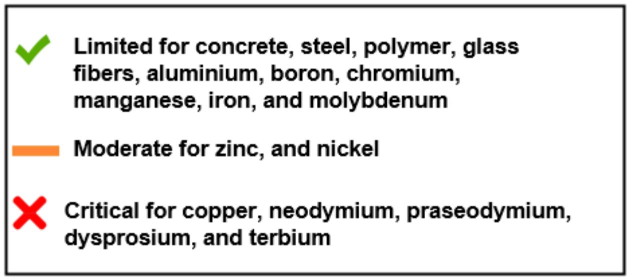

Figure 3.12: *Results of the raw materials analysis for the wind industry.*

First industrial large scale wind turbines projects were installed back in the 2000s, and are gradually reaching their end of life[4]. It is hence estimated that in Europe almost 12 000 wind turbines will be decommissioned in the next five years. Besides, an additional 2.5 million tons of composite materials are currently in used. In France, wind turbines are covered by strict regulation, and the operator has to include 50 000 € plus an extra 10 000 €/MW over 2 MW for each turbine he wants to install [67].

During the dismantling process, the different parts are separated, sorted and then sent to specialised recovery channels. Concrete coming from the foundation is recovered and reused in public work sites. Steel and aluminium found in the tower, the nacelle, and the rotor are sent to foundries or steelworks while the copper is easily recovered. The most challenging part is however the blades which are composed of glass/carbon fibers reinforced polyester resin/epoxy making it difficult to recycle effectively.

The current existing technologies to recycle the thermoset composite coming from the blades can be grouped in different levels. The primary recycling is the possibility to reuse the blades when they need to be replaced, for example for economic reasons (e.g. subsidy period). The secondary recycling involves a mechanical modification of the materials without the use of chemical process. Blades can be cut, shredded in smaller pieces, and then crushed. The dust is mixed with humid material to homogenize and bind it, to be used as cement. The tertiary recycling is performed by pyrolysis (thermal treatment) or chemical decomposition (solvolysis). In the pyrolysis process, the material is heated in absence of oxygen so that the polymer matrix is converted into gas, or oil, while the fibers remain inert and can be latter recovered. The quaternary recycling relies on the incineration of plastics to recover energy in the form of heat [68].

Many projects aiming at improving the sustainability of this industry are ongoing. Among them, an innovative project called ZEBRA (Zero wastE Blade ReseArch) gathering industrial and academic partners is working on the development of eco-designed thermoplastic wind turbine blades to facilitate their recycling [69].

Regarding the REE contained in the permanent magnet of generators, they are today hardly recycled. The growing stream of end-of-life wind turbines and BEV is however expected to intensify this recycling industry. Today, some processes using hydrometallurgy and pyrometallurgy are tested at lab scale but the economic challenge still need to be overcome [70]. Figure 3.13 shows the projected growth of REE secondary supplies which would reduce the primary demand growth rate of dysprosium, neodynium, and praseodynium by approximately 5%.

[4] It should be noticed that in the 80s, smaller wind projects around 20 turbines, were installed during the oil crisis

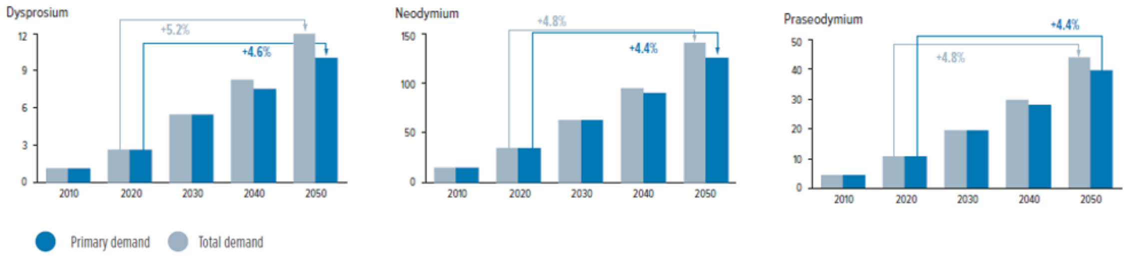

Figure 3.13: *Global total and primary REE (dysprosium, neodymium and praseodymium) demand outlook(kt) [71]. Secondary supplies could reduce the primary demand growth rate by approximately 5%*

3.3 Lithium-ion batteries materials analysis

Figure 3.14 shows typical structure of battery containing several modules made of cells, which are the batteries building blocks. Those cells account for 70% to 85% of the battery weight and are made of the active cathode material (e.g. lithium, nickel, cobalt, manganese), the anode (e.g. graphite, and the current collector (e.g. copper). The rest of the pack mainly consists of aluminium, steel, or electronic components. Today, the raw materials in batteries represent around 50-70% of the cost up from 40-50% in 2015 [14]. A further price increase, together with the risk of materials shortage could be barriers to the world electrification due to the huge demand of batteries in minerals.

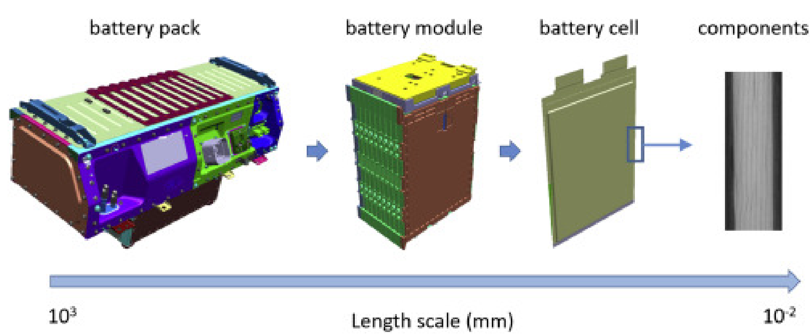

Figure 3.14: *Structure of lithium-ion battery pack [12]. The battery pack contains several modules with each containing cells made of an anode, a cathode, and a current collector containing the main minerals.*

In BEV, stationary storage, and electronic applications, the lithium-ion batteries are dominating the market. Within this technology, batteries can be categorized depending on the anode and cathode chemistry leading to various properties.

For cathodes, the most famous chemistry is the Lithium Cobalt Oxide (LCO) which has a good energy density (150-190 Wh/kg) and a high cycling stability making it popular for portable electronics. Usage of cobalt, thermal instability, and short cycle life (500-1000 full cycles) are the main drawbacks. Lithium Manganese Oxide (LMO) has a better thermal stability, a good cycle life (1000-1500 cycles) and is cobalt free. Its small energy density (100-140 Wh/kg) is an issue so that this technology is mainly used for power tools or medical devices.

Lithium iron Phosphate (LPF) offers a high cycle life (more than 2000 cycles with limited efficiency loss), a low cost, and a high thermal stability even at high temperature. Again, the low energy density (140 Wh/kg) is the main limitation. Its reliability makes of this technology the ideal candidate for applications where the weight is not the first criteria of decision, as the stationary storage. The lithium Nickel Cobalt Aluminium oxide (NCA) has very good performances with the highest energy density (200-250 Wh/kg), while keeping a good life cycle (1000-1500 cycles). Although expensive, this technology is largely used by the automotive manufacturers like Tesla, in back-up power system, and load shifting applications. Finally, the lithium Nickel Manganese Cobalt oxide (NMC) has a smaller energy density than NCA, but offers a longer life cycle (1000-2000 cycles). It has been the most used technology in the BEV market from the beginning [4, 35].

For anodes, the graphite technology is ubiquitous in the lithium-ion batteries due to good charges collection capability. Alternative as lithium titanate providing superior safety, and better low-temperature performance can also be used. Today, developments focus on the possibility to replace some carbon atoms of the graphite anode by atoms of silicon (Porsche, Tesla) what could drastically boost the energy density. However, the main advances could directly come from the deployment of pure silicon metal anodes. Up to now, deformation during charging lead to cracks and performance degradation, but the deployment of solid-state technology could make the use of this type of anode possible.

Figure 3.15 shows the expectations relative to the cathode market for both the BEV and the stationary storage industry. The two main factors driving the industries are the energy density and the shift away from cobalt due to its high price and additional concerns over human rights abuses [13].

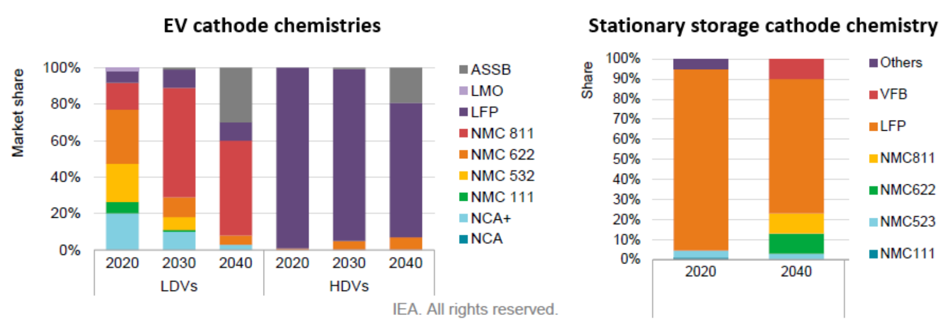

Figure 3.15: *Market shares of cathodes evolution for both BEV and stationary storage applications [4]. In LDV, there is a shift towards higher nickel ratio, while LPF cathode is expected to dominate the HDV and stationary storage industries.*

In this context, the Light Duty Vehicle (LDV) will gradually make a shift from the NCA and NMC towards alternative with increasing ratio of nickel and manganese, meaning sucessively NMC 111, NMC 532, NMC 622, and ultimately NMC 811 will dominate the market after 2030 [5]. All Solid State Battery (ASSB) will take time to penetrate the market but should have a certain market share from 2040. On the other hand, the Heavy Duty Vehicle (HDV) market is widely dominated by the LFP technology. Regarding the utility stationary storage market, the LFP is also the dominant player thanks to its essential safety at relatively low price. Vanadium Flow Battery (VFB) starts to be commercialized in 2030 taking some market shares, especially in large renewable energy projects.

It is very difficult to estimate the quantity of raw materials in batteries due to the wide variety of compo-

[5] They have the general formula $LiNi_xMn_yCo_zO_2$ and are then called NMC XYZ representing their stoechiometric ratio.

sitions, manufacturers, and capacity. Values of weighted composition for different types of lithium-ion technology were found in the literature [4, 72]

Figure 3.16 gives a map highlighting the top three mining producer countries for selected raw materials involved in the battery industry. Extraction of those minerals are very concentrated in some area of the world, in particular the cobalt in DRC 69%, the lithium in Australia 46%, or the graphite in China 56%, making this industry vulnerable to supply shocks.

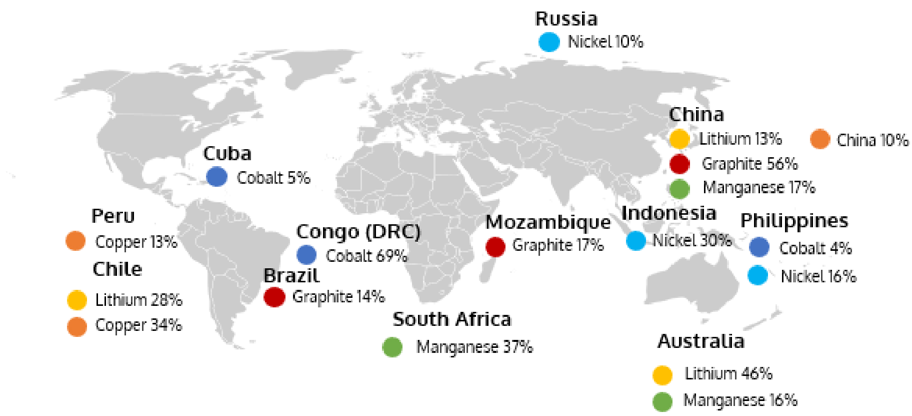

Figure 3.16: *Map indicating the distribution of annual production for some strategic minerals in the battery industry. It shows that extraction of cobalt is concentrated in DRC, lithium in Australia, and graphite in China.*

Besides, Figure 3.17 illustrates the fact that other steps of the BEV battery supply chain are outrageously dominated by China. It shows that 70% of cathodes and 85% of the anodes are directly produced in this country while only Europe takes a small share in the BEV production and the cobalt processing steps. Efforts are however made by Europe to relocalize this strategic industry as proved by the creation of the European Battery Alliance, involving 80 industrial and innovation actors, as well as the 200 million euros of investments in this sector [73].

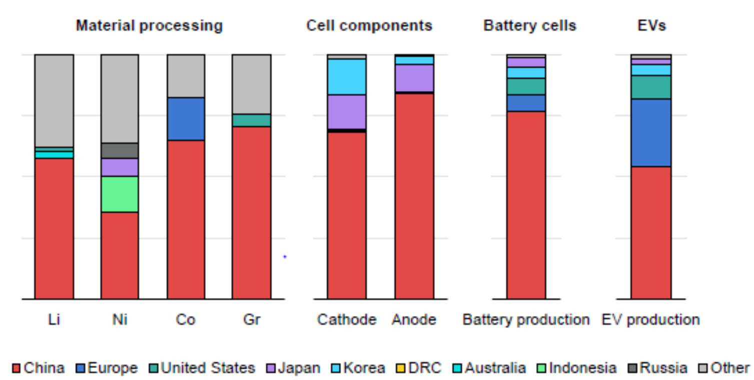

Figure 3.17: *Geographical distribution of the global BEV battery supply chain [74]. All the manufacturing steps are dominated by China while Europe has only significant influence in the cobalt processing and the BEV production.*

Figure 3.18 shows the minerals consumption if the NZE scenario. Demand for BEV batteries is multiplied by 40 between 2020 and 2040 reaching 6200 GWh what leads to a final minerals consumption close to 12 000 kt. Consequently, the graphite consumption is multiplied by 25 and the silicon demand is multiplied by 460 due to the penetration of graphite anodes doped with silicon. During the same period, battery storage capacity is multiplied by 11 to stand at 420 GWh. In parallel the quantity of minerals is multiplied by 33, outpacing the growth of battery due to the shift from LFP to NMC cathodes which are more material intensive. Largest demand increases come respectively from nickel (140 times), cobalt (70 times), and manganese (58 times).

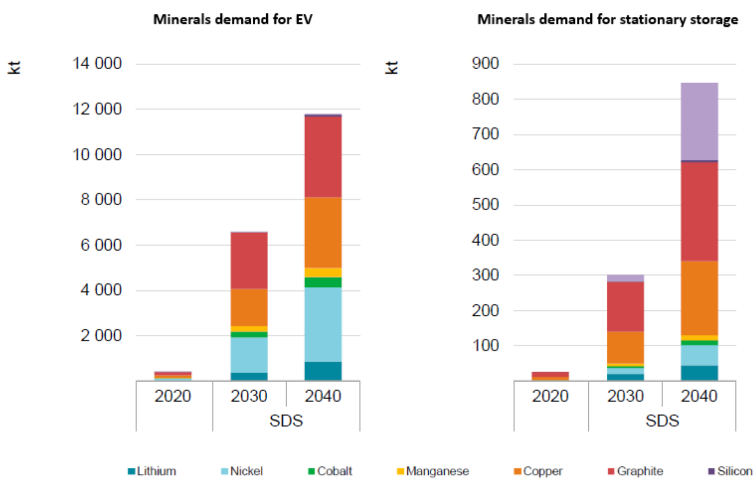

Figure 3.18: *Minerals demand for BEV and stationary storage batteries in the NZE scenario [4]. Demand for all minerals drastically increases.*

Figure 3.19 estimates the raw materials demand based on the production of 6600 GWh of battery capacity (72 millions of cars and 105 GW of stationary storage) as expected for 2040 in the NZE scenario. This is set in perspective with the 2020 total annual production of each metal.

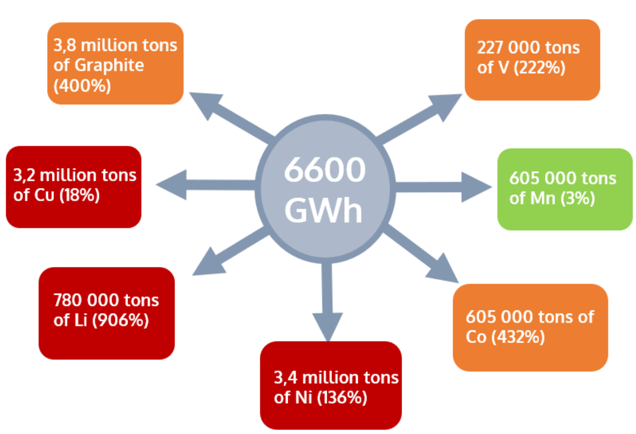

Figure 3.19: *Raw materials demand to install 6600 GWh of additional batteries capacity. The impact is limited for manganese and moderate for vanadium, cobalt, and graphite. The impact is critical for nickel, lithium, and copper.*

Although the required quantities are tremendous compared to current productions, some of those materials are not considered as highly critical due to the fact that they are very abundant on the earth's crust. Risk of shortage is however important for the short term, as it takes a certain amount of time to launch the production of new extraction site.

Impact on manganese is limited as LMO technology having the highest fraction of Mn in its composition is not expected to be part of the future market. In addition, the NMC technology will contain less and less Mn in the coming years, shifting to a higher nickel composition. Impact on cobalt is moderated even if the demand is expected to largely exceed the current production which is dedicated at 24% for the BEV industry. It arises from the willingness of the manufacturers to move to higher nickel content as the cobalt is expensive and raises a lot of ethical concerns regarding its extraction in DRC. Impact is moderate for graphite as it is expected to stay the main resource for anodes production but the production can be scaling up. Criticality of vanadium is difficult to assess and will depend on the battery flow market penetration.

Impact is critical on copper as it is largely used in all the energy transition technologies. Nickel is critical despite the possibility to scale-up the industry as it is more and more used to replace cobalt and manganese. Besides, recent incidents in Russia increased the supply pressure since it is an important supplier. Lithium is also a critical material as it is irreplaceable in the lithium ions batteries. The BEV industry is the main contributor accounting for 47% of the demand, it therefore sets the price which has been multiplied by seven between January 2021 and May 2022 due to an unbalance offer compared to the huge demand. Such price increase drives significant projects of lithium extraction, tough they can take around one decade before being exploitable.

In addition to the battery, most BEV contain a permanent-magnet motor which offers a highest efficiency compared to induction motors which suffer from losses through copper wires. This type of motor is however expensive and demands a lot of neodynium 0.25-0.50 kg/vehicle, other REE 0-06-0.35 kg/vehicle, as well as copper 3-6 kg/vehicle, iron 0.9-2kg/vehicle, and boron 0.01-0.03 kg/vehicle. Considering that half of the electrical market uses this technology in 2040 and that the average quantity of Nd is 0.35 kg per vehicle. It is estimated that the demand could reach 12600 tons while the annual production is only 8000 tons. This does not take into account its use in the wind industry so that the availability of this element is critical.

Figure 3.20 highlights the results of the raw materials criticality analysis for the battery industry.

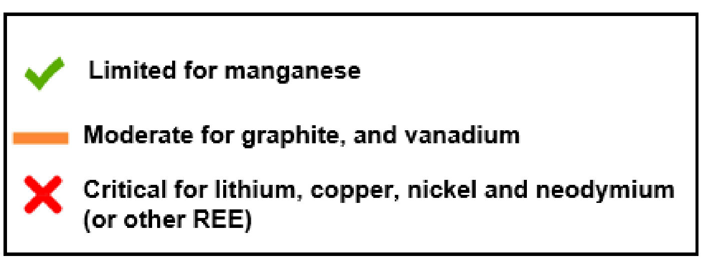

Figure 3.20: *Results of the raw materials analysis for the wind industry.*

Recycling of batteries is an essential road toward the energy transition as the amount of spent lithium-ion batteries will soar from 2030. Besides, tremendous demand of raw materials and their continuous price increase will lead to cost effective recycling solutions. Nevertheless, the various chemistry and the rapid innovations are important challenges faced by this industry since it modifies the recycling process needs. Besides, batteries are sometimes difficult to collect due to the wide variety of applications. In this context, EU member states have imposed objectives to achieve a minimum collection rate for lithium-ion batteries of minimum 70% by the end of 2030. Furthermore, a "battery passport" will be introduced and specific material recovery rates for lithium, nickel, copper, cobalt, and further valuable materials will be imposed. For example, by 2030 the recycling rate of Ni, Cu, and Co should reach 95%, while 70% must be achieved for lithium [75]. This therefore requires large investments from the different players to strengthen the processes.

Figure 3.21 represents the current recycling road which firstly starts with the collection of end-of-life lithium batteries. Then, a pre-treatment phase made of mechanical and thermal treatments allows to recycle components of the housing, electronics, and some other metals while enriching the valuable materials of the cathodes in an intermediate product called black matter. Subsequently, the black matter can be refined either with a pyro or hydrometallurgical process to recover a maximum quantity of cathode materials as Co, Li, Ni. An alternative technique based on biometallurgy also exists but is not industrially available. Metal recovery without performing the pre-treament phase results in open loop, meaning that the recovered materials can only be used in other industries (for example in alloys). Application of pre-treatments allows to close the loop thanks to a certain purity achieved.

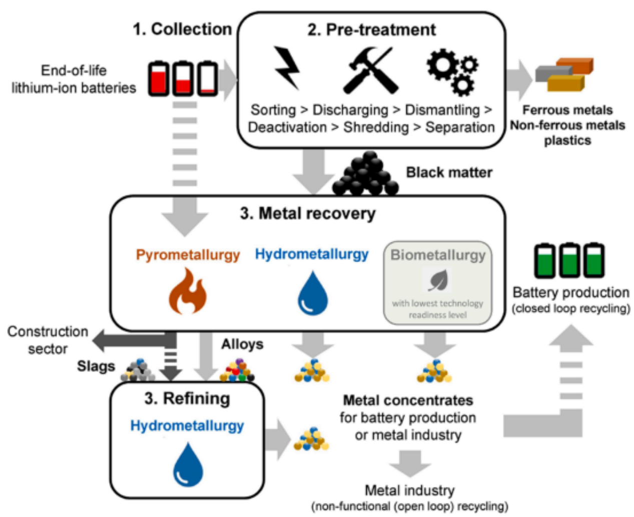

Figure 3.21: *Road toward an efficient recycling process of lithium-ions batteries [76]. After the collection of end-of-life batteries, a pre-treatment can be performed followed by either a pyro or hydrometallurgic treatment allowing to recover the metals. Without pre-treatment materials can not directly be used in the battery industry while when applied the material loop can be closed.*

By 2040, the recycling of lithium-ions batteries could reduce the primary demand for materials up to 12% for Co, around 7% for Ni, and 5% for Li and Cu. Reuse of batteries is also under investigations, in particular by Nissan Motor Co. and American Electric Power which launched a pilot study to reuse expired Nissan Lead batteries to test their stationary storage performances. Reused batteries must however follow costly refurbishing processes and suffer from a lack of transparency regarding their ageing state. Legislation over the repackaging, the certification, and the standardization could help to overcome those limitations [77].

3.4 Electrolysers material analysis

Electrolysers used to produce green hydrogen are composed of an anode and a cathode separated by an electrolyte allowing the charges transfer[6]. Figure 3.22 shows the different technologies existing on the market which are characterized by the medium in which ionic species are transported.

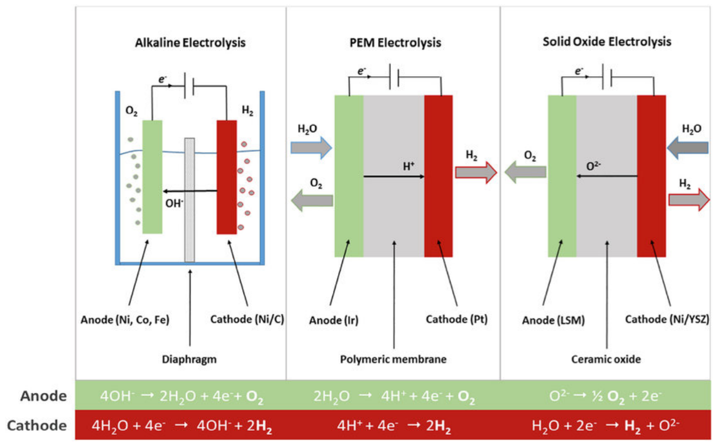

Figure 3.22: *Exiting electrolyser technologies: alkaline electrolyser which is the most mature technology, polymer electrolyte membrane which is the challenger technology, and solide oxide electrolyser which is an emergent technology not yet industrially commercialized [78].*

ALkaline Electrolysers (AEL) are currently the cheapest and most mature technology as it is used at an industrial scale for already one century. This technology relies on a liquid alkaline solution of sodium (Na) or potassium (K) hydroxide. Typically, the cathode is made of nickel, being the least active non-noble metal, with a catalytic coating such as platinum (Pt) or iron [79]. Anode is most often made of nickel coated with metal oxides such as manganese or tungsten (W). All those compositions can widely vary depending on the model, but nickel stays the core of the system. The membrane separator is composed of zirconium (Zr) oxide with additional polymers [80]. Steel is used for all the tanks, pipes, cells frame reinforcement and containers while power electronics contained aluminium and copper [81]. Other advantages of this technology are the lifetime around 20 years due to an exchangeable electrolyte and a slow dissolution of the anodic catalyst, together with a high gas purity coming from the low oxygen diffusivity in the alkaline electrolyte. Main drawbacks are the low flexibility in operation and the low start-up rate due to the high thermal capacity.

Polymer Electrolyte Membrane (PEM) electrolyser is the main challenger of the alkaline electrolyser. PEM have an increased flexibility in operation, are more compact, and can allow higher pressure output. However, this technology is less mature, has a higher cost arising from the precious raw materials, and has a smaller lifetime [82]. The ionic carrier membrane is typically a polymer. The anode is most often made of titanium (Ti) recovered with a Platinum Group Metal (PGM) element which can be an oxide of iridium (Ir), ruthenium (Ru). The cathode is made of carbon fleece coated with other PGM as platinum or palladium (Pd) [83].

[6] Analysis of hydrogen fuel cells go out of the scope of this thesis.

Solid Oxide Electrolysis Cell (SOEC) electrolyser is the most recent technology but not yet developed at the industrial scale. It has interesting characteristics with a highest efficiency and a better robustness. Besides, its high operational temperature around 800 °C enables to use non precious metals as catalyst [84, 85]. This technology relies on a solid oxide electrolyte made of a dense ionic conductor containing a zirconium oxide doped with Y_2O_3. This brings a great conductivity and high resistance to corrosion, togetehr with good mechanical properties. Most often the cathode is made of nickel doped with Yttrium-Stabilized-Zirconia (YSZ), a perovskite-type Lanthanum Strontium Manganese (LSM) might be used as alternative. The anode is also made in LSM [86].

In 2020, the worldwide cumulative capacity of alkaline electrolysers was only 176 MW but this industry is currently soaring. Today, the factories have an annual capacity of new electrolysers manufacturing reaching 2 GW mainly coming from China while Europe has already plans to expand its production capacity to 6 GW. Regarding the PEM technology, the total installed capacity in 2020 was 89 MW. Those electrolysers were mainly used out of China on project test to produce hydrogen and determine if the additional cost related to this technology is worth. Presently, the manufacturing capacity of factories for PEM stands at 500 MW, but Europe has running projects on two sites to reach 1 GW per year by 2023.

Figure 3.23 exhibits the quantity (kg/GWh) of selected raw materials required for each electrolyser technologies. Considering 1 GW of power addition, demand in material for alkaline electrolysers would be 1000 tons of nickel, 100 tons of zirconium, but also 500 tons of aluminium and 10000 tons of steel. Reduction in nickel demand is expected as a result of technology improvement, but it should stay at high level. For a similar capacity, PEM technology demand would result in 700 kg of iridium, 300 kg of platinum, and 300 kg of palladium. Structural materials were not taken into account. Finally, the hypothetical demand in raw materials in case of similar capacity for SOEC technology would be 150 tons of nickel, 40 tons of zirconium, 20 tons of lanthanum (La), and 5 tons of yttrium (Y).

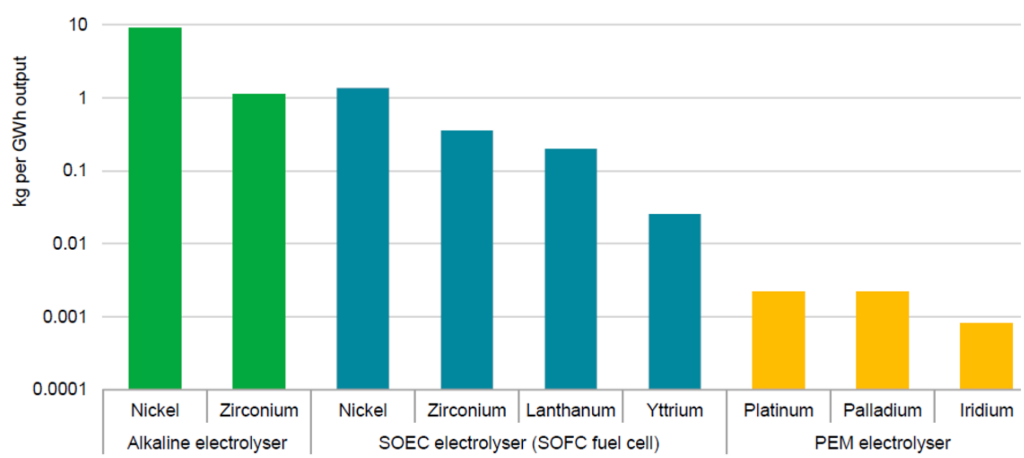

Figure 3.23: *Estimated demand of minerals (kg/GWh output) for the different electrolyser technologies [4]. The full load hours of electrolysers is assumed to be 5000 hours per year.*

Figure 3.24 shows that alkaline and PEM electrolysers are expected to be the two dominant technologies in the future with annual capacity addition that could go from 2 GW to 6 GW per technology between 2025 and 2040 [87].

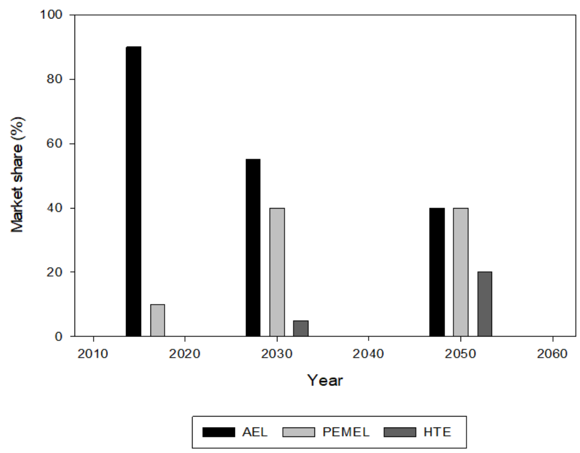

Figure 3.24: *Market share evolution (%) of the electrolyser technologies. Alkaline and PEM technologies are expected to be the dominant players in the following years with a possible emergence of SOEC=HTE*

Figure 3.25 shows the annual production concentration of some of the essential minerals for the manufacturing of electrolysers. It arises that the PGM production is widely concentrated in South Africa and the rare earths (yttrium and lanthanum) are almost exclusively produced in China.

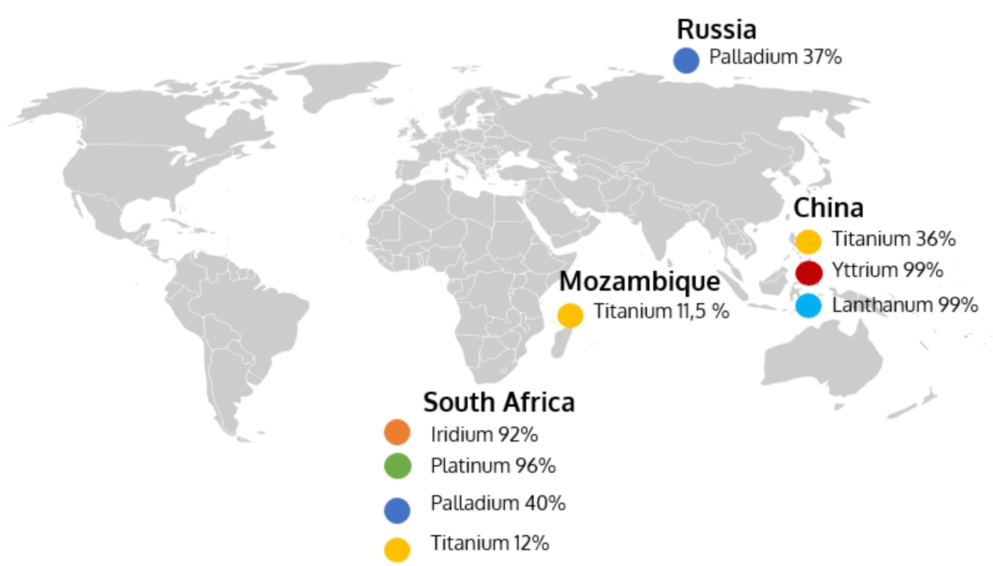

Figure 3.25: *Map indicating the distribution of annual production for some strategic minerals in the electrolyser industry. Data from [88–90]. It shows that extraction of PGM (iridium, platinium, palladium) is highly concentrated in South Africa, while the REE (yttrium, and lanthanum are almost uniquely produced in China).*

Considering a theoretical average annual capacity addition of 4 GW. It would have a limited impact on steel, nickel, zirconium and titanium, as it corresponds to less than 1% of the annual production. However, the increase demand of nickel for batteries might lead to drastic price variations slowing down the cost reduction of electrolysers. Impact on yttrium and lanthanum is moderate due to the high fraction of total annual production, respectively 130% and 640% and the high production concentration [91, 92]. Nonetheless, this technology is not expected to largely penetrate the market in a close future reducing the risk on supply chain. In addition, reserve of lanthanum amounts to 6 million tons, making it one of the least rare earth metal and offering the possibility to increase the production[7]. The most critical elements are likely to be the PGM which are found in the PEM technology. This kind of electrolyser could be preferred to decentralize production of hydrogen where the plant size is limited and in public area. Despite the fact that the amount of PGM required is limited, the low annual production (191 tons of Pt, 7.1 tons of Ir, 210 tons of Pd) combined to the high geographical concentration are risky factors for the supply chains [87].

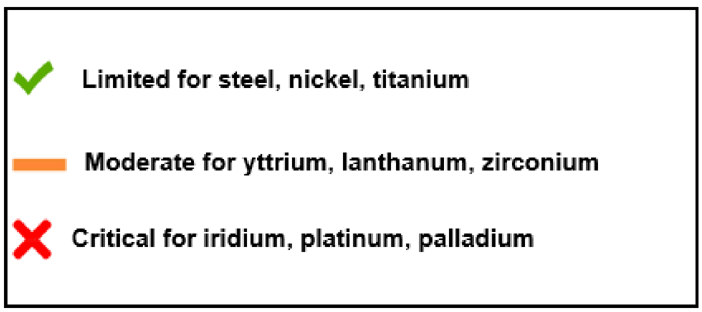

Figure 3.26: *Results of the raw materials analysis for the electrolyser industry*

Despite the relatively good recycle techniques for PGM, the secondary sources of supply is not expected to drastically reduce the supply pressure due to both the long lifetime of electrolysers and the collection difficulty which can be explained by small quantity dispersed in various applications. Nevertheless, the demand for PGM should be relaxed by the technology improvements, as the quantity required is expected to be reduced by a factor 10 in the future [87].

[7] Reserves represent the amount of an already developed raw material that can be economically extracted with the currently available technical technologies.

Conclusion

This thesis analysed the effect on material availability of the soaring wind and solar markets as energy sources, together with the deployment of batteries and the green hydrogen production as storage alternatives. It demonstrated that following the NZE scenario will require a tremendous amount of minerals which are sometimes geographically concentrated or limited on the earth's crust what raise concerns over the risk of their supply chains.

The cumulative solar capacity is expected to exponentially increase to reach 15 TW of power by 2050. It is boosted by the continuous increase of cells efficiency and the development of huge solar farms. The leading technology will likely stay the c-Si which could be used in tandem configuration with perovskite in the future. Critical risk of materials shortage exists for silver and copper due to a tremendous demand compared to the annual production. In addition, the fact that China accounts for more than 95% of the pollysilicon and silicon wafers fabrication represents a considerable vulnerability.

The wind industry is expected to reach 8 TW of power by 2050 arising from both onshore and offshore turbines. The turbine dimensions increase leading to better capacity factors, together with the economy of scale, enables the wind energy to be cost competitive in certain parts of the world where it was previously subsidiary driven. In the coming years, the onshore industry will be dominated by the GB-DFIG technology, while the offshore industry is mostly covered by the DD-PMSG turbines. Critical risk of materials shortage is attributed to the rare earth elements (neodymium, praseodynium, dysprosium, and terbium) which are highly concentrated in China and also much needed to produce electrical motors. Besides, the wind industry also demands a huge quantity of copper for the electrical cables into the sea.

The batteries industry previously driven by electronics is switching to ensure the demand of both the electrical vehicle and the stationary storage rising markets. Despite the announcement of revolutionary solid state batteries, the conventional lithium ions technology will likely stay the dominant player. Consequently, the critical risk of supply chain perturbation comes from lithium, nickel and copper while the cobalt use should be reduced due to ethical concerns.

In the hydrogen industry, the critical materials will depend on the intense competition between the different electrolyser technologies. PEMs containing very limited PGM (iridium, platinum, palladium) might dominate the future market taking the advantage over alkaline electrolysers. In this situation, a critical risk regarding the PGMs supply chain exists as those elements are geographically concentrated and limited on earth's crust.

This work has demonstrated that for all selected technologies there are critical raw materials risks regarding the supply chains. However, solutions to reduce the materials supply pressure and hence mitigate the risk to see the energy transition slowed down exist. It includes the technological improvement leading to better energy production efficiency, the development of eco-designs using less detrimental materials or leading to easier decommissioning, and the recycling increase providing secondary materials sources. Besides, other solutions must be considered as large investments and incentive policies to increase the sustainability of energy industries. It could either be by respecting the 5 R'S rules of sustainability: refuse, reduce, reuse, repurpose, recycle or by the development of a materials passport increasing the traceability and the composition knowledge leading to an optimized recycling.

A point of view which was not taken into account in this analysis is the environmental impacts of minerals production. The extraction of raw materials are energy intensive processes which can lead to water and ground pollution, geopolitical tension, human health dangers, or child labor. Today, those factors must be considered in the phase development of projects when installing new energy sources or energy storage equipments. Figure 3.27 illustrates an adaptation of the historical 2D McKelvey-diagram integrating the ecological and political aspects in addition to the classical economical and technological feasibility. These impact could be the subject for another thesis.

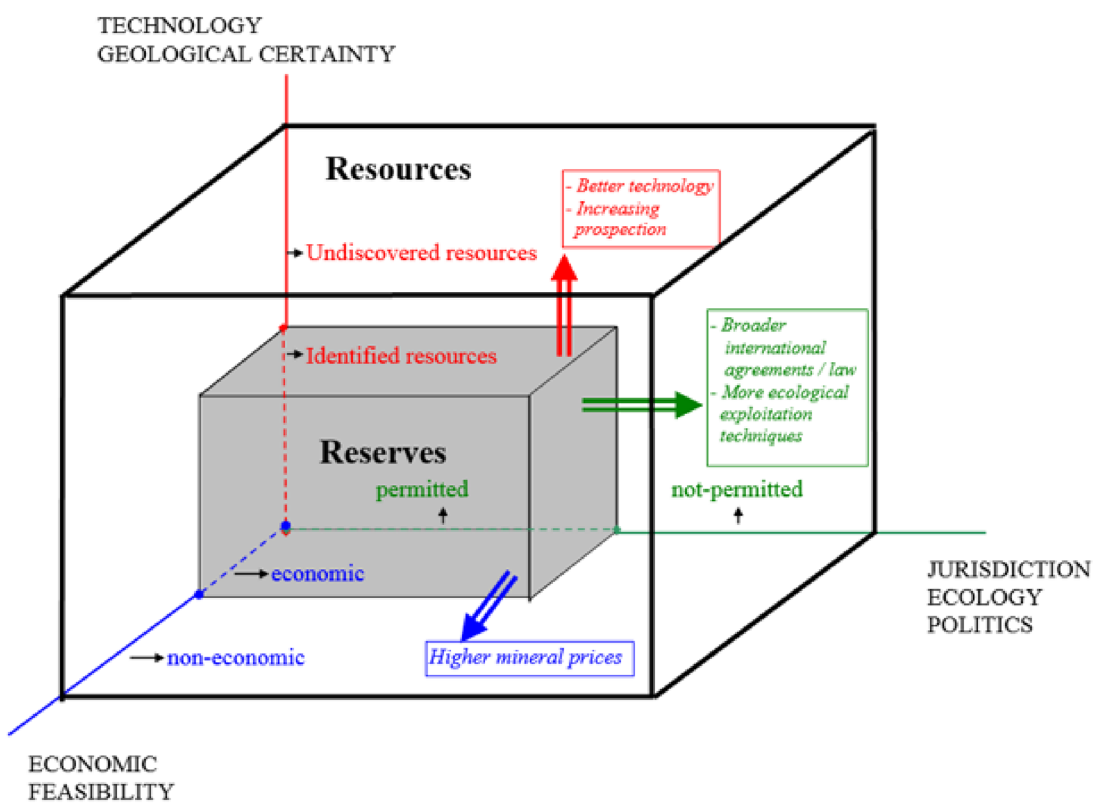

Figure 3.27: *Three dimensional vision of the McKelvey-diagram [93].*

The energy transition is certainly the biggest challenge ever faced by humanity. Despite the exciting technological improvements which are needed to make it easier, it is essential to remember that the world only contains a limited amount of resources. In this context, the energy sobriety stays the best way to fight the global warming as the greenest energy is the one which has not been consumed.

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