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Introduction

The main purpose of this paper is to provide an accurate forecast about the future use of hydrogen in various market. Starting from traditional energy sources and proceeding with a comparison about pros and cons, leaving also a space to see how future trends in the energy field will have hydrogen as leading actor. In these regards, Chapter 1 will focus on current situation about the shortage of energy sources and various issues that arise from it, with an overview on several developing alternatives. Chapter 2 will talk about a 100% sustainable future, introducing hydrogen and deepening other sustainable energy sources.
In Chapter 3, we will have a focus only on hydrogen. First of all, we will talk about the running hydrogen's panorama explaining it through conveniences and disadvantages. At a later time, we will talk with respect to the possible industry applications in a future perspective and also about some interesting statistics.

Before going into detail, in order to a better understanding of what we are going to deal with, let's start from the basics, defining and classifying the various energy sources. Energy is the physical quantity that measures the ability of a body or physical system to do work or produce heat. Energy manifests itself in many forms: heat, light, motive force, etc. and can be captured from diverse sources that can be found in various physical states, and with varying degrees of ease or difficulty of capturing their potential energies.
According to the physical sciences, two basic laws of thermodynamics govern energy flows:

1) [1]A mass of energy can neither be created or destroyed, it can only be transformed. This indicates the overall balance of energy at all times;
2) [2]Any conversion involves generation of low-grade energy that cannot be used for useful work and this cannot be eliminated altogether. This imposes physical restriction on the use of energy.

Energy can be also classified under different categories:

- Primary and secondary;
- Renewable and non-renewable;
- Commercial and non-commercial;
- Conventional and unconventional.

[1, 2] *Subhes C. Bhattacharyya "Energy Economics: Concepts, Issues, Markets and Governance" - Springer-Verlag (2011)*

Primary and secondary: Primary energy is extracted from a stock of natural resources or captured from a flow of resources and has not undergone any transformation or conversion other than separation and cleaning. Solar energy is an example of primary energy because it is already present in nature and does not derive from the transformation of any other form of energy. Secondary energy is obtained from any primary energy source employing a transformation or conversion process. Indeed, oil products or electricity are both secondary energies as these require refining or electric generators to produce them.

Renewable and non-renewable: Non-renewable sources of energy are those primary energies come coming from a finite stock of resources.
Renewable sources of energy are those that are obtained from a constantly available flow of energy. Some stocks could be renewed and used like a renewable energy if its consumption or extraction, does not exceed a certain limit. However, if the extraction is above the natural forest growth, the stock would deplete and the resource turns into a non-renewable one.

Commercial and non-commercial: Commercial energies are those that are traded wholly or almost entirely in the marketplace and therefore would command a market price. Examples of commercial energies are coal, oil, gas and electricity.
Non-commercial energies are those which do not pass through the marketplace and do not have a market price. But when a non-commercial energy enters the market, becomes a commercial form of energy.

Modern and traditional: Modern energies are those which are obtained from some extraction and/or transformation processes and require modern technologies to use them.
Traditional energies, instead, are those which are obtained using traditional simple methods and can be used without modern gadgets. Often modern fuels are commercial energies and traditional energies are non-commercial. But this definition does not prevent traditional energies to be commercial either. Thus, if a traditional energy is sold in the market it can still remain traditional. In fact, it reduces some overlap, but the definition remains subjective as the practices and uses vary over time and across cultures and regions.

Conventional and unconventional: This classification is based on technologies used to capture the various energy sources.

Conventional energies are those which are obtained through commonly used technologies.

Non-conventional energies are those obtained using new technologies or sources.

These conventions are subject to change over time, allowing non-conventional forms of energies to become quite conventional at a different point in time. Based on the above discussion, it is possible to group all forms of energy in two basic dimensions: renewability as one dimension and conventionality as the other, as we can see from the tab below[3].

Table 2.1 Energy classifications

Conventionality	Renewability	
	Renewable	Non-renewable
Commercial	Large scale hydro Geothermal Nuclear	Fossil fuels Other nuclear
Traditional/non-commercial	Animal residues Crop residues Windmills and watermills Fuelwood (sustainable)	Unsustainable fuelwood
New and novel	Solar Mini and micro hydro Tidal and wave Ocean thermal	Oil from oil sands Oil from coal or gas

Source Codoni et al. (1985) and Siddayao (1986)

[3] *Codoni and Siddayao (1985/1986)*

1. Current energy sources and related issues

In this first chapter we will analyze the current availability of energy resources, distinguishing them in sustainable or non-sustainable. In a second step we will pay attention to issues deriving from the use of unsustainable resources, both from an economic and an environmental point of view, giving more attention to oil and its economic history.

1.1 Overview

The human being to survive and evolve has always resorted from different sources of energy present on earth. Today, however, for the first time we are facing a situation in which some fundamental sources are starting to become scarce and creating evident issues for the surrounding environment. This situation is therefore pushing the world towards research and development of new and more sustainable energy sources that can replace those that are currently in short supply. Going into detail this is a list of energy sources currently in use in order of importance and current exploitation, with a brief description:

- **Oil**, or petroleum, is a liquid mixture of various hydrocarbons found in geological formations beneath the Earth's surface and recovered by oil drilling. Oil is called "crude" as it is extracted from the fields, before undergoing any treatment to transform it into a processed product: it is refined and then transformed into various types of fuels. The use of petroleum as fuel is a major cause of global warming and ocean acidification. According to the UN's Intergovernmental Panel on Climate Change[4], without fossil fuel phase-out, including petroleum, there will be *"severe, pervasive, and irreversible impacts for people and ecosystems"* (UN's Intergovernmental Panel on Climate Change, 2017).

[4] *https://www.ipcc.ch*

- **Coal** is a fossil fuel or sedimentary rock extracted from underground or artificially produced. Its formation happens when dead plant matter decays into peat and is converted into coal by the heat and pressure of deep burial over millions of years. Coal is primarily used as a fuel and today remains an important source, as it supplied about little less a quarter of the world's primary energy and two-fifths of electricity. But the coal industry damages the environment, including by climate change as it is the largest anthropogenic source of carbon dioxide, 14 gigatonnes (Gt) in 2016, which is 40% of the total fossil fuel emissions and almost 25% of total global greenhouse gas emissions[5]. Coal use peaked in 2013 but to meet the Paris Agreement target of keeping global warming to well below 2 °C coal use needs to halve from 2020 to 2030. In fact, as part of the worldwide energy transition many countries have stopped using or use less coal.
- **Natural gas** is a naturally occurring hydrocarbon gas mixture consisting primarily of methane. In nature it is commonly found in the fossil state, together with oil, coal or alone in natural gas fields. It is formed when layers of decomposing plant and animal matter are exposed to intense heat and pressure under the surface of the Earth over millions of years. Natural gas is a non-renewable source of energy used for heating and electricity generation. It is also used as a fuel for vehicles and as a chemical feedstock in the manufacture of plastics and other commercially organic chemicals. Although not as damaging as coal natural gas is a major cause of climate change and creates carbon dioxide during oxidation. Indeed, carbon dioxide emissions resulting from the combustion of natural gas are approximately 74% of those relating to petrol fuels (in addition to emissions produced during extraction and transport)[6].

[5] *Dethroning King Coal "How a Once Dominant Fuel Source is Falling Rapidly from Favor" - Resilience (24 January 2020)*
[6] *"Carbon dioxide produced by burning different fuels" - U.S. Energy Information Administration (2020)*

- **Biomass** is plant or animal material used for energy production, or in various industrial processes as raw substance for a range of products. Burning plant-derived biomass releases CO_2, but it has still been classified as a renewable energy source in the EU and UN legal frameworks because photosynthesis cycles the CO_2 back into new crops. In some cases, this recycling of CO_2 from plants to atmosphere and back into plants can even be CO_2 negative, as a relatively large portion of the CO_2 is moved to the soil during each cycle. So cofiring with biomass makes possible to release less CO_2 without the cost associated with building new infrastructure.
- **Nuclear power** is the use of nuclear reactions that release nuclear energy to generate heat. Nuclear power has one of the lowest levels of fatalities per unit of energy generated compared to other energy sources, indeed, since its commercialization in the 1970s, has prevented about 1.84 million air pollution-related deaths and the emission of about 64 billion tonnes of carbon dioxide equivalent that would have otherwise resulted from the burning of fossil fuels[7]. There is a debate about nuclear power. Proponents, such as the World Nuclear Association, contend that nuclear power is a safe and sustainable energy source that reduces carbon emissions. Nuclear power opponents, such as Greenpeace and NIRS, contend that nuclear power poses many threats to people and the environment and it could be really dangerous in case of plant design errors and consequent explosions.
- **Hydropower** is considered an alternative and renewable energy source, which exploits the transformation of gravitational potential energy, possessed by a certain mass of water at a certain altitude, into kinetic energy, when a certain height difference is overcome; this kinetic energy is finally transformed into electrical energy in a hydroelectric plant thanks to an alternator coupled to a turbine. International institutions such as the World Bank view hydropower as a means for economic development without adding substantial amounts of carbon to the atmosphere, but dams can have significant negative social and environmental impacts.

[7] *Kharecha, Pushker A.; Hansen, James E. "Prevented Mortality and Greenhouse Gas Emissions from Historical and Projected Nuclear Power" - Environmental Science & Technology (2013)*

- **Wind energy** is the use of wind to provide the mechanical power through wind turbines to activate electric generators. Wind power is a sustainable and renewable energy and has a much smaller impact on the environment compared to burning fossil fuels, indeed, supports the green, clean economy, which does not produce greenhouse gas emissions during operation and requires a not excessively large surface area. But wind is an intermittent energy source, which cannot make electricity or be dispatched on demand (varies over shorter time scales). Therefore, it must be used together with other electric power sources or storage to give a reliable supply. Talking about numbers, in 2018, wind supplied 4.8% of worldwide electricity[8], with the global installed wind power capacity reaching 591 gigawatts.
- **Geothermal energy** it is the energy generated by means of geological sources of heat and can be considered a form of alternative and renewable energy. Geothermal power is cost-effective, reliable and sustainable, but is limited to areas near tectonic plate boundaries. Thanks to the peculiarity of geothermal, this energy can be used both as a source of electricity and as a source of heat. Also, recent technological advances have expanded the range of reliable resources, opening a potential for widespread exploitation. The Earth's geothermal resources are theoretically more than adequate to supply humanity's energy needs, but only a very small fraction may be profitably exploited. Drilling and exploration for deep resources is very expensive. Thus, forecasts for the future of geothermal power depend on several variables like assumptions about technology, and energy prices.

[8] *https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/renewable-energy.html.html#wind-energy*

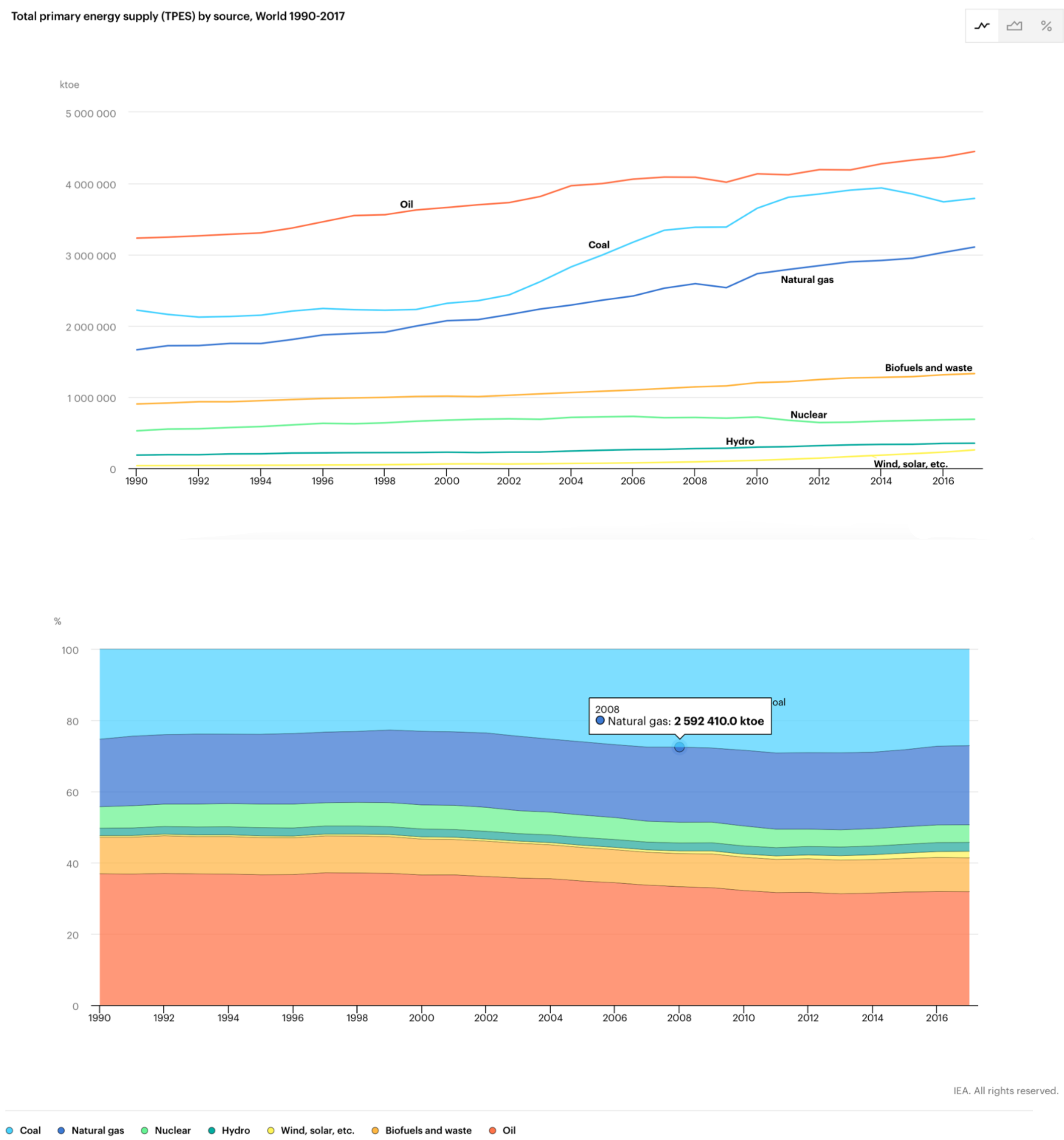
- **Solar energy** is the energy associated with solar radiation and is the primary source of energy on Earth. Almost all other energy sources available to man derive more or less directly from this energy with the sole exceptions of nuclear energy and geothermal energy. It can be used directly for energy purposes to produce heat or electricity with various types of systems. It is an essential source of renewable energy, and its technologies are broadly characterized as either passive solar or active solar depending on how they capture and distribute solar energy or convert it into solar power. In 2011, the International Energy Agency said that *"the development of affordable, inexhaustible and clean solar energy technologies will have huge longer-term benefits. It will increase countries' energy security through reliance on an indigenous, inexhaustible, and mostly import-independent resource, enhance sustainability, reduce pollution, lower the costs of mitigating global warming, and keep fossil fuel prices lower than otherwise. These advantages are global. Hence the additional costs of the incentives for early deployment should be considered learning investments; they must be wisely spent and need to be widely shared"* (International Energy Agency, 2011)[9].

As we can see, hydrogen is missing in the list. This because of it is an energy source still unknown to ordinary people. It is under development; a lot of research is being carried out on it and many companies are investing in this field for the future, but again, it is not yet being exploited.

[9] *Solar Energy Perspectives "Executive Summary" - International Energy Agency (2011)*

1.2 Economic and environmental impact of present-day energy sources

We have seen how the energy supply is currently divided and the sources from which it is drawn. We also need that overview to understand which sources of energy are sustainable and which are not, but also which ones satisfy the world energy needs more than the others, and unfortunately the positive aspects do not always coincide[10].



[10] *World total energy supply 1990-2017 (IEA)*

In fact, as we can see from the graphs[11], sustainable energy sources are also the same ones that cover the smaller slice of energy needs (natural gas, hydroelectric, solar, biomass, wind, geothermal) reaching in 2017 just 35% of the world one. Today the situation is better, we are just over 40%, but it is still not enough.

The remaining 60% is therefore covered by oil, coal and nuclear power, or rather, the energy sources that will run out and will have to be replaced in the coming years, as well as the most harmful to the environment.
This is the key information to understand the role of hydrogen in the future, i.e. a fundamental role. Indeed, this will be able to cover alone or almost that remaining 60%.
All this will be possible thanks to the characteristics of this element, therefore its presence in large quantities, the low supplying and management costs, but also and above all the fact of being absolutely sustainable, allowing industries and means of transport to operate at zero emissions. However, we will return to this topic later.

Having taken stock of the situation, is now necessary analyze specifically the problems arising from using oil, coal and (to a lesser extent) nuclear power. A statistical and economic analysis that will highlight facts like that these sources are not renewable, they are the cause of pollution and global warming and they can also be the cause of important economic shocks.

[11] *https://www.iea.org/data-and-statistics*

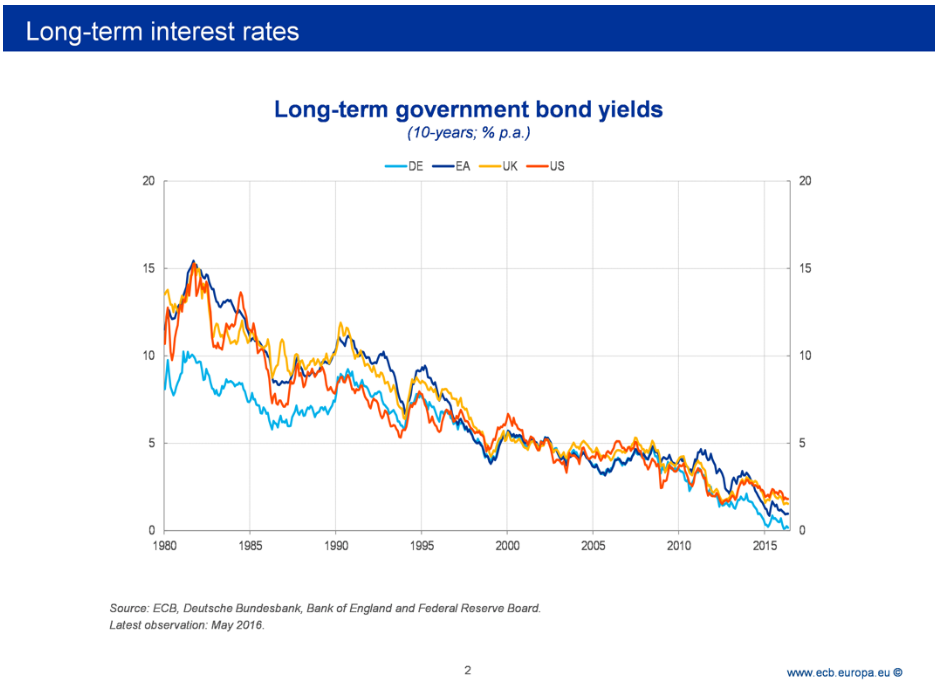
1.2.1 Oil issues

Oil has been and It is still is the lifeblood of our planet and our economic system, but now it is time to move forward. Throughout history there have been several oil crises and nowadays, in addition to the worrying prices fluctuations (due to COVID-19), there are also serious problems about pollution, as well as the increasingly poorness of this resource.

Economics. Talking about the economic side, let's start with the oil shocks analysis.
<u>The first oil shock</u> occurred in middle east, during the post second WW, specifically in 1973. Since 1948, the region was characterized by a precarious situation because of the establishment of the Israeli state, supported by occidental countries. After its foundation, the state immediately found itself in contrast with the Palestinians who lived in those lands for centuries, also because the number of Jewish coming from Europe after the Nazi's persecution was rapidly growing. The rivalries with Palestinians and Arabs of the neighboring countries intensified year after year, leading to several conflicts, all won by Israel.
For these reasons, after the 4th Arab-Israeli war of 1973, called Kippur war, some oil exporting countries gathered since 1960 in OPEC, organization promoted by Venezuela but mostly represented by Arab countries, decided to penalize those States who had backed Israel. In fact, they reduced their level of oil production and consequently the price spiked, reaching in few months $12 per barrel from a starting level of $3 per barrel (159 liters).
The industrialized countries, who relied on oil importation for the correct functioning of their factories and their mass consumption, suffered a real shock and were forced to start a strict energy saving policy. In fact, the "oil bill", term used to represent the cost of oil importation, became particularly onerous for countries (like those of Western Europe) who had to acquire petroleum and its derivatives from abroad.
In addition, exporting countries of OPEC decided to end the established concession regime and started the nationalization of local companies previously controlled by foreign multinationals. *Essentially, in this way, the management of the oil market passed from the "Seven Sisters"* (Mattei, 2016) (term used by Enrico Mattei to describe seven companies who ruled the global petroleum industry from the mid 1940s to the 1970s) to the governments of the exporting countries. A real revolution.
Therefore, the first shock represented a "watershed" event able to bring Western Countries on their knees and upset the world equilibrium.

The second oil shock occurred in 1979, to make matters worse after few years.
This unpleasant event took place when the Iranian production went missing as a consequence of Islamic revolution, which brought to power religious extremists and put an end to the modernization process previously started.
Once again, the oil price consistently increased, shortly arriving to double. In 1980, its price reached the level of $38 per barrel: more than ten times the figure of 1973. In order to explain the magnitude of the shock, we shall add that adjusted for inflation the 1980 peak oil price would be equivalent of paying approximately $120 today.
The rise in the price of oil had two main effects: it produced a rise of production and distribution costs for all goods and made available to oil exporting countries a huge amount of dollars, defined "oil dollars". The major part of that money poured into Arabian countries (for instance, Saudi Arabia and Kuwait had 37 billion dollars more per year for their budget) and were used for unproductive expenses or deposited in foreign banks.
Indeed, oil dollars were largely deposited in European and American financial institutions, which, being unable to invest them all in occidental companies, made loans to developing countries who needed resources in order to pay for their oil imports. Thus, many Asian, African and South American countries contracted huge debts towards lending countries, which at the end of 1986 reached the astonishing figure of a thousand billion dollars.
Loans were taken out in dollars and at variable rates, meaning that if the benchmark interest rate increased or decreased, the rate on the loans would have moved symmetrically. Given that interest rates increased because of the inflation who hit developed countries, and that dollar appreciated with respect to other currencies, weight of debt repayment became unsustainable. In 1982, with Mexico on the edge of bankruptcy, the problem became obvious.
Since it was inconceivable that creditor banks could fail, International Monetary Fund, World Bank and governments of industrialized countries, granted additional loans that borrower countries used to repay occidental banks. In this way, the debt became a public issue and many loans were renegotiated, with reductions and delays.
The IMF, as the main financier, imposed politics of austerity over borrower countries in order to recover the loans.

The situation got slowly better when interest rates started to decline[12] as a consequence of the decreasing inflation in developed countries.



The reasons behind the high-inflation environment of 70s and 80s were several:

a. Rising oil prices: which implied a specular increase on transportations and electric energy production costs;
b. Rising wages: claimed by labor unions of the principal developed countries, which led to an upturn in the production costs of goods and as a consequence to higher prices;
c. Rising goods' demand: because of demographic increase and to the growing incidence of new countries over markets of mass-consumption.

For the first time a prolonged inflationary period occurred in peace times and together with a negative phase of the economic cycle. The term stagflation was coined in order to represent the coexistence of stagnation and inflation.
The advantage of oil exporting countries produced by the enormous mass of oil dollars that they were able to collect didn't last long. When prices of industrialized countries' products began to rise as a consequence of the inflation, the "exchange factor" between goods and oil came back to previous and more stable levels.

[12] *ECB, Deutsche Bundesbank, Bank of England and Federal Reserve Board (2016)*

The years following the second oil shock, the economic context began to improve but the unemployment rate reached dimensions similar to the Second WW ones.

In Europe, labor unions got weakened and were unable to prevent the spread of precarious and more unstable forms of work contracts. On the other hand, firms gained more bargaining power and managed to increase their freedom to hire and impose temporary or part-time contracts on workforce.

In these regards, economists spoke about jobless growth, meaning with that a period of economic growth without the creation of new stable jobs.

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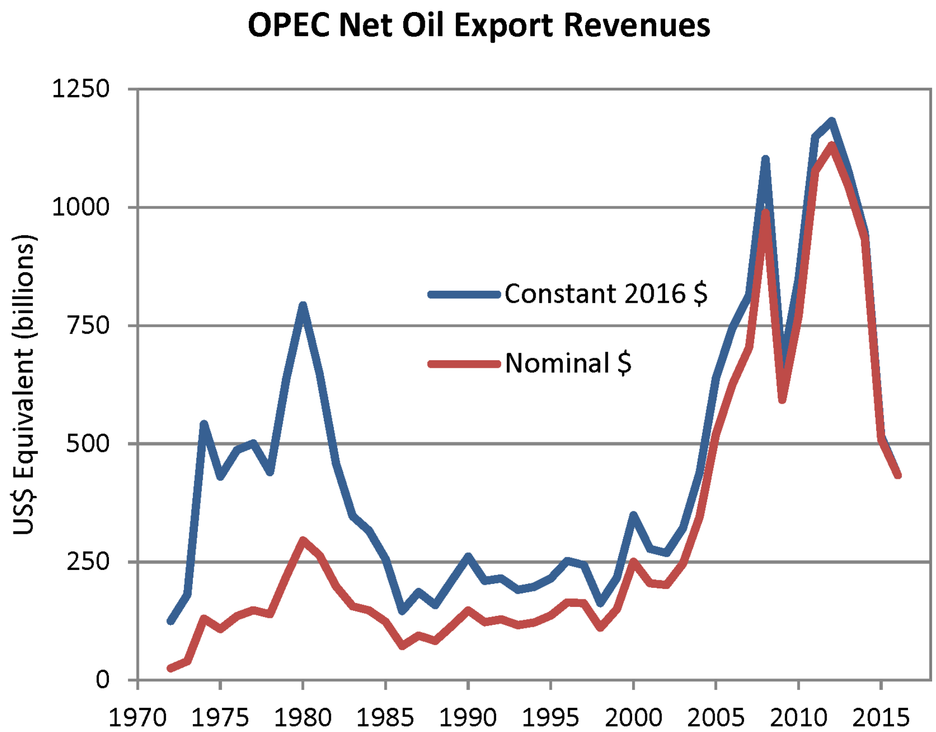

As we can see from the graph[14] above, oil prices between 1973 and 1980 are extremely high due to two oil shocks, and then stabilize. Indeed, between 1985 and the beginning of the new millennium, oil market went through a relatively stable period. This, up to the most recent years, where prices are undergoing worrying fluctuations, confirming what as previously said.

[13] *OPEC Net Oil Export Revenues 1970-2016*

[14] *https://commons.wikimedia.org/wiki/File:Opecrev.gif*

These fluctuations are due to several downward cycles, mainly caused by political nature events. This path starts in 2001 and reaches present days.

The internet blister and September 11, 2001. First, the oil crisis was caused by the blister of hi-tech companies, which finally burst. By 1995, stock in tech companies was more expensive and it looked like this could last forever. However, on March 10, 2000, the Nasdaq index reached its all-time high and then fell on the same day.
Oil had begun to fall at intervals on March 7, and this continued until December.
In January 2001, the price of black gold began to fall sharply, with the threat of a US recession. Seeing the weakening of demand, OPEC has decided to cut the oil extraction quota to 1.5 million barrels. In March, the agreement reduced deliveries to more than a million barrels. On September 11, 2001, the world stock markets experienced another shock: the terrorist attacks on the United States. Two months later, prices hit the bottom, until spring 2002, and then returned to pre-crisis level.

- Maximum price: January 19, 2001 -> 32,2 $
- Minimum price: November 15, 2001 -> 17,5 $
- Duration: 10 months
- Loss level: - 45,8%

The Second Lebanon War, 2006. The outbreak of the second war in Lebanon was a catalyst for the crisis. After Hezbollah's attack on an Israeli border patrol on July 12, Tel Aviv launched a major military operation. On July 14, the WTI price per barrel peaked in years, but from the following Monday it began to decline - neither Israel nor Lebanon have large oil reserves, but another conflict in the Middle East worried investors. In addition, North Korea's ballistic missile tests and the first UN resolution against Iran's nuclear program were carried out in July 2006. The rise in global tension has added to the oil surplus. In the fall of 2006, OPEC's decision to temporarily reduce mining caused prices to adjust slightly; the complete recovery then began in January.

- Maximum price: July 14, 2006 -> 77 $
- Minimum price: January 18, 2007 -> 50,5 $
- Duration: 6 months
- Loss level: - 34,5%

Economic crisis, 2008. After the stagnation of 2005, the price per barrel began to rise rapidly. In the spring of 2008, the bull market was triggered by the threat of war between Iran and Israel and attacks by Nigerian rebels on the oil company Royal Dutch Shell. During the first half of 2008, oil became more than 50% more expensive. Once a barrel of Brent and WTI prices hit record highs on July 3, prices fluctuated in the $ 140-145 range for two weeks. In 2008, the average daily volume of trade exceeded 15 times the daily oil extraction in the world. A major fall began on July 13, and two days later US President George Bush made the situation worse by announcing the lifting of the offshore drilling ban. Added to this were the war in Georgia and the financial crisis. In early September, the value of a barrel had dropped below $ 100.

- Maximum price: July 3, 2008 -> 145,3 $
- Minimum price: January 18, 2007 -> 91,2 $
- Duration: 2,5 months
- Loss level: - 37,2%

Lehman Brothers' failure, 2008. The decline in prices stopped in September. On September 19, the US government announced the economic bailout plan to save the Wall Street financial system. The document assumed that the Federal Reserve had purchased approximately $ 700 billions of troubled assets. The value of a barrel of oil increased by more than $ 25 on Monday 22 September. But the decline in fuel demand in Europe, the strong dollar and the Lehman Brothers bankruptcy proceedings that began on the same day left the market in a panic, significantly affecting oil. From September 28, prices began to fall, and this continued until the end of the year. In the space of a month, oil cost about $ 30-35 per barrel. In January, the price went up a bit, with the conflict in the Gaza Strip. The recovery of oil has thus begun again, after an acute phase of the crisis.

- Maximum price: September 22, 2008 -> 120,9 $
- Minimum price: Decembre 19, 2008 -> 33,9 $
- Duration: 3 months
- Loss level: - 71,9%

Second wave of crisis, 2011. The oil crash in 2011 was caused by a few reasons. First, the threat of a "second wave" of recession made world demand for oil significantly weaker. The unstable economic conditions in Europe and the negative forecasts of GDP aggravated the situation. The dollar was growing steadily against other reserve currencies, affecting prices as well. In addition, markets were awaiting a review of 1.5 million barrels per day oil deliveries to Libya, which had been "frozen" due to the civil war in the Jamahiriya.

- Maximum price: April 29, 2011 -> 113,93 $
- Minimum price: October 4, 2011 -> 75,67 $
- Duration: 5 months
- Loss level: - 33,58%

The shale revolution and OPEC, 2014. The main reason for this other oil crisis is simple: global supply exceeds demand. In particular, the sharp increase in oil extraction in the United States is attributed. Thanks to shale deposits, the USA has significantly increased supply. Another factor is the slowdown in economic growth in Asia and Europe, which has led to reduced consumption. The demand for oil in China has declined as a result of economic problems. Also, in early 2014, Saudi Arabia reduced oil prices to the US, which greatly affected the market. Oil futures have been greatly affected by the decision taken in the fall of 2014 by OPEC (which controls one third of the world's oil extraction) not to take measures to solve the problem of too much supply. With this dumping, the cartel intends to make mining less profitable for other producers and reduce supply, even if it is becoming a source of internal strife.

- Maximum price: July 1, 2014 -> 112,36 $
- Minimum price: December 8, 2015 -> 40,72 $
- Duration: 18 months
- Loss level: - 45%

Fracking years, 2016-2019. In recent years, however, with the application of new extraction techniques of "fracking" and the use of shale oil, the previously armored oil market has undergone the deadly shock described at previous page. The surge in the US currency was a reflection of the decrease in the price of crude oil. Since oil is quoted in dollars, countries in other monetary areas must first buy dollars, which increase the price of crude oil in terms of euros, yen or rubles to buy it. As the price rises, demand falls, producers have a surplus and to reduce it they have to cut the price. In times of economic stagnation, they should therefore reduce production. But this did not happen, indeed the production of crude oil has increased and will continue to increase despite the recession. This because Saudi Arabia has come up with a plan to eliminate shale oil producers and regain lost market share.

At 30 $ a barrel, the frackers would surely have been wiped out, but the Saudis would also have destroyed their budget. At 80 $ a barrel, the price would have been convenient from a Saudi economic standpoint, but it would have given frackers too much leeway.

It turned out that the optimal solution to the Saudi problem would be contained in a range of 50 $ to 60 $ per barrel. This was a price range that would over time eliminate the frackers but would not put too much strain on Arab finances.

What makes Saudi Arabia unique among energy producers is that in a certain way it manages to dictate the market price. It has the largest oil reserves in the world and the lowest average production costs of all. Saudi Arabia can make money on its oil production as low as 10 $ a barrel. This is why oil price has dropped dramatically since 2014, without ever rerise, but going through a period of relative stability and growth until the advent of coronavirus.

- Maximum price: October 31, 2018 -> 76,90 $
- Minimum price: June 30, 2017 -> 42,05 $
- Duration: 3,5 years
- Gain level: + 45,8%[15]

[15] https://www.money.it/prezzo-del-petrolio-storico-WTI *(for all data from 2001 to 2019)*

COVID-19 oil-market demand collapse, 2020. The large contraction in oil demand due to the spread of COVID-19 and the dissolution of the OPEC+ agreement has combined to generate large shockwaves through oil and financial markets. The impact on prices and balances has been severe with Brent and WTI falling by more than 50% over two weeks in March 2020. Daily Brent tumbled to $ 24.9/b on March 18 from $ 51.9/b on March 2, while at the same time WTI fell to $ 20.4/b from $ 46.8/b. Volatility has heightened and the market has seen some extremely volatile price movements. The market has flipped from backwardation to deep contango with time spreads reaching levels wider than those during the 2008 global financial crisis. According to the Oxford Institute for Energy Studies[16] VAR model, the supply-demand imbalance is projected to reach 5.7 mb/d in 2020 and 3.3 mb/d in 2021 which will further deepen the contango as inventories continue to build and traders increasingly resort to floating storage[17]. Combined with the increase in exports from OPEC+ producers, this has already caused a large increase in Very Large Crude Carriers (VLCC) rates. Concerns about availability of storage will continue to put severe pressure on front prices and the shape of the forward curve. Physical differentials have also come under severe pressure and there are reports that prices for some US crudes in physical markets have turned negative. The ramping up of exports by OPEC+ producers in the face of collapsing demand is already causing a massive shift in trade flows with oil exporters such as West African producers finding it increasingly difficult to clear their loading programs, forcing them to slash differentials and offer their crude at large discounts. In short, this is a market that is being tested to its limits and all previous records in terms of price movements and physical indicators are being, or are set to be, broken.

16 *https://www.oxfordenergy.org*
17 *Historical Price Wars, Brent Index 1985-2020*

This long and winding path provides a clear picture of how many issues and crises the economic system has had to deal with due to political and non-political events, all linked to oil. The main reason that links all these events is that oil is a limited resource and above all unevenly distributed on our planet. This allows the owners not only to be able to put together a real economic empire (given the exorbitant earnings) but also to exercise ample political power.
If hydrogen is compared from this point of view to a resource like oil, it would create much fewer problems, above all for two reasons:

1) Hydrogen is distributed evenly throughout the planet;
2) Hydrogen is present in enormous quantities.

Being distributed evenly, each nation would be more independent than the others and this would avoid the start of political turmoil and then shocks/crisis. Furthermore, being an almost infinite resource, prices would be much more stable in the long run.

Pollution. Petroleum is a naturally occurring substance and because of this, its presence in the environment need not be the result of human causes such as accidents and routine activities. Phenomena such as seeps and tar pits are examples of areas that petroleum affects without man's involvement. Regardless of source, petroleum's effects when released into the environment are similar.
The production process of petroleum, from its extraction to its use, is extremely harmful to the environment in several respects:

Global warming. Oil is the main cause of global warming. When burned, Oil releases carbon dioxide, a greenhouse gas. Along with the burning of coal, petroleum combustion is the largest contributor to the increase in atmospheric CO_2. Atmospheric CO_2 has risen over the last 150 years to current levels of over 415 ppmv, from the 180–300 ppmv of the prior 800 thousand years. This rise in temperature has reduced the minimum Arctic ice pack to 4320000 km^2, a loss of almost half since satellite measurements started in 1979. Because of this melt, more oil reserves have been revealed. About 13% of the world's undiscovered oil resides in the Arctic[18, 19].

[18] *NASA Global Climate "Arctic Sea Ice Minimum" (2020)*
[19] *Climate Change "Vital Signs of the Planet" (2020)*

Ocean acidification. Ocean acidification and crude oil pollution have been highlighted as some of the most pervasive anthropogenic influences on the ocean. In marine teleosts, early life-history stages are particularly vulnerable to disturbance by CO_2-driven acidification as they lack pH-mediated intracellular regulation. Embryos exposed to trace levels of crude oil constituents dissolved in water exhibit a common syndrome of developmental abnormalities. So far, little is known about the combined effects of OA and crude oil on the early life history of marine fish. Eggs and larvae of the marine medaka were treated with CO_2 (1080 μatm atmospheric CO_2), the water-soluble fraction (WSF) of crude oil (500 μg/L) and a CO_2 (1080 μatm atmospheric CO_2)/WSF (500 μg/L) mixture within 4 hours after oviposition. Isolated and combined OA/WSF had no detectable effect on embryonic duration, egg survival rate and size at hatching. Histopathological anomalies of tissue and lipid metabolic disorder were significant when CO_2 or WSF was given alone at 30 days of age. Combination of CO_2 and WSF enhanced their toxicity compared to their separate administration. Since the early life-history stage of marine fish is thought to be impacted more heavily by increasing CO_2 partial pressure (pCO_2) levels and crude oil pollution, OA and crude oil pollution have the potential to act as an additional source of natural mortality[20].

Extraction. There is no doubt that oil extraction follows the rules of supply and demand. The tricky part is that there exists a great variation in how much it costs to bring one barrel of oil to market. Added to this is the fact that uneconomic products and oversupply are frequent risks for oil companies and their investors. This is, of course, why investors are also attracted to the sector. If you follow a few basic factors and calculate the cost per barrel of some of the smaller companies, it is possible to profit from the swings in the benchmark oil prices, as uneconomic deposits become profitable. After all, the overall economics of oil extraction point of the fact that is that there is money in it, both for companies and their investors. Upstream oil extraction, which includes exploration and operation to bring crude oil to the surface, frequently occurs near human populations. There are approximately 40,000 oil fields globally and 6 million people that live or work nearby. Oil extraction can impact local soil, water, and air, which in turn can influence community health demonstrating the fact that, being man a selfish creature, it is necessary to start using sustainable sources, giving life to a real interconnected ecosystem between the environment and the economic system.

[20] *Combined effects of ocean acidification and crude oil pollution on tissue damage and lipid metabolism in embryo–larval development of marine medaka - Oryzias melastigma (2019)*

Shortage. Since oil is a non-renewable energy source, it is questionable when it will end and what will happen next. To answer these questions, we need to appeal to several theories. Recently, new theories have emerged, known as the peak of demand, according to which oil is not close to running out but its consumption will instead decrease.

Although crude oil resources are one of the favorite energy sources in the energy world for flexibility and ease of transport, the new awareness in consumption that has developed in recent years will lead to an ever greater attention towards sustainable development and a reduction in harmful emissions.

Climate change and global warming induced by fossil fuel waste have prompted the international community to sign agreements for a common commitment against pollution, from the Kyoto Protocol to the Paris Agreement in 2015.

This requires a net decrease in consumption from fossil sources, including oil, which will necessarily have to undergo a downsizing.

Contrary to what most analysts predict, the Boston Consulting Group[21] in its recent studies, developed on three forecasting scenarios, hypothesizes that peak oil could be reached between 2025 and 2030.

In fact, oil reserves seem to have grown dramatically in the last twenty years, going from 1,141,000 barrels in 1998 to 1,730,000 in 2018, in tandem with technological progress and price trends.

Other theories of the subsoil lead to a technical count of 50 years, but the crude oil reserves could last for another 70 years compared to current consumption.

These forecasts seem to be confirmed in a recent study published by the Bloomberg[22] finance site, which, based on the latest data provided by the United States Geological Survey, assumes the possibility of still extracting 2,000 billion barrels of crude oil from the subsoil.

These optimistic estimates are based, in reality, on the consideration of the exploitation of deposits in very large territories such as those of Patagonia, the Rift Valley in Africa or the sands of Alberta, Canada, without, however, considering the environmental consequences.

The common point of all these analyzes, whether optimistic or not, is that oil is short-lived and needs to be replaced without making mistakes, to avoid collapse.

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[21] *Boston Consulting Group website: https://www.bcg.com/it-it/*

[22] *Bloomberg finance website: https://www.bloomberg.com/europe*

2. Sustainable alternatives

The aim of this chapter is to provide a picture of what a 100% sustainable energy procurement configuration could be, with particular regard to hydrogen and the various methods to actually produce it in a sustainable manner.

2.1 100% sustainable energy supply

Then, there is not much time left. World's need a sustainable and renewable energy production system. Oil and many other energy sources used today are the major cause of pollution and consequently of global warming, in addition to the fact that oil itself will run out between 50 and 70 years.

This is why the topic of sustainable and renewable energy is currently one of the most debated and everyone is asking questions about the future and what to invest in.

What is certain is that many companies have already started investing in hydrogen and this is generating a chain reaction, attracting more and more investors.

In this chapter we will hypothesize a future made up of 100% sustainable energy, with hydrogen covering the largest percentage, accompanied by other important resources.

In a second step, we will compare the various methods of hydrogen production, paying more attention to the sustainable ones both economically and environmentally.

2.1.1 Hydrogen

Pure hydrogen (H_2) is an invisible, odorless and non-toxic gas, lighter than air. Before we can use it, however, we must separate it, as it is not present in nature in its pure form.
Hydrogen is also environmentally friendly, safe and available everywhere: it constitutes 70% of the matter in the universe. Thanks to the wide availability, it can be obtained on site.

Hydrogen is therefore considered a central element of the energy transition and as one of the most promising energy carriers to replace fossil fuels. However, the use of hydrogen to store electricity and use that power is still reduced.
The idea of using hydrogen as a means of powering everything from factories to your own car may seem a bit futuristic, but in reality it has existed since the dawn of the industrial revolution: hydrogen powered the first internal combustion engine and from it became an integral component of the modern refining industry.
Many countries around the world, including here in Europe, are increasingly supporting initiatives and policies to extend hydrogen technologies and integrate them more into our energy and transport systems. The challenge is to produce it in a sustainable and safe way.

Hydrogen could represent almost a fifth of the energy consumed in the world in 2050 and almost a half in 2100 and also could power 10-20 million cars and a half million trucks by 2030 according to a study carried out by the Hydrogen Council, a group that brings together 18 multinationals (including General Motors, Honda and Shell) launched during the 2017 edition of the World Economic Forum (WEF).
This development, argued by the group, could contribute for 20% to the reduction of CO_2 emissions necessary to limit global warming to 2 °C[23].

[23] *Zero-energy hydrogen economy for buildings and communities – RSER (2017)*

A legitimate question that many ask about it is: will hydrogen run out naturally over time and will its short rise be nothing more than the latest fad in the search for clean and ecological energy alternatives? For example, for over a decade we have heard of hydrogen fuel cells as a clean alternative to fossil fuels, yet it seems that their great rival, the electric car, has captured the public and political imagination. Trying to answer this question, this may actually be the best time for hydrogen, as the recent interest and enthusiasm for hydrogen-based solutions don't seem to be fading anytime soon.

Indeed, its popularity could increase further as the global trauma of COVID-19 is starting to focus minds on how to build a truly sustainable new economy in the post-pandemic world. As noted by the IEA, the supply of hydrogen to industrial users is now a booming business and the demand for hydrogen has tripled compared to 1975 and is still growing. The agency also noted that today most of hydrogen production comes from fossil fuels, particularly natural gas. This doesn't seem very green at first glance, but many recent projects and demonstrations are showing how hydrogen production can be shifted from fossil fuels to renewable energy sources. Thanks to the lower costs of solar, hydro and wind energy, building electrolyzers in locations with good renewable resource conditions to produce hydrogen could become a low-cost and green solution, although there are additional costs for the effective transport of the hydrogen to end users. In the long run, good ideas about hydrogen integration are already being promoted in sectors that have not yet been touched by it, such as construction and power generation, although transportation is likely to be the first sector that is truly capable to use hydrogen to its full potential.

The European Commission has its own joint venture dedicated to hydrogen and fuel cells, an initiative that aims to demonstrate that hydrogen and fuel cells technologies as one of the fundamental pillars of future European energy and transport systems. All the joint venture's projects are dedicated to demonstrating how hydrogen can truly be a low-cost and economically efficient fuel of the future and potentially making an important contribution to the EU's ambitious goal of being fully carbon neutral by 2050.

2.1.2 Other sources

In the previous paragraph dedicated to hydrogen, we saw how the latter can potentially satisfy, in less than 80 years, about a half of the world's energy needs.
So now it remains to be verified how the remaining 50% will be composed by analyzing the other forms of energy already presented in the first chapter (1.1). In this part, however, instead of describing them in a general way, they will be analyzed above all from an economic and statistical perspective.

Nuclear power will not be among the energy sources that will be analyzed, even though it is sustainable energy. This is due to the simple fact that, as already mentioned in the first chapter, it is a sustainable energy resource from the point of view of production but not from the point of view of risks. In fact, if used in a careless and reckless manner, it can cause very serious damage to the environment and therefore also to the economy as happened in 1986 with the Chernobyl nuclear power plant in Russia and more recently with the Fukushima nuclear power plant in 2011 in Japan (both places are still uninhabitable and hostile)[24].

Having excluded nuclear power, there remain five sustainable energy sources that can satisfy the remaining part of energy needs: biomass energy, hydropower, wind energy, geothermal energy and solar energy. Some of these energy sources may also be useful for a green hydrogen production, but this will be seen later.

Biomass energy. Biomasses used to produce electricity are waste materials that are reconverted through thermal, chemical or biochemical processes. When biomasses are burned, they release heat, emitting a quantity of carbon dioxide substantially similar to that emitted in nature during a normal photosynthesis process.
The heat released allows the evaporation of the water in the thermodynamic circuit, where it becomes steam and is channeled into the pipes. Steam drives turbines which, in turn, produce electricity or heat for use in domestic or industrial plants.

[24] *Kharecha, Pushker A.; Hansen, James E. "Prevented Mortality and Greenhouse Gas Emissions from Historical and Projected Nuclear Power" - Environmental Science & Technology (2013)*

It goes without saying that biomasses are renewable sources: the exploitation time of biomass is almost similar to that of regeneration and their combustion re-releases the carbon dioxide that had previously been absorbed by the biomass itself into the atmosphere.
Installation costs of biomass power generation systems are estimated based on several key factors, including the equipment arrangement, plant size, and geographical factors. These costs can be reduced applying economies of scale, that are critical with regards to operating costs. While larger plants are more efficient, cost per kilowatt is also lower due to labor costs. Therefore, it is understandable from an economic point of view, a biomass energy production system is convenient only by applying economies of scale and therefore having a plant of significant size.

Biomass energy demand has grown a lot over the past 10 years and is continuing to grow. In fact, each year's requirement refers to the average of each utility's one-hour retail peak demand for the previous 3 years:

- 2011-2015: 10%
- 2016-2019: 15%
- 2020 ongoing: 20%.

The good news is that many of the investor-owned and cooperative utilities have utilized wind power generation to maintain a green energy production[25].

Biomass available for energy purposes is increasing, in Italy and in Europe both in terms of forest resources, and in terms of the use of forest and agricultural residues.
The valorization of residues appears to be particularly in line with the concepts of sustainability and with the principles of the circular economy.
Referring to Italian territory, a study by the Ca 'Foscari University of Venice identified the socio-economic impact of the sector of solid biomass energy generation, examining the role in terms of employment, income and tax effects. The analysis refers to 2017 and shows that the aggregate value of energy production and its related activities is estimated between 210 and 280 million euros and it generates about 1,300 full-time jobs, with a total income from work of 22 million euros.

[25] *Darby, Thomas "What Is Biomass Renewable Energy" - Real World Energy (2014)*

In addition to the employment and income effects, the production of energy from biomass involves further stimuli for the local economy, thanks to the supply chain strongly rooted in the territory, with a positive effect on consumption expenditure of about 20 million euros. Positive data also comes from the analysis of the environmental impact, in fact, compared to the use of non-renewable sources, the activity of these plants allows to drastically reduce CO_2 emissions, saving up to 100 million euros[26].
Also, the CNR report addressed the environmental implications of the use of solid biomass for the production of electricity. The report highlights how technological evolution, especially on industrial plants, has made it possible to substantially reduce the emissions of pollutants to levels so low as to be imperceptible, as confirmed by the monitoring campaigns on environmental effects which confirm the absence of fallout of pollutants in the areas where the latter arise.

Nowadays, biomass satisfies about 15% of primary energy uses in the world, with 55 million TJ/year (1,230 Mtoe/year). The use of this source, however, shows a strong degree of inhomogeneity between the various countries.
Anyhow, the use of biomass has an excellent potential, and in the near future, it will be able to supply over 20% of energy in the world[27].

[26] *Alessio Agrillo, Martino dal Verme "Rapporto Statistico 2019" - GSE (2019)*
[27] *Haugen R.; C. Gustafson "Biomass Compare" - North Dakota State University (2016)*

Hydropower. Hydropower is a renewable energy, so it can be considered a green energy. It is obtained from the water of lakes and rivers by creating dams that exploit the fall of water from great heights or the large masses of water in rivers. The storage systems draw water from specific basins purposely built while the run-of-the-river systems use the natural motion of waterways and rivers to create energy. The task of transforming mechanical energy into electrical energy is entrusted to hydroelectric power plants. To achieve this, they exploit the potential of mechanical energy contained in a mass of water, positioned at a higher altitude than the turbines. These are activated by the falling water flow and, the greater is the difference in height between the mass of water and the turbines, the is greater the power of the hydraulic system.

The production of energy through hydroelectricity is the cheapest system for the moment. Once the investments necessary for the creation of dams, plants and maintenance works have been completed, the precipitation of rain and snow ensures, in fact, the complete free and continuous availability of the raw material. This availability, moreover, thanks to the technologies used for the turbines, takes place very quickly.
Of course, this clean energy also has its downsides. The variability of meteorological conditions with the possibility of long periods of drought make it dependent on atmospheric agents which, obviously, cannot be kept under control. It should also be considered that the construction of dams, penstocks and power plants involves, in most cases, a disfigurement of the environment. Another issue is that the different structures cannot be built everywhere, but only on suitable terrain.

Today, hydroelectric energy supplies the 90% of the world's electricity production from renewable sources and about 10% than the total in the world. This percentage may also grow in the future, but to a limited extent due to the reasons listed above, such as the territorial suitability for the installation of the systems[28].

[28] *IEA (International Energy Agency) - https://www.iea.org/data-and-statistics?country=WORLD&fuel=Energy%20supply&indicator*

Wind energy. To "cultivate" wind energy many parameters are needed to know: maximum wind speed, daytime, night and seasonal variations, wind speed with the height above the ground, etc.
Before installing a wind turbine, it is advisable to carry out anemometric measurements that give a general picture of the characteristics of the wind in the exact installation point. This study is carried out with devices called anemometers.

It is demonstrated that only 59.3% of the power possessed by the wind can theoretically be absorbed by the wind system. The reason is easy to understand: to give up all its energy, the wind would have to reduce its speed to zero immediately behind the rotor, with the absurdity of a mass in motion first and a perfectly immobile mass of air immediately after.
In reality the wind, passing through the rotor, undergoes a slowdown and releases part of its kinetic energy: this slowdown occurs partly before and partly after the wind turbine.
The kinetic energy of the wind varies with the cube of its speed: if the latter doubles, the energy increases approximately eight times and if the wind speed increases by 10% there is an increase of 30% in energy. In addition to the weather conditions, among the various factors that influence wind speed there are local geographical effects, such as the roughness of the ground and the height of the air currents.
Evaluating the windiness of a site requires a thorough investigation, which can take years. The sites must be selected on the basis of biological and geomorphological indicators and then, the final selection is made after a period of measuring wind speed and direction.
Important is the availability of the source and that of the machine itself.
Interesting sites guarantee around 100 wind days/year (around 2400 h/year). Good machines allow to use at least 95% of the available wind.

The work that a wind turbine can do depends on the rotor area and its aerodynamic efficiency. A wind turbine that can use the wind force ranging from 3 m/s to 30 m/s can produce on average 860 kWh per year for every m2 of intercepted air flow; a wind rotor can have a nominal power of 0, 3-0.5 kW/m2.
Actually, wind energy supplies about 5% of world's energy need, percentage destined to grow in the future but, as for hydropower, growth is hampered by the nature of territory for the installation of the plants.

Geothermal energy. The origin of geothermal heat is due to the physical processes that take place in the underlying layers of the earth's crust of our planet. This heat is present in enormous and practically inexhaustible quantities.
The internal heat dissipates regularly towards the surface of the earth, which gives off energy into space quantifiable in an average thermal current of 0.065 Watt/m^2.

In addition to the production of electricity, various uses are possible depending on the temperature of the geothermal fluid: aquaculture (maximum 38 °C), greenhouse cultivation (38-80 °C), district heating (80-100 °C), industrial uses (at least 150 °C) and many others.

The development of a geothermal field requires a high initial use of capital followed by a relative low operating cost.
The economic evaluation of this development implies taking into account a certain number of factors like topography and geographical area where to build the plant.
Most of the costs (46.58%) are absorbed by the construction of the plant largely built with special steels, followed by the cost of drilling the development and exploration wells (42.1%), that for the construction of pipelines for transporting the steam to the plants (6.85%), the connections with the power distribution lines (2.74%), the remaining costs are distributed among the geological and geophysical exploration activities, the practices for obtaining and managing government permits.

Today, geothermal energy supplies a little more than 5% of world's energy need. Geothermal power has a high potential that some luckier nations are already able to exploit, such as New Zeland. But with the appropriate technological developments this can be a very important sustainable resource for the future[29].

[29] *IEA (International Energy Agency) - https://www.iea.org/data-and-statistics?country=WORLD&fuel=Energy%20supply&indicator=Total%20primary%20energy%20supply%20(TPES)%20by%20source*

Solar energy. Solar energy is the primary source of energy par excellence.
Every year the sun radiates on the earth 19,000 billion TOE (Tonnes of Oil Equivalent), while the annual world demand for energy is about 13 billion TOE and the Italian one is about 190 million TOE.

To exploit solar energy, the most common method is using photovoltaics.
Currently about 85% of the photovoltaic modules on the market are built starting from silicon semiconductors. The size of the plant can be even less than 1 kW, currently the largest photovoltaic plant is installed in India and has a power of 214 MW[30].
It is often the most suitable system for isolated users where it would be expensive to connect to the electricity grid or where there are no other primary sources such as constant winds, water courses, etc.

The potential of solar energy is such that it can satisfy the entire energy needs of the planet, but the weak point of this resource is the production of technologies to exploit it, such as the photovoltaics mentioned above. In fact, the production process of these technologies is very harmful to the environment and for this reason there is a heated debate on the effective sustainability of solar energy.

Therefore, in addition to hydrogen, there are various forms of renewable and sustainable energy that can accommodate the planet's demand for energy. Many of them have great potential which, if unlocked, can go beyond what we need. Furthermore, some of them can be very useful for the sustainable production of hydrogen and for this reason it is desirable to establish an interconnected ecosystem among these priceless resources.

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[30] *Antonio Luque, "Will we exceed 50% efficiency in photovoltaics?" - aip.org. (2016)*

2.2 Methods for hydrogen production

Hydrogen can be produced using several processes. Thermochemical processes use chemical and thermodynamic reactions to obtain hydrogen from organic materials such as fossil fuels and biomass. Electrolysis and solar energy foresee water (H_2O) broken down into hydrogen (H_2) and oxygen (O_2).

Thermochemical Processes. Some thermal processes use energy to obtain hydrogen from their molecular structure. In other processes, heat, in combination with closed chemical cycles, produces hydrogen from raw materials such as water.

Thermochemical processes are divided in[31]:

- Coal gasification: hydrogen is produced by first reacting coal with oxygen and steam under high pressures and temperatures to form synthesis gas, a mixture consisting primarily of carbon monoxide and hydrogen.

  $$CH_{0.8} + O_2 + H_2O \rightarrow CO + CO_2 + H_2 + \text{other species}$$

  After the impurities are removed from the synthesis gas, the carbon monoxide in the gas mixture is reacted with steam through the water-gas shift reaction to produce additional hydrogen and carbon dioxide. Hydrogen is removed by a separation system, and the highly concentrated carbon dioxide stream can subsequently be captured and stored.

  The production of hydrogen from coal also offers environmental benefits when integrated with advanced technologies. The integration of these technologies facilitates the capture of multiple pollutants such as sulfur oxides and mercury, as well as greenhouse gases such as carbon dioxide and also, when hydrogen is used in efficient fuel cells, emissions can be nearly eliminated.

  Many sectors could thus operate practically with zero emissions, such as industries and transports.

[31] *Zweifel, "Energy economics - Theories and applications" (2017)*

- Biomass gasification: is a mature technology pathway that uses a controlled process involving heat, steam, and oxygen to convert biomass to hydrogen at high temperatures (over 700 °C) without combustion.

  $CO + H_2O \rightarrow CO_2 + H_2$ (+ small amount of heat)

  In general, biomass does not gasify as easily as coal, and it produces other hydrocarbon compounds in the gas mixture exiting the gasifier; this is especially true when no oxygen is used. In fact, an extra step must be taken to separate hydrogen and then the separated hydrogen is purified.

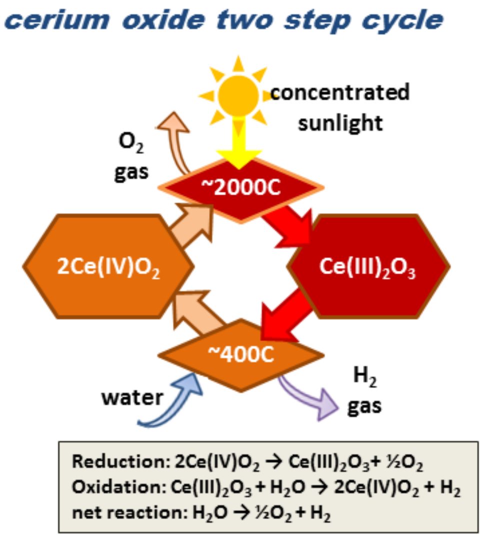
  Because growing biomass removes carbon dioxide from the atmosphere, the net carbon emissions of this method can be low, especially if coupled with carbon capture, utilization, and storage in the long term. Gasification plants for biofuels are being built and can provide best practices and lessons learned for hydrogen production. This kind of plants could be up and running in few years.
- Natural gas reforming: Natural gas contains methane (CH_4) that can be used to produce hydrogen with thermal processes, such as steam-methane reformation and partial oxidation.

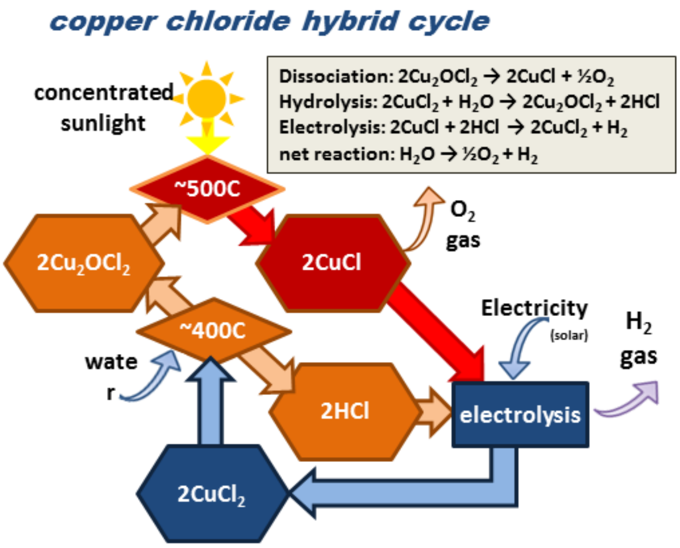
  Most common method to produce hydrogen with natural gasses is steam-methane reforming. This is a production process in which high-temperature steam (700 °C–1,000 °C) is used to produce hydrogen from a methane source, such as natural gas. In steam-methane reforming, methane reacts with steam under 3–25 bar pressure in the presence of a catalyst to produce hydrogen.

  In a final process step called "pressure-swing adsorption," carbon dioxide and other impurities are removed from the gas stream, leaving essentially pure hydrogen.

  $CH_4 + H_2O$ (+ heat) $\rightarrow CO + 3H_2$

- <u>Solar thermochemical hydrogen (STCH)</u>: Thermochemical water splitting uses high temperatures and chemical reactions to produce hydrogen from water. This is a long-term technology pathway, with potentially low or no greenhouse gas emissions. Two examples of thermochemical water splitting cycles are[32]: 1) the "direct" two-step cerium oxide thermal cycle (left picture); 2) the "hybrid" copper chloride cycle (right picture). Typically, direct cycles are less complex with fewer steps, but they require higher operating temperatures compared with the more complicated hybrid cycles.





[32] *Hai Wang; Christof Schulz, "Progress in Energy and Combustion Science – An International Review Journal" (2019)*

- Electrolysis: Electrolyzers use electricity to split water into hydrogen and oxygen. This technology is well developed and commercially available and systems capable of efficiently utilizing intermittent renewable energy are being developed.
  Electrolyzers consist of an anode and a cathode separated by an electrolyte.
  Anode Reaction: $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$
  Cathode Reaction: $4H^+ + 4e^- \rightarrow 2H_2$
  Hydrogen produced via electrolysis can result in zero greenhouse gas emissions, depending on the source of the electricity used. Hydrogen production via electrolysis may offer opportunities for synergy with variable power generation, which is characteristic of some renewable energy technologies. For example, hydrogen fuel and electric power generation could be integrated at a wind farm, allowing flexibility to shift production to best match resource availability with system operational needs and market factors. Also, in times of excess electricity production from farms, instead of curtailing the electricity as is commonly done, it is possible to use this excess electricity to produce hydrogen through electrolysis.

Two other types of hydrogen production process are also noteworthy, namely: direct solar splitting of water and biological processes[33]. However, the description of these techniques is useless, given the still embryonic state of both. But it must be said that they are under development and that potentially, especially the direct solar splitting of water, they will be able to contribute to a good slice of a 100% green production of hydrogen.

Sustainable production of hydrogen can be done through electrolysis, STCH and biomass gasification. These processes practically eliminate the emission of carbon dioxide and greenhouse gases despite coal gasification and natural gas reforming which are not entirely sustainable given the use of non-renewable and highly polluting sources. Moreover, sustainable production methods are also cheaper at an economic level due to the fact that it is enough to implement some technologies in the original plants for the final production of pure hydrogen, while with coal and natural gas it is necessary to have a separate plant.

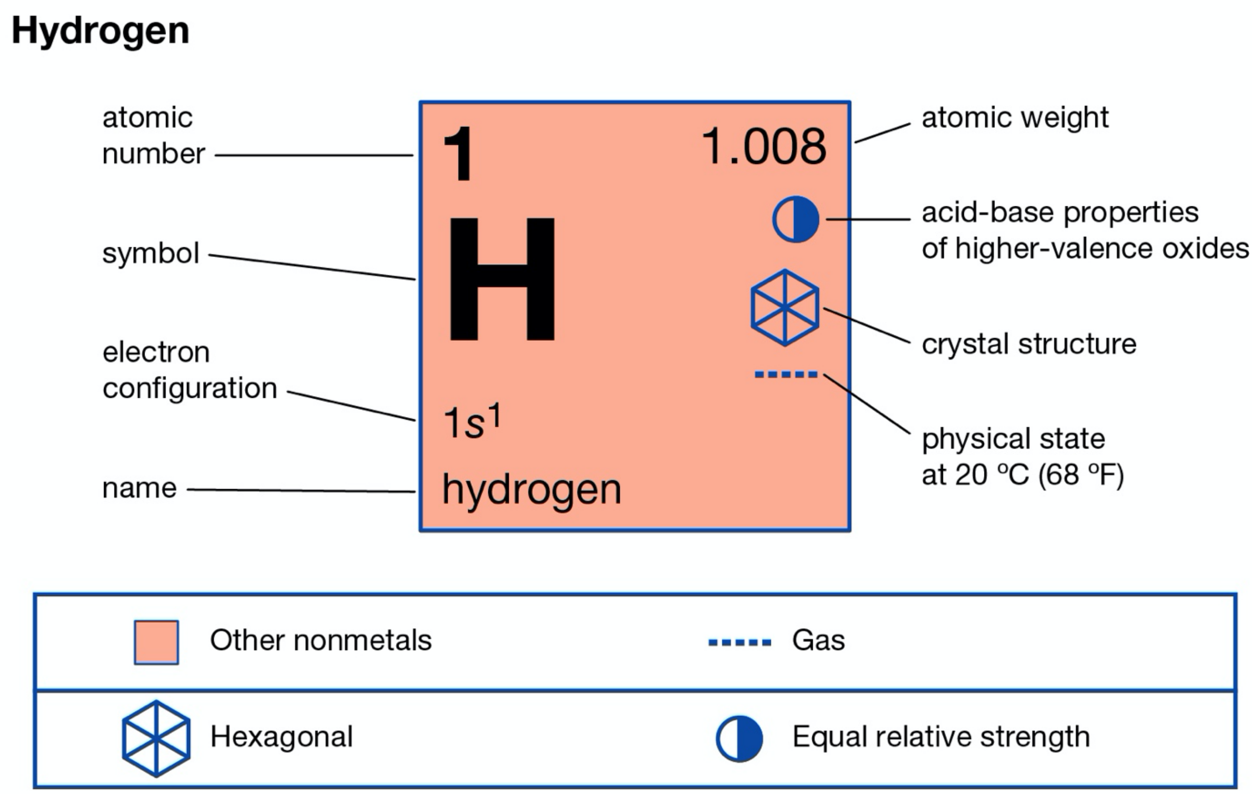
[33] *N. Waters, "Hydrogen Basics – Solar Production", University of Central Florida (2014)*

3. Unlock the potential of the most common element in the universe

We already said that hydrogen is the most common element in the universe, and it is precisely for this reason that compared to the other energy resources on which we are working for the future, it is with no doubt the one with the greatest potential. Thus, as oil and coal have been protagonists from the era of industrialization to this part, hydrogen will have the same role from the recent future onwards and to this we will owe most of the discoveries and progress.

3.1 H_2 is the key

Just because hydrogen is an almost infinite and extremely sustainable resource, it will be the key to a future in the name of a clean world. To unlock this enormous potential, however, it is necessary to develop different technologies and above all use them correctly.



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[34] *William L. Jolly, "Chemical Properties of Hydrogen", Encyclopædia Britannica (2018)*

3.1.1 Use of hydrogen in the contemporary economy

Hydrogen today is a resource widely used in some fields of research and it is starting to expand also in some sectors of the industry. What is certain is that it is not yet used as energy for mass consumption.

The main and most important role played by hydrogen in the world today is in the synthesis of ammonia, but its use is rapidly extending to fuel refining, hydrogen splitting and sulfur elimination.
Among the consumed quantities of hydrogen, the ones that end up in the processes aimed at the manufacture of organic chemicals are enormous. The same is true of those who see it as the basis of rocket fuels, along with oxygen or fluorine, and as a propellant for nuclear-powered rockets. In fact, hydrogen seems to be suitable for use as a fuel or in fuel cells but also aspires to become an important alternative source of fuel.

Hydrogen is very successful, and has green implications, even when used in fuel cells (cells consisting of two electrodes separated by an electrolyte). The green side is the little if any formation of nitrogen oxides, which are not very good for us, for our lungs, and for the planet as a whole.

The world of transport has for some time put its eye on this element of the periodic table placed at the beginning for many valid and profitable reasons. For example, the aviation sector, has been happy to use hydrogen for decades, mainly for convenience related to weight. Also because of the increasingly pressing environmental problems, road transport has also moved, in fact, large producers as Toyota, Hyundai, Honda and BMW are investing heavily in this sector and have already put some hydrogen-powered vehicles on the market. The beauty, the green, the future and even the present of all this is that, with the hydrogen used in fuel cells, energy can be obtained in the form of electricity (from the oxidation of hydrogen) without direct combustion and obtaining greater efficiency. This, coupled with the fact that it is possible to produce hydrogen from renewable sources, gives us a valid clean alternative to current internal combustion engines powered by fossil fuels.

3.1.2 Benefits and conveniences

Clean energy. If produced from sustainable sources, in the use phase, hydrogen is a clean fuel because it does not emit pollutants. This can make a huge difference in several sectors, especially the transport sector, since the distribution system would not be upset, indeed, it would remain very similar to that of fossil fuels. Furthermore, the production process of hydrogen cars is green compared to that of electric cars because the production and disposal of the batteries of the latter has a very heavy impact on the environment. Also, technologies such as lithium batteries guarantee very short intervention times but do not allow the accumulation of large amounts of energy, with discharge times not exceeding days.
On the contrary, the use of hydrogen guarantees a seasonal accumulation of electricity, making extensive use of renewable sources possible. On a large scale, it has been shown that hydrogen can be efficiently stored in gaseous form inside salt caves, with low costs of up to 50 euros per MWh. This solution, given the potential in Europe, is significantly investigated and promoted in demonstration projects by FCH-JU[35]. Hydrogen also allows the energy produced to be transferred to other sectors and regions efficiently.

Energy vector. Hydrogen allows the transport and conservation of energy over time. One of the factors that favor the use of hydrogen is that with it is possible to accumulate energy, produced from various sources, and transport it at a distance, where this energy can be used. Hydrogen is transported via networks, it is interchangeable through fuel cells and it is, once generated, a clean vector from an environmental point of view, such as also the respective energy conversion processes. The peculiarity of hydrogen is that it transports and conserves energy even in large quantities and for this reason, thanks to these characteristics, hydrogen in some fields, such as aeronautics is an extremely more effective element than others. Exactly for these reasons, several projects that use hydrogen as an energy vector are still under development. In Germany, a consortium of companies and universities has invested 20 million euros in the construction of an electrolyzer to convert excess wind energy and produce approximately 1,500 kg of hydrogen per day. In the Netherlands, the conversion of a 1,320 MW plant for hydrogen operation is being considered, while in Japan, several companies are developing technologies for the storage and conversion of hydrogen[36].

[35] *Fuel Cells and Hydrogen Joint Undertaking (FCH-JU)*
[36] *Noordelijke Innovation Board – "The Green Hydrogen Economy" (2019)*

3.1.3 Handicaps and disadvantages

Hydrogen has to be produced. On Earth, hydrogen is not found in a pure state but only in a combined form in molecules with other chemical elements. Hydrogen as we have already seen is not a ready-to-use resource but must be produced. There are several methods for hydrogen production, some sustainable and others polluting. So, the fact of having to produce it already implies additional costs and additional energy use.

The production of hydrogen can cause pollution. The production of hydrogen has a strong environmental impact if it uses polluting energy sources such as oil, gas or coal. On the other hand, it has a minimal impact if it is based on clean energy sources such as solar, wind, hydroelectric, etc. However, it must be specified that whatever method is used, the production process would be much less polluting than ones for fossil fuels production.

It is a flammable gas. Flammability is the most important chemical property of hydrogen. Hydrogen reacts with all oxidizing agents such as oxygen, color, etc. and in all cases the reactions are accompanied by a high level of heat development. In fact, in the presence of an ignition source, the reactions can become explosive, especially if they take place indoors. That is why in its pure state, hydrogen is highly flammable. It is therefore particularly dangerous when stored in large quantities in a closed container.
The fact that hydrogen is potentially explosive is certainly an obstacle to overcome, especially in the transport sector but it must be said that if the hydrogen itself were not flammable it would not be a perfect substitute for the various types of fuel.

3.1.4 Properties of hydrogen

The long and turbulent cosmic evolution has also brought some hydrogen on Earth, combining with other elements and distributing themselves in a different way in the spheres that constitute it. It prevails as water in the atmosphere, hydrosphere and, in part, in the lithosphere which, with the biosphere, also contains it in the form of organic compounds. Hydrogen in the elementary state, is present in negligible quantities, being a gas so light that it escapes the force of gravity and leaves the atmosphere.

Hydrogen was discovered in 1766 and it has been called like this because in Greek it means "water generator". After the discovery, all that remained was to study its properties.

First element of the periodic table. Under normal circumstances it is a colorless and tasteless gas, made up of diatomic molecules, H_2. The hydrogen atom, symbol H, consists of a nucleus with a unit of positive charge and an electron. Its atomic number is 1 and its atomic weight is 1.00797 g/mol[37]. It is one of the main constituents of water and all organic matter and is widely scattered not only on earth but also throughout the universe. There are three isotopes of hydrogen: protium, mass 1, which is found in more than 99.985% of the natural element; deuterium, mass 2, which occurs in nature in approximately 0.015% and tritium, mass 3, which appears in small quantities in nature, but can be artificially produced by various nuclear reactions.

Common hydrogen has a molecular weight of up to 2.01594 g.

As a gas it has a density of 0.071 g/l at 0 ºC and 1 atmosphere.

Its relative density, when compared with that of air, is 0.0695.

Hydrogen is the most flammable of all known substances and it is also slightly more soluble in organic solvents than in water.

At normal temperatures, hydrogen is not a very reactive substance, unless it has been activated in some way, for example, through a suitable catalyst, in fact, at high temperatures it is highly reactive. Although in general it is diatomic, molecular hydrogen dissociates into free atoms at high temperatures.

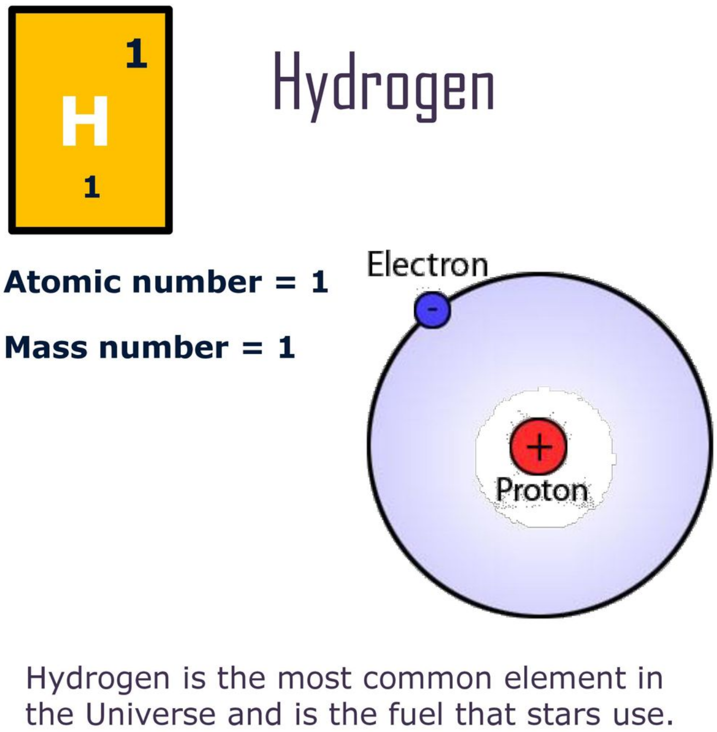
[37] *P. Patnaik, "A Comprehensive Guide to the Hazardous Properties of Chemical Substances" (2007)*

Atomic hydrogen is a powerful reducing agent, even at room temperature. It reacts with the oxides and chlorides of many metals, such as silver, copper, lead, bismuth and mercury, to produce free metals. It reduces some salts to their metallic form, such as nitrates, nitrites and sodium and potassium cyanide. It reacts with a number of elements, metals and non-metals, to form hydrides.

Hydrogen also reacts with organic compounds to form a complex mixture of products; with ethylene (C_2H_4) for example, the products are ethane (C_2H_6) and butane, (C_4H_{10})[38].

The heat released when hydrogen atoms recombine to form hydrogen molecules is used to achieve high temperatures in atomic hydrogen welding.

[39]



Particle	Charge	Number	Overall charge
Proton	+1	1	1
Electron	-1	1	-1

[38] *E. W. Schefer; B. Patterson, "Visible emission of hydrogen flames" (2009)*

[39] *Inspire Enterprise Academy of Southampton*

3.2 Hydrogen market

Hydrogen could be the right solution to achieve the climate goals set for 2050, by which time its market could reach a total value of 1 trillion dollars[40]. Provided, however, that the sector is supported by public policies and becomes the subject of massive investments. Hydrogen, indeed, could make a decisive contribution to decarbonise sectors that otherwise would have difficulty in breaking down own CO_2 emissions.

The role of hydrogen could be particularly relevant in allowing a reduction of the environmental impact of some industrial and transport chains, but it would also be a valid tool for storing energy produced from renewable sources and not immediately worn out.

In the scenario outlined by Barclays, green hydrogen (produced from renewable sources) will however reach a significant market share only in 2030, and to ensure that by 2050 the production costs are sufficiently competitive to allow this energy vector to become 'scale up', investments in the order of 500 billion dollars per year will be required for the next 30 years. If these conditions actually occur, global hydrogen production could rise from the current 70 million tons per year up to 575 million tons per year.

To achieve this goal, however, a substantial increase in installed electrolysis capacity will also be required, which currently according to Barclays is only 3 gigawatts, and which should instead reach 900 gigawatts.

Finally, to make hydrogen truly competitive, production costs will have to drop, compared to current levels, by 75% for green hydrogen and 30% for blue hydrogen (hydrogen produced by steam methane reforming with CO_2 capture produced).

[40] *Barclays Capital "Hydrogen, a climate megatrend" – Report (2019)*

3.2.1 Possible industry applications

Hydrogen, in addition to its current uses, can potentially be used for many types of industrial activities. Hydrogen can be used to produce other compounds or as fuel to produce energy. In particular, the hydrogen produced is used in the chemical industry to produce ammonia, methyl alcohol (methanol), fertilizers for agriculture and petroleum products, and in the metallurgical industry for the treatment of metals.

Hydrogen is also an excellent fuel that can be used to produce energy in two ways. The first method consists in burning hydrogen alone or burning it added to other fuels.

The second method consists in making hydrogen react chemically with oxygen (not by burning it), directly obtaining electricity through a device called fuel cell.

- **Chemical reactions supply**: Hydrogen is used in many chemical processes.
  The main processes in which it is used are the Haber Process and the hydrocracking.
  The Haber-Bosch Process[41] consists in combining hydrogen with nitrogen to produce ammonia (NH_3), which can be primarily used as a fertilizer in agriculture. To carry out this procedure, however, very high temperatures would be required which at the same time would not favor the synthesis reaction. The discovery and subsequent improvement of the catalytic system used by Fritz Haber and Carl Bosch made it possible to use significantly lower operating temperatures, thus solving the problem.
  Hydrocracking[42], in the other hand, is a catalytic process and consists in converting heavy oil sources into lighter fractions suitable for use as fuel. It is therefore one of the two main conversion processes used in the modern refining industry. Hydrocracking plays a versatile role, adapting to the production of middle distillates and therefore it is widely adopted for its ability to provide superior quality products such as high-quality middle distillates and gasoline fractions (naphtha).
  Hydrocracking is a process that admits a wide range of fillers and provides a great variety of products. It is an environmentally friendly process as it eliminates from fuels those compounds that would otherwise diffuse into the atmosphere in the form of sulfur and nitrogen oxides, also, the exothermic reactions of hydrocracking imply a low net fuel requirement and therefore a low quantity of gas emissions.

[41] *"Papers, Chemistry - Haber's process chemistry", Arihant Publications (2018)*
[42] *Enciclopedia Treccani*

- **Transport sector/Internal combustion engines**: Hydrogen can be used for energy purposes in internal combustion engines, properly designed, with the typical efficiency of such engines, good power and the advantage of an already mature technology with relatively low costs. The intervention in this sector is aimed at the development of both internal combustion engines and fuel cell engines, the latter essential for a transport system with minimum environmental impact.
  In the first case it is an engine with cylinders and pistons, which burns hydrogen instead of petrol or diesel and does not force us to rethink the technology of internal combustion engines. In the second case, it is a technology in which fuel cells produce electricity and power electric motors.
  One of the advantages of using fuel cells for vehicle traction is their energy efficiency; in fact, the percentage that is actually usable for the movement of the vehicle is more than 50%[43] of the energy produced by the fuel while, in petrol engines is reached a maximum of 40%. Furthermore, in urban traffic the energy efficiency of hydrogen vehicles is about double that of classic cars. Finally, the waste material is made up of water vapor only, therefore with an almost zero environmental impact.
  Hydrogen can be supplied to the cells of a vehicle from a tank where it is stored in the liquid or gaseous state. Alternatively, it can be extracted from hydrocarbons, such as methane or methanol directly on board by means of a reformer. The possibility of exploiting sodium borohydride and sunflower oil is currently being studied.
  The characteristics of the fuel cells also allow the construction of vehicles with very different sizes (bicycles, cars, buses, railway engines) with the same technology and with equivalent performance characteristics, consumption and environmental impact.
  Currently, many car manufacturers are making experimental models of hydrogen cars and buses. Some prototypes already circulate in various Italian and foreign cities. Other manufacturers, indeed, have already put on the market hydrogen-powered cars and buses. Car producers currently are Toyota, Hyundai, Honda, BMW and among bus producers there are Mercedes, Irisbus and Toyota.
  The problem for the development of hydrogen vehicles, in addition to that of the production of this fuel, is the lack of a distribution network and refueling stations for this gas.

[43] *Z. Stevic; I. Radovanovic, "Energy Efficiency of Electric Vehicles" - Technological Development Republic of Serbia (2018)*

Today, hydrogen dispensers are a rarity but the IEA, the European Commission, governments and cities have long believed that hydrogen is essential to be able to eliminate emissions in public transport and reduce air pollution. For example, Paris, Mexico City and Amsterdam plan to replace their current buses and trucks with hydrogen or battery-powered models as early as 2025. Similarly, DHL and La Poste are adopting hydrogen-powered road transport solutions. As for hydrogen trains, the French manufacturer Alstom has introduced the Coradia LINT model, an articulated railcar designed for non-electrified rural lines.
At sea, hydrogen technologies are less advanced and progress is slower. An exception is Viking, a cruise ship brand, which has ordered a series of hydrogen ships.
In the field of container shipping, progress is even more uncertain, although ABB is working with Hydrogène de France to develop a large-scale hydrogen fuel cell system to power container ships. Regarding the luxury yachting segment, in recent days has been announced that Bill Gates commissioned a 600M dollars hydrogen powered yacht[44] that could be the beginning of a new frontier for the nautical world.
There are still many concerns regarding safety aspects due to the unfamiliarity with this energy vector. However, a more careful analysis resizes the concept of the danger of hydrogen. This gas is less flammable than petrol (it has a higher self-ignition temperature). Hydrogen is the lightest of the elements and therefore is diluted and dispersed very quickly in open spaces. It is practically impossible to detonate it, except in confined spaces (to identify potentially dangerous concentrations, sensors that can easily control adequate safety systems are used). Moreover, when it burns, the hydrogen is consumed very quickly, always with flames directed upwards.
On the other hand, materials such as petrol, diesel, LPG or natural gas are heavier than air and, by not dispersing, remain a source of danger for much longer times. It has been calculated that the fire of a petrol vehicle lasts 20-30 minutes, while for a hydrogen vehicle it lasts no more than 1-2 minutes. Furthermore, in the case of hydrogen flames, there is little chance that nearby materials can be set on fire, thus reducing, in addition to the duration of the fire, also the danger of toxic emissions. Also, hydrogen unlike fossil fuels, is neither toxic nor corrosive and any leaks from the tanks do not cause problems of soil pollution or of underground aquifers.

[44] *Bill Springer, "The Ultimate Sustainable Superyacht" - Ocean Home Magazine, via Forbes (2020)*

- **Fuel cells**: The fuel cell is a device capable of use hydrogen to produce electricity with good efficiency. A fuel cell consists of two electrodes in porous material, the cathode (negative pole) and the anode (positive pole). The electrodes act as catalytic sites for cell reactions that basically consume hydrogen and oxygen, with the production of water and the passage of electric current in the external circuit. The electrolyte is placed between the two poles, which has the function of conducting the ions produced by one reaction and consumed by the other, closing the electrical circuit inside of the cell. The electrochemical transformation is accompanied by the production of heat, which must be extracted to keep constant the temperature of the operating cell. This structure is very similar to that of common electric batteries but, unlike the latter, hydrogen fuel cells consume substances that come from the outside and therefore are able to operate without interruption as long as they are supplied with fuel and oxidizer. The cell has a flat structure with three layers: the central one, between the cathode and the anode, constitutes or contains the electrolyte. The individual cells are superimposed on each other and connected in series in order to obtain a current voltage of the desired value. Multiple stacked cells are called a stack. Generally, a fuel cell system consists not only of the electrochemical section, but also of a current converter and a transformer which convert the direct current generated by the battery into alternating current. Fuel cells differ according to the chemical nature of the electrolyte and the temperature at which they operate. The cells that release temperatures between 60 and 200 degrees centigrade are called low-medium temperatures, while those that develop heat up to 1000 degrees centigrade are defined as high temperatures[45]. The latter are often used for applications that require both electricity and heat.

  The technology that uses hydrogen as an energy source is rapidly developing both for stationary applications and for mobile systems.

[45] *U.S. Department of Energy – Energy Efficiency and Renewable Energy office report*

Fuel cells are of considerable interest for the production of electricity, as they have energy and environmental characteristics that make their adoption potentially advantageous: high electrical efficiency, with values ranging from 40-48% (referring to the lower caloric value of the fuel) for systems with low temperature cells, up to over 60% for those with high temperature cells, very low environmental impact, both from the point of view of gaseous and acoustic emissions, which makes it possible to place the systems also in residential areas, making the system particularly suitable for the production of distributed electricity possibility of cogeneration (associated production of electricity and heat): the cogenerated heat can be available at different temperatures, in the form of steam or hot water, and used for sanitary purposes, air conditioning, etc.

Hydrogen can be used to power up many things such as vehicles and many commonly used electronic devices, such as laptops, cell phones and toys, which today require heavy and expensive batteries. A miniaturized fuel cell is lightweight, economical, and longer-lasting than an ordinary battery. Mobile phones, for example, could work continuously for months and it would be enough to periodically buy a vial of a fuel rich in hydrogen (such as methane or methanol), to be inserted into the device, to power the small fuel cell[46].

Liquid hydrogen is also used on board the spacecraft to power the fuel cells that provide the electricity necessary for the operation of the onboard instrumentation. The water obtained as a by-product from these fuel cells can be drunk by the crew.

[46] *Janneke Pieters, "Hydropowered devices" (2016)*

- **The hydrogen fuel**: The combustion of hydrogen does not present particular problems and gives rise to much fewer polluting emissions than other fuels. The products of combustion with air are water, unburned hydrogen and traces of ammonia. So, if car engines or home boilers were fueled with this gas, energy could be produced while avoiding emissions of harmful substances. Furthermore, any other fuel mixed with hydrogen improves combustion and its efficiency. For this reason, the use of methane has been tested in the United States with the addition of 15% by weight of hydrogen, commercially defined as Hythane[47]. If methane (or rather natural gas) were to become the main source of hydrogen, it would be more sensible to store it and transport it with special compressed methane car tanks and run a series of reformers and fuel cells directly from methane. The resulting system uses methane energy more efficiently, produces less total CO_2, and requires fewer new infrastructure.
  An added benefit is that methane is much easier to transport and handle than hydrogen. However, the methane used in the fuel cells must not have traces of methanol or ethanol, the foul-smelling substances that are injected into the gas distribution to help users immediately discover any leaks, therefore with the inevitable risks associated with leaks. The sulphones responsible for the odor cause the poisoning (or deactivation) of the catalyst in the membrane of the fuel cell. Furthermore, since the technology to run internal combustion engines directly from methane is well developed, low-polluting, and extends the life of the engine, compressed natural gas (CNG) is more likely to be used for transportation in this way rather than in fuel cells, at least in the near future.

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[47] *Bolzonella David, "Hythane Production", ScienceDirect Topic (2019)*

3.2.2 Gradual oil replacement

The recent crisis in the price of oil has accelerated the debate on the future of black gold and planetary energy balances. Just as the stone age did not end due to a lack of stones, the oil age will not end due to the exhaustion of all oil wells but will turn to sunset when more efficient and economically/environmentally sustainable energy mixes will be found on a global scale.

The alarm has been raised several times for a future depletion of the wells, but the economy will dictate the definitive decline of the curve.

The current situation is characterized by an anemic market which could lead to a million unemployed in the oil sector and for this reason is decidedly dramatic. Oil was already experiencing a slow decline in energy mixes, given that its share predicted by many analysts for 2020 was 32% of global energy needs versus 46% in 1970.

Oil is on the avenue of the sunset, an avenue that however promises to be long and will be traveled with slow and gradual steps. The thirst for oil of the large fast-growing economies of East Asia is too high and the geopolitical importance of areas such as Venezuela and the Russian Arctic is too high to reduce, as things currently stand, the black gold to a memory of the past. Any resource that will replace oil in the global market as a reference energy resource must have exploited in a versatile way: have the ability to create around itself a market and a reference system; be able to be marketed with convenient economies of scale; to be applied in the two fields currently relevant to oil, industry and transport; have, a need arisen in recent years, an environmental impact in terms of emissions reduced compared to black gold. As things currently stand, only hydrogen can substitute oil.

In fact, as Filippo Astone, director of Industria Italiana emphasizes: *"hydrogen does not generate climate-altering and polluting emissions in its various uses and can be transported and stored using existing infrastructures"* (Italiana) F. A.), such as gas pipelines. The use of electrolysis for electricity generation and the construction of hydrogen vehicles and infrastructures with reference stations for vehicles of this type have already been hypothesized in the European and US top decision-making spheres.

The main ambiguity regarding hydrogen is linked to the fact that the resource, in its natural state, is not present in nature and its production must take place with an upstream process with environmental impact and costs.

The main reason why a gradual replacement of oil in favor of hydrogen is desirable is that the latter provides a use very similar to oil. For this reason, the conversion costs of production and distribution plants (such as fuel stations into hydrogen stations) would be much lower and would not upset the functioning of the existing network, while also maintaining a high degree of efficiency.

In fact, the prospect of replacing oil with more efficient and green resources is far from remote. Both in 2018 and 2019, to make only the case of Italy, hydroelectric, bioenergy, wind, photovoltaic and geothermal together guaranteed over 40% of generation[48]. On a global level, it is hoped that among the major investors in these fields there are countries, such as China, which exploit not only oil but also coal for generation.

In conclusion, it is possible to hypothesize that the end of the oil era could take place in leopard's spot, with black gold that over the course of the 21st century will be gradually reduced in its role and impact on the economy, without ever disappearing because relatively cheap and versatile in transport, giving way in the individual sectors to those resources that will prove to be more exploitable.

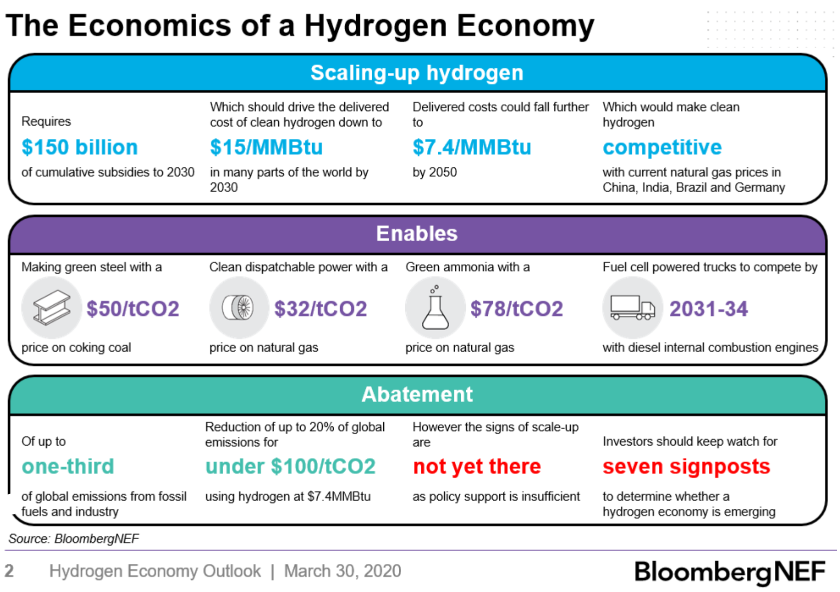
48 *IRENA, "Renewable Power Generation Costs" – Report (2019)*

3.2.3 Supplying, costs and prices

The availability, the economy in extraction/production, ease of transport and storage, as well as ease of use, are equally important factors in the energy economy and often determine the success of a fuel; hydrogen has yet to establish itself as a fuel: in this race it starts at a disadvantage due to the fact that it has to pay high energy production costs. It is therefore likely that the road to its affirmation will be long and will start through the conquest of some markets and then move on to other markets, facing competition with the current ones. fuels. In this competition, traditional fuels will also improve their environmental characteristics; at the same time an improvement of the engines that use these fuels is foreseeable.

Today, green hydrogen produced by electrolysis can cost $ 4 per kilogram, equivalent to $ 100 per megawatt/hour or about $ 160 per barrel, roughly double the average oil price of the past two years. Blue hydrogen, obtained through fossil fuels and the capture of carbon dioxide, costs about half and can therefore play a role in the transition, despite being non-renewable and therefore considered less valuable than green hydrogen. The demand for green hydrogen can begin to grow significantly at a production cost of $ 3 per kilogram and reach the tipping point at $ 2 per kilogram. The main factors on which to intervene are the cost of renewable sources, that of capital and that of electrolyzers.
But, with an ambitious plan hydrogen could be competitive with oil in many applications. Governments, companies and associations are working on their hydrogen plans.
The electrolyzers industry, fundamental components for the production of green hydrogen, is still young and artisanal. With the development of greater production capacity, the price of the devices will drop significantly, thus reducing the cost of hydrogen. Combining this with the rapid reduction in the cost of renewables, it is possible to glimpse a scenario in which a turning point for hydrogen is reached at the price of about $ 2 per kilogram, which could become a competitive energy source in various sectors.
According to "Hydrogen Economy Outlook" report from BloombergNEF, it is estimated that renewable hydrogen could be produced for a value of between 0.8 and 1.6 dollars per kilogram in most of the world within the next three decades, a cost roughly equivalent to today's prices of natural gas in countries like Brazil, China and India.

But to achieve this price, roughly $ 150 billion in subsidies would be needed over the next 10 years to ramp up the technology and build the necessary supply infrastructure, along with joint policy coordination between governments and new private investment frameworks.
At present, however, political support for the hydrogen economy is insufficient, but it is constantly growing.
There are several aspects to consider in this regard: while infrastructure for renewable hydrogen production remains relatively scarce in many parts of the world, the costs of producing clean hydrogen are decreasing, largely due to falling costs of the electrolyzers used in the process and the falling cost of hydrogen. For example, the cost of renewable hydrogen in China, India and Western Europe, once the storage and pipeline infrastructure are considered, could drop to around $ 2/kg by 2030 and to $ 1/kg by 2050.
But despite falling costs, carbon prices and emissions policies will be essential to drive its use, as hydrogen will likely remain a more expensive form of energy for some time by virtue of its production.
Furthermore, the low density of hydrogen makes it much more difficult to store than fossil fuels. For this reason, the BNEF notes that approximately $ 637 billion may be needed for storage infrastructure to allow green hydrogen to replace and provide the same level of energy security as natural gas[49].
[50]



[49] *BloombergNEF, "Hydrogen Economy Outlook" – Report (2020)*
[50] *The Economics of a Hydrogen Economy – BloombergNEF (2020)*

3.2.4 ENI forerunner in Italy

The European Commission has recently indicated the direction to 2050 to raise the current weight of hydrogen up to 13-14%, which today is worth less than 2%, in the energy mix, focusing in the long term above all on generation from renewable sources. To achieve this goal, Brussels has therefore decided to significantly increase the production of electrolyzers which, by using electricity to break down water into hydrogen and oxygen, make it possible to obtain green hydrogen, and to promote a transitory phase with blue hydrogen, that is the one obtained from natural gas with carbon capture and storage in order to reduce its emissions and make its production competitive.

Italy and its industry are preparing to embrace this hydrogen revolution.
Wind, solar power and the sea cannot be enough to meet the demand for a manufacturing that still depends on foreign energy, once decarbonization is complete.
Italy has its tricks up its sleeve because the gas of which our seabeds are rich is precisely hydrogen. The incubator of this change is ENI, the leading national energy player in the energy sector, that have already taken action starting their decarbonization strategies.

ENI aims to achieve an 80% reduction in net emissions referable to the entire life cycle of energy products sold by 2050 and 55% of the emission intensity. ENI is also investing in the production and use of blue hydrogen with the project to build the largest carbon dioxide capture and storage center in the world in Ravenna. This goal can be pursued by exploiting, on the one hand, the enormous storage potential connected to the now depleted offshore gas fields of the middle Adriatic, with a capacity of between 300 and 500 million tons, and, on the other, by pooling, in a circular economy perspective, the industrial and logistic fabric already present, the existing infrastructures still operational, a highly skilled supply chain and CO_2 capture systems.

The project will be divided into steps and will allow to enhance the local supply chain and the specific skills acquired over the years, to create new job opportunities and, above all, to decarbonize the entire activity of ENI, favoring the development of a blue energy district, also thanks to the production of hydrogen.
The first phase involves capturing part of the emissions from the Casal Borsetti gas plants and the Versalis chemical hub and then storing CO_2 in depleted or depleting fields.
The start of the project is expected by 2021 following the green light for the necessary authorizations with the group which is already collaborating with the Ministry of Economic Development for the prototype. The field that will be used for storage is instead that of Porto Corsini which is part of the Casal Borsetti plant: the choice of the site is linked to the particular proximity to the industrial center of Ravenna and to its characteristics since it is in the mature phase of its production cycle and its identikit makes it a suitable field for storage.

With the transition to the development phase of Ravenna, destined to become a real hub for the whole Mediterranean Sea, the project is getting to the heart with the decarbonisation of ENI's activities in the area in order to reach up to 2 million tons per year (Mtpa) of CO_2 volumes. A bar destined to rise with the next step which will sanction the expansion in support of other industrial areas of the group close to Ravenna, such as Ferrara and Mantua, to reach a capacity of 5 Mtpa. The further element, in ENI's intentions, would then help reduce the carbon footprint of national and international industrial sites that can be connected by sea or by rail. Together with the capture and storage of CO_2, Ravenna will therefore also represent a driver for the production and use of blue hydrogen with the possible distribution to industrial users and sustainable mobility.

Conclusions

This study was carried out with the aim to provide a forecast about the likely future of a hydrogen economy. In fact, hydrogen has what it takes to replace unsustainable energy sources and thus solve the resulting economic and environmental problems. Enormous problems, namely, the depletion of the main worldwide energy sources (oil and coal) and the resulting pollution, which causes global warming and serious damage to the environment. The intensive use of oil, coal and other non-sustainable energy sources during the past 300 years, being non-renewable sources, has indeed led us today to see their respective deposits running out. In addition to being non-renewable and polluting, oil and coal are unevenly distributed on the planet. For this reason, various economic crises deriving from oil have followed one another throughout history.

So, today we are starting to reduce the use of fossil fuels and other harmful energy sources, in favor of others that are environmentally friendly. In fact, great strides are being made in this field, but it has been realized that the green energy sources currently in use, even when developed, will not be able to meet the world's energy needs.

Then, starting with governments and energy companies, up to cities and citizens, the question is what is going to replace oil and coal? The answer is hydrogen.

Hydrogen, if produced from sustainable energy source, will turn in a sustainable energy source too, guaranteeing almost zero emissions. The latter, being available in huge quantities, if matched with the other sustainable energy resources, many of wich already available, can potentially and realistically be the missing piece for a 100% sustainable energy supply. In fact, according to the IEA (International Energy Agency) and the Hydrogen Council, hydrogen could be a significantly used energy source by 2050 and the main one by 2100, satisfying about 50% of the world energy needs.

Hydrogen is already used today in various chemical and production processes, but its use is expanding to various markets, especially industrial and transport. In fact, many companies are investing in this field to ensure a clean future for the world.

Companies like Toyota, BMW and DHL are aiming a lot on this resource so much so that the latter aspire to replace all current vehicles with hydrogen-powered ones by 2025.

Also, Bill Gates invested the monstrous amount of 600M dollars to develop a hydro-powered yacht and many airline companies already use hydrogen as a fuel to reduce planes weight; this is to say that hydrogen can cover the entire transport sector: land, air and sea.

Furthermore, the development of hydrogen technologies and the various production/distribution plants will lead to the latter being sustainable not only from an environmental point of view but also from an economic point of view.
This because the electrolyzers industry, fundamental components for the production of green hydrogen, is still young and artisanal but, with the development of greater production capacity, the price of the devices will drop significantly, thus reducing the cost of hydrogen. Combining this with the rapid reduction in the cost of renewables, it is possible to glimpse a scenario in which renewable hydrogen could be produced for a value of between 0.8 and 1.6 dollars per kilogram (less than oil price) in most of the world within the next three decades, according to BloombergNEF. But to achieve this price, huge subsidies would be needed over the next 10 years to ramp up the technology and build the necessary supply infrastructure, along with joint policy coordination between governments and new private investment frameworks.
But despite falling costs, carbon prices and emissions policies will be essential to drive its use, as hydrogen will likely remain a more expensive form of energy for some time by virtue of its production.
Surely using hydrogen has pros and cons, but it must be pointed out that the advantages deriving from its use outweigh the disadvantages, which among other things are not impassable.
This is why building a hydrogen-based economy will not be a walk in the park, but through research and investment it will be possible, rather, likely to see in the recent future a global economic network connected in a completely sustainable way.
This is the real promise of hydrogen.

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