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HYDROGEN ENERGY EVALUATION WITH A LOOK AT PUBLIC-PRIVATE PARTNERSHIPS

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“What the system has done, as a mechanism to continue with growth at all costs, is actually to burn the future. And the future is the least renewable resource”

Carlos Alvarez Pereira

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Introduction

There has been a lot of talk in recent years about renewables for an energy transition promoted to progressively decrease the use of climate- and human-damaging fossil fuels, where the quantification of damages, living in an image society, is difficult to be adequately considered. After the Covid pandemic and with the war in the Ukrainian territories, energy is perhaps one of the most important issues for any government. Worldwide demand is steadily growing and with it the CO_2 emissions; however, in more developed parts of the world, such as the European Union, there is a gradual stabilization, as if the strong economic growth driven by capitalism finds its own limit in energy. Renewables aim to meet this demand by reducing global emissions, but on their own it is very difficult to achieve a completely clean energy system. Therefore, other forms of energy are currently being researched and promoted; one of them is hydrogen, an energy carrier capable of storing and releasing massive power as needed. However, it must be produced and obtaining it in a sustainable manner requires the use of renewable energy and water to power a process called electrolysis. In addition, hydrogen has several limitations mainly due to production and distribution costs that may discourage investments. Nonetheless, it may find a place where renewables cannot be efficient, i.e., when they cannot directly meet demand due to energy content or storage issues. Its potential is attracting more and more attention from both governments and private companies. Public supports are directed toward projects promoted through Public-Private Partnerships (PPP), a public-private collaboration tool that allows resources to be pooled to achieve a common outcome.

Our purpose is to find out whether hydrogen is an economically feasible resource to produce and commercialise in the current context, examining the types of hydrogen and their characteristics, focusing on green hydrogen with a parenthesis on the transport sector and CO_2 assessment, comparing the energy carrier with other fossil fuels, methane in particular. In addition, we aim to understand how PPP can contribute to the deployment of hydrogen, understanding how alliances between the public and the private sector address the needs of improving its network and exploitation, considering the limitations and potentials of them including the most important risk allocation benefit, value-for-money, and the ability to involve private companies. We will conclude with the prospects for hydrogen, to understand whether focusing on partnerships for its deployment can help accelerate this energy transition that has become inevitable.

Chapter 1 – Towards a new energy frontier

1.1 Current context

1.1.1 Economic growth and environmental quality

Energy is the engine of the world, and its relationship with pollution is extremely important nowadays since as humans we produce and consume a vast quantity of it without considering the environmental consequences of this use for the future. There is an important link between the level of richness of a country and its level of pollution, which is helpful to understand the current context. Starting with a general overview, the environmental Kuznets curve is a theoretical instrument useful to estimate the latter link. Named by the American economist Simon Smith Kuznets, it originally refers to the relationship between income and inequality, where during the development of an economy, inequality first increases and then decreases returning approximately to the starting level, but it can be also used to graphically describes the relationship between economic growth and the environmental quality of a generic country, thus taking the name of "Environmental" Kuznets Curve. To sum up its meaning, during the process in which a country becomes richer, its impact on the environment initially increases and eventually decreases, following a hump shaped curve as shown in Figure 1, with the economic developments divided in three different stages from a predominantly agricultural economy with limited production, labour, and class variation, to an industrialized economy where services, information, and research are the driving forces.[1]

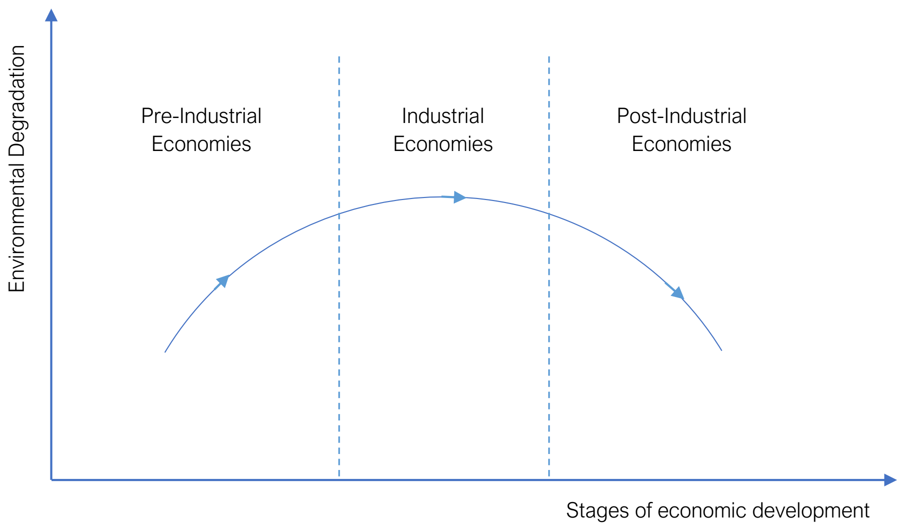

Figure 1 - Environmental Kuznets Curve. (Adaptation from Itskos et al., 2016)

[1] Itskos, et al. (2016). Chapter 6 - Energy and the Environment. In N. Katsoulakos … V. Kotsios, *Environment and Development* (pp. Pages 363-452). Elsevier.

However, it is not immediate to state which type of environmental degradation follows a reduction when a country reaches the last stage of the economic development, also giving a constraint on the country development, and there is statistical evidence that questions the robustness of the curve and the methods from which we arrive at such conclusion[2]. To obtain more consistent results, we can take a specific component to represent the environmental degradation by choosing the level of CO_2 emissions, since carbon dioxide is one of the main greenhouse gases with a significant impact on climate. The inverted U-shaped curve can hence describe the relation between CO_2 emissions (per capita) and level of income, as stated by the polish Andrej Kacprzyk and Zbigniew Kuchta in a study of 2020 containing information on 161 countries for the period 1992-2012[3]. They acknowledged that an initial increase in the average income corresponds to an initial increase in the emission of pollutants, but once the income reaches a certain level, the CO_2 emissions start to decrease. To verify the statement, we consider and elaborate the absolute value in 2019 and the trend of CO_2 metric tons emissions per capita measured by the World Bank[4] showed in Figure 2, with the colours indicating the types of countries. The trends are divided considering the type of economies, distinguish the countries with high, upper-middle, middle, lower-middle, and low level of income. What we notice is that only the trend for high-income countries is negative, while for all the others the CO_2 emissions continue to increase, but the absolute value in 2019 for the richest countries, which is equal to 9.8, does not suggest that they are in the third stage of economic development represented in the Kuznets curve, but still in the second since the value is the highest one, indicating that the most advanced economies are still the most polluting ones.

High income	●	2019	9.8	
Upper middle income	●	2019	6.4	
Middle income	●	2019	3.8	
Lower middle income	●	2019	1.8	
Low income	●	2019	0.3	

Figure 2 - CO2 emissions (metric tons per capita) in absolute value of 2019 and trends. (World Bank Data)

[2] Stern, D. I. (2018). The Environmental Kuznets Curve. *Reference Module in Earth Systems and Environmental Sciences*.

[3] Kacprzyk, A., & Kuchta, Z. (March 2020). Shining a new light on the environmental Kuznets curve for CO2 emissions. *Energy Economics, Volume 87*, 104704.

[4] The World Bank. *CO2 emissions (metric tons per capita).* https://data.worldbank.org/indicator/EN.ATM.CO2E.PC [August 10, 2022]

	Change in annual CO2 emissions per capita	Average of annual CO2 emissions per capita
High income	-1.408	11.228
Upper middle income	1.803	4.614
Middle income	0.961	2.812
Lower middle income	0.458	1.312
Low income	-0.101	0.397
World	0.563	4.150
European Union	-2.379	7.520

Figure 3 - CO2 emissions (metric tons per capita) from 1990 to 2019. (Own elaboration from Word Bank Data)

In the personal elaboration showed in Figure 3, it is positive to state that the change for the richest countries is negative, especially for the European Union with a reduction of 2.379 annual metric tons per capita in 30 years, but it is not enough to compensate the increasing of the other countries, because globally the emissions increased by 0.563, and it is small since the average is still equal to 7.520. The global economy emits CO_2 more than ever before so we can make two considerations: where the countries are in the stages of the Kuznets curve, to understand the future perspective of development, and who are the main actors which can change direction right away. For the first consideration, we can approximately represent the countries in the Kuznets curve according to their incomes and the CO_2 emissions per capita trends. (low-income countries are located on the left). From our results, shown in Figure 4, following the colours that indicate the type of countries we can notice that the three stages of economic development should be shifted one-step behind since some of the countries with medium income are nowadays industrial economies and the ones with high income are certainly service economies. Anyway, it is reassuring to note that with economic development we can also have environmental benefits in a theoretical fourth stage yet to be reached.

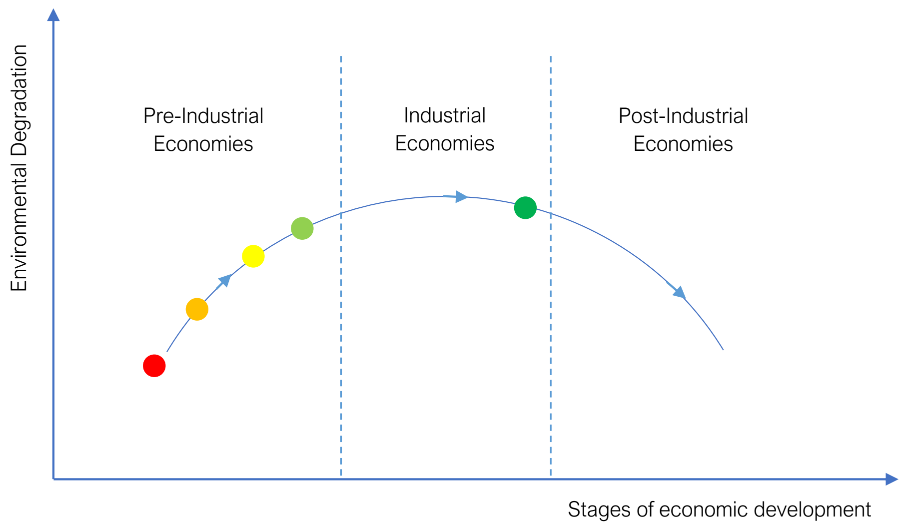

Figure 4 - Possible position of different countries in the environmental Kuznets curve based on CO_2 trends and income.

For the second consideration, we look at what are the singular most polluting countries considering the total CO_2 emissions and look at the income type of country, obtaining an image of what are the actors responsible and capable to take actions given their economic development. With the data from CDIAC, the Carbon Dioxide Information Analysis Centre[5], which measured the top twenty CO_2 emitting countries in 2014, we build Figure 5 that shows the relation between single country type and level of pollution, stating that the main gross pollutants are both high- and middle-income countries.

1	CHINA (MAINLAND)	2806634
2	UNITED STATES OF AMERICA	1432855
3	INDIA	610411
4	RUSSIAN FEDERATION	465052
5	JAPAN	331074
6	GERMANY	196314
7	ISLAMIC REPUBLIC OF IRAN	177115
8	SAUDI ARABIA	163907
9	REPUBLIC OF KOREA	160119
10	CANADA	146494
11	BRAZIL	144480
12	SOUTH AFRICA	133562
13	MEXICO	130971
14	INDONESIA	126582
15	UNITED KINGDOM	114486
16	AUSTRALIA	98517
17	TURKEY	94350
18	ITALY (INCLUDING SAN MARINO)	87377
19	THAILAND	86232
20	FRANCE (INCLUDING MONACO)	82704

Figure 5 - Top twenty CO2 emitting countries in 2014, emissions are expressed in thousand metric tons of carbon. (CDIAC)

It is not reassuring to see countries that didn't reach the peak yet continuing to pollute, but we will see that most of the high-income countries are making the investments to diminish the impact on environment with different strategies, and therefore the focus will be on them, i.e., the countries which have overcome the peak of the Kuznets curve. We can conclude that once reached an economic growth, the direction on the environmental impact can change since there is the option to invest in technologies to avoid environmental detriment, while many countries are still behind in the economic growth to pursue the decreasing trend of the curve. A focus should be put on the opportunity that high income countries have on aggregate like in the case of the European Union: with higher influence and economic strength, invest in a technological solution to address the climate challenge that affects everyone. But still, countries seem to act non-cooperatively.

[5] Carbon Dioxide Information Analysis Center: https://cdiac.ess-dive.lbl.gov/trends/emis/top2014.tot [August 10, 2022]

1.1.2 Energy sources and dependencies in Europe

Energy pushes economy with production, travelling, house living and so on, and therefore we look at the ways on which countries produce energy and analyse the relationship between their production methods and pollution generated. It is worth pointing out that it would be better to look at energy consumption rather than production: taking the system globally, what we produce is what we consume, precisely because we produce the amount of energy we need, but for a single country it could be different if the energy used is not produced but imported. Therefore, if a country that wants to be self-sufficient in terms of energy, it must produce by itself the amount of energy that it needs and is crucial to understand how this energy is created.

The economic development should bring to the implementation of new technologies, less pollutant, whose consequences of their use do not affect our health, and for a developed country the trend of requiring always more and more energy is not always true. We take as reference the European Union, a governmental entity formed mainly by high-income countries, and we look at its energy mix to see what resources are used to produce energy. Figure 6 shows Eurostat data[6] of the Gross available energy, the quantity necessary to satisfy the energy needs of a country, and we can appreciate the fact that the EU is increasing its use of renewables and biofuels which become the third source of energy, but still having oil and petroleum products as the primary source. Dramatically, ignoring 2020 due to pandemic impacts, oil and petroleum products continue to be the highest source with a value of 22 822.66 petajoule (PJ) in 2019, keeping a fluctuation between 25 000 and 20 000 PJ with a timid downward trend from 1990, while all the other sources remain below 15 000 PJ.

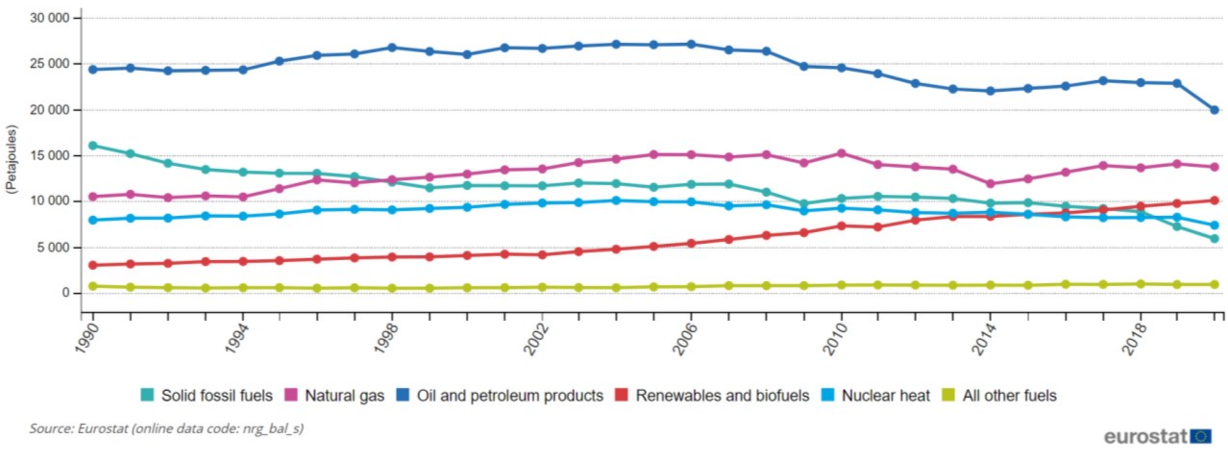

Figure 6 - Gross available energy in the EU from 1990 to 2020.

[6] Eurostat. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_statistics_-_an_overview#:~:text=Renewable%20energies%20accounted%20for%20the,renewable%20waste%20(2.4%20%25). [August 14, 2022]

It is significant though the reduction of the use of solid fossil fuels which started from a level of 16 032.01 PJ in 1990 and reached a value of 7 197.36 PJ in 2019. Moreover, we can appreciate the positive upward trend for the renewable energies, from a value of 4 040.2 PJ in 2000 to a value of 10 046.86 PJ in 2020, and they are the only sources that did not slow down their use during the Covid pandemic year of 2020. A mention must be made for nuclear heat which was slowly and constantly growing up to 2004, with a peak value of 10 046.75 PJ, before starting a declining pattern reaching 8 213.7 PJ in 2019. Finally, the total energy demand is not increased significantly: always considering the data, in 1990 the total Gross available energy was equal to 62 380.6 PJ, in 2000 was equal to 64 419.97 PJ, and in 2019 was equal to 62 846.39 PJ, meaning that in 30 years the amount of energy needed to run European society has not significantly increased despite industrial growth and technological advances present in our daily lives.

As previously stated, the production of energy does not always correspond to the final consumption. In the same data source from Eurostat[7], we can compare the primary energy production with the final consumption. Figure 7 shows the sources for the energy production, while in Figure 8 is shown the final energy consumption in the EU, and what we can conclude from the following figures is that the energy consumption is significantly higher with respect to the production, with values that in 2019 are respectively for the production not even 25 000 PJ and for the total consumption approximately 40 000 PJ. The only consolation is that of the energy produced nowadays most comes from renewable sources, while the others are in significant decline, but it is essential to see where the rest of the energy needed by the Union comes from, which instead of being produced must be imported.

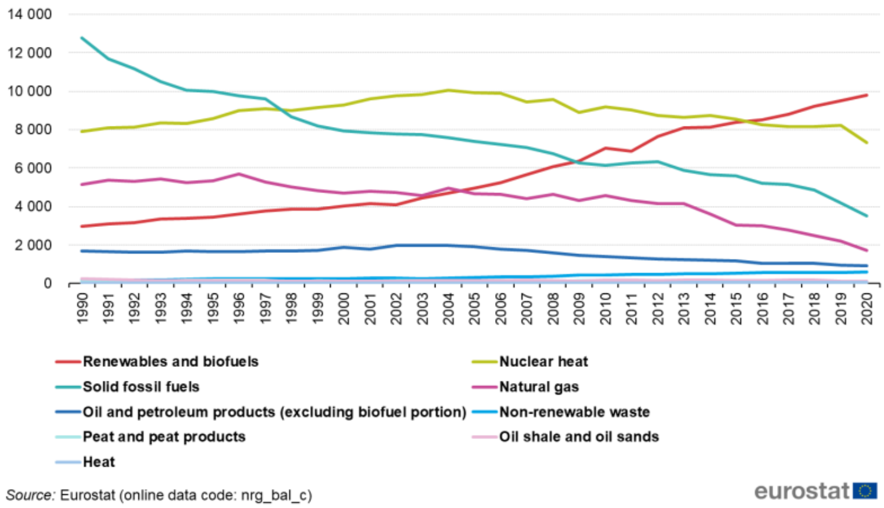

Figure 7 - Primary energy production by fuel from 1990 to 2020 in EU (in Petajoule).

[7] Eurostat. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_statistics_-_an_overview#:~:text=Renewable%20energies%20accounted%20for%20the,renewable%20waste%20(2.4%20%25). [August 14, 2022]

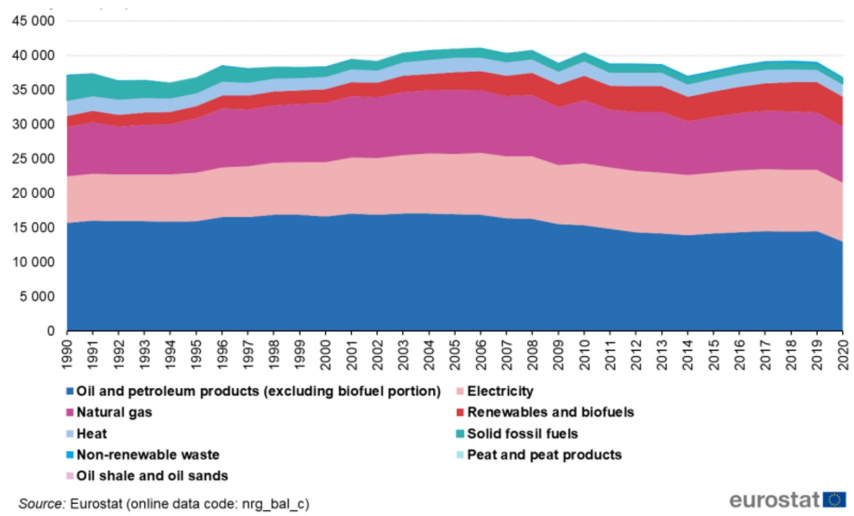

Figure 8 - Final energy consumption by fuel from 1990 to 2020 in EU (in Petajoule).

In this regard, we can consider what is called "Energy dependency", which by definition is the "ratio between net imports and gross available energy indicates the ability of a country or a region to meet all its energy needs." (Eurostat, Energy statistics - an overview, 2022). As illustrated in Figure 9, the light-coloured proportion of the column shows the level of net imports with respect to the Gross available energy. In 2020, the top demanded energy source was again oil and petroleum products for a value of 19 944 PJ, for which 97% was imported, and the demand for natural gas was impressive too, with 83.6% of it covered by imports, while for the solid fossil fuels even with the internal production's declining pattern the resource is still demanded for a 35.8% of it. From 1990 to 2020, even if the total consumption decreased, the import dependency has increased, passing from a 50% of all fuels consumed covered with import to a value of 57.7%.

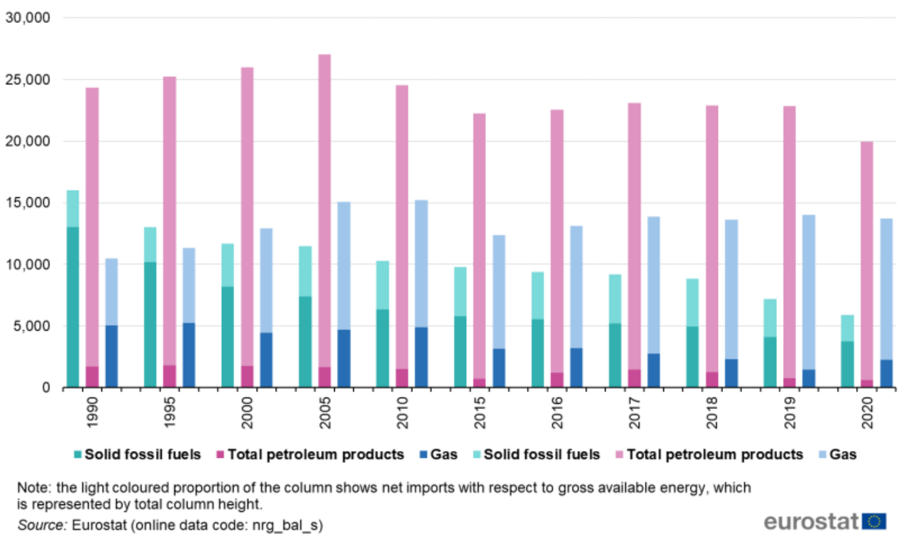

Figure 9 - Energy dependency by fuel from 1990 to 2020 in EU (in Petajoule).

It is easy to conclude that we are in a context in which the European Union is a net energy consumer, and it has a worrying dependency from others regarding the primary sources of energy, importing oil and petroleum and natural gas, where having a dependency means standing to conditions that could change significantly, rapidly, and unexpectedly. Examples are the petroleum crises and the most recent war in Ukraine, which has consequences on the amount of furniture of natural gas and its price, describing why this dependency must be considered an important risk to manage. Italy is one of the most vulnerable states as clarified by Nicola Armaroli, Italian chemist and research executive at the Italian National Research Council, who explained in a recent interview[8] that there is a strong imbalance towards natural gas and Italy is the only country in the G7 in which it is the main source of primary energy, in particular to produce electricity, with a 40% share compared to the European average of 25%. He further compared the Italian energy model to the Russian model but with the latter that has estimated reserves of gas for the next 58 years and the other not, continuing to depend on Russia, adding that methane, which is the imported natural gas, is moreover a fossil fuel that brings to a major impact on environment. Another significant dependency to highlight is the one related to oil and petroleum products: according to the World Bank data[9], the emissions related to petroleum-derived fuels, measured by the Carbon dioxide emissions from liquid fuel consumption, are significantly high and continuously growing, meaning that the consumption is increasing and so the reliance on exporters. Furthermore, the reaching of the peak of the oil and petrol production is still on discussion by experts, but almost all world's remaining exploitable oil reserves in the future will be controlled by a few Muslim countries, on whom the dependency will increase if fossil fuels are still needed, thus potentially compromising the balance of power in the world[10], just as is happening with the methane in Russia.

Eventually, the dependence of a high-income country should bring it to the disposition of a new energy strategy to avoid these dangerous dependencies and at the same time to reduce pollution. The challenge is to solve the problem of usage of non-renewable sources and to mitigate the problem of dependencies. High-income countries, since they have the potential to invest, should collaborate to find sustainable solutions and, among the various proposals, thinking about hydrogen as a new way to have energy. Hydrogen is therefore presented as a complementary solution with several limitations to be analysed and overcome, we will review the main characteristics of hydrogen and the possible strategies to implement it in several sectors of the economy. It is not a new source; indeed, it is already used in

[8] See: Armaroli, N. (2022, April 22). Armaroli: l'attuale sistema energetico è inefficiente. Ecco cosa serve per la transizione (ENERGY UP TECH). (G. Torchiani, Interviewer)

[9] The World Bank. *CO2 emissions from liquid fuel consumption*: https://data.worldbank.org/indicator/EN.ATM.CO2E.LF.KT [August 14, 2022]

[10] Rifkin, J. (2002). *The Hydrogen Economy: The Creation of the Worldwide Energy Web and the Redistribution of Power on Earth.* United States: Polity Press.

specific industries, but it is not mentioned in the glossary of Eurostat[11] since it is not considered as a source of energy and because it is not currently relevant. This is also the case in Italy as mentioned in the report "Energia da fonti rinnovabili in Italia" of Gestore dei Servizi Energetici (GSE) S.p.A.: "According to Directive 2009/28/EC, as amended by Directive 2015/1513/EU (ILUC Directive), hydrogen produced from renewable sources in the transport sector can also be counted as a renewable source; however, its consumption is currently negligible."[12] In the following paragraphs, we will analyse what hydrogen is, introducing what do we mean for energy from hydrogen, how it is produced, and what is the perspective for the use of this small but energetic resource.

[11] *Eurostat*. Glossary:Renewable energy sources: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Renewable_energy_sources [August 16, 2022]

[12] Agrillo, A., dal Verme, M., Liberatore, P., Lipari, D., Lucido, G., Maio, V., & Surace, V. (March 2020). *RAPPORTO STATISTICO 2020 Energia da fonti rinnovabili in Italia.* Rome: GSE – Gestore dei Servizi Energetici S.p.A.

1.2 Why hydrogen: history and types

Hydrogen (H_2) is the lightest element and most abundant in the universe, one of the four primary plastic elements with oxygen, carbon, and nitrogen. On earth, it is rare to be found in gaseous form since it is mainly combined with oxygen in water (H_2O) and with carbon in gases (CH_4, C_2H_6, etc.). Hydrogen is considered as an energy "carrier" with a high energy content that can be used for example in fuel cells in order to generate electricity, power and heat.[13] What distinguishes an energy source from a carrier is that the latter allows the transport of energy, created by a source, in a usable form from one place to another. Hydrogen is therefore like electricity: produced from another substance, like water, fossil fuels, or biomass, and used as a source of energy or fuel. It is capable of storing energy in itself to be released when needed, in nature we found it bounded with other elements and the main challenge is just how to get it alone. It has the highest energy content with respect to any common fuel by weight (about three times more than gasoline), which is why it is used as a rocket fuel and in fuel cells to produce electricity on some spacecraft, but it has the lowest energy content by volume (about four times less than gasoline), requiring considerable space in which to keep it, partly explaining why it is not commonly used as a fuel now. There are sectors in which hydrogen is already in use: in the United States for instance, approximately 10 million metric tons of hydrogen are produced every year[14] for chemical and metallurgical applications, in the food industry, the space program, petroleum refining and ammonia production, but it seems that it has the potential for greater use in the future of many other sectors like transportation and utilities[15], industrial processes with the steel manufactory market, integrated clean energy systems, in order to reduce or actually zeroing CO_2 emissions.[16] The knowledge of its potential finds the roots many years ago: Sir William Grove, a Welsh judge and physicist, in 1842 developed the first fuel cell in which for the first time the formation of water from hydrogen and oxygen gas generated an electric current[17]. Moreover, French inventor Jean-Joseph Étienne Lenoir created the "Hippomobile" in 1860, a sort of vehicle with an engine powered by a mix of hydrogen gas produced from the electrolysis of water[18], a crucial method discovered by William Nicholson in 1800 based on the

[13] Martinez-Garcia, G. (1 July 2017). *Cost-benefit analysis of a hydrogen supply chain deployment case for fuel cell vehicles use in Midi-Pyrénées region.* Barcelona: Projecte Final de Màster Oficial, UPC, Escola Tècnica Superior d'Enginyeria Industrial de Barcelona.

[14] Office of Energy Efficiency & Renewable Energy. *Hydrogen Production*. Retrieved from Energy.gov: https://www.energy.gov/eere/fuelcells/hydrogen-production [August 16, 2022]

[15] *Hydrogen*. U.S. Energy Information Administration: https://www.eia.gov/energyexplained/hydrogen/ [August 16, 2022]

[16] Office of Energy Efficiency & Renewable Energy. *Hydrogen Production*. Retrieved from Energy.gov: https://www.energy.gov/eere/fuelcells/hydrogen-production [August 16, 2022]

[17] *Sir William Robert Grove*. Encyclopedia Britannica: https://www.britannica.com/biography/William-Robert-Grove [August 16, 2022]

[18] *Internal Combustion 1803-1883*: http://www.quantium.plus.com/derivaz/isaac/isaac.htm [August 16, 2022]

breakdown of water into hydrogen and oxygen gas[19] that we are going to highlights further on. Another method to produce hydrogen was discovered in 1930 by the American company Standard Oil with its first steam methane reformers installed in Bayway, USA, in a process by which hydrogen is obtained from gas methane[20]. Therefore, hydrogen must be "produced" unlike petroleum sources and natural gas and there are different ways to generate it; depending on the mode of production, it can be of different origins and with different environmental impacts. In Figure 10 are summarized the main "colours" of hydrogen, in relation to the ways of production, and related environmental impact, based on Enel Green Power data.[21]

Obtained from/by	Color	Level of CO2 emissions (per kg of hydrogen)	Raw material
Gasification of coal	Brown hydrogen	≈ 20 kg	H_2O + C (carbon)
Steam reforming of natural gas	Grey hydrogen	≈ 9 kg	CH_4 (methane)
Steam reforming of natural gas (partial capture, transport and storage of CO2)	Blue hydrogen	≈ 5 kg (CO2 not captured)	CH_4 (methane)
Electrolysis of water (powered by nuclear energy)	Pink hydrogen	0 kg + nuclear waste	H_2O
Electrolysis of water (powered by renewable energies)	Green hydrogen	0 kg + renewable resources waste	H_2O

Figure 10 - Main methods to obtain hydrogen.

We could have brown hydrogen from the gasification of coal, emitting more than 20 kg of CO_2 per kilo of production, involving the treatment of coal with water vapor, $C + 2H_2O \rightarrow CO_2 + 2H_2$, or we could have grey hydrogen by steam reforming natural gas, with more than 9 kg of CO_2 emitted for every kg of hydrogen produced, obtaining gas mixture which contains residual methane (CH_4), carbon monoxide (CO), water (H_2O) and hydrogen (H_2), $CH_4 + 2H_2O \rightleftarrows CO_2 + 4H_2$. These first two options are the most pollutant and the more used to produce hydrogen at the moment, but there are other options with a smaller environmental impact. Blue hydrogen is obtained by steam reforming natural gas with a partial capture, transport, and storage of CO_2 underground, still emitting about 5 kg of uncaptured CO_2 for every kg of hydrogen; it could be useful as a short-term solution for its cost-efficiency, but not as optimal answer in the long-term due to the environment impact, where the greenhouse gas emissions are only

[19] *Willian Nicholson*. Encyclopedia Britannica: https://www.britannica.com/biography/William-Nicholson-English-chemist-and-inventor [August 16, 2022]

[20] Murkin, C., & Brightling, J. (2016). Eighty Years of Steam Reforming. *Johnson Matthey Technology Review*, 263–269.

[21] *Idrogeno*. Enel Green Power. https://www.enelgreenpower.com/it/learning-hub/energie-rinnovabili/idrogeno [August 8, 2022]

18% to 25% less than grey.[22] Following, pink hydrogen is obtained by electrolysis of nuclear-powered water, but we should consider the social opinion and the environmental impact due to nuclear waste even though it does not emit CO_2. Finally, green hydrogen is obtained from the electrolysis of water powered by renewable energies such as solar and wind, with 0 kg of CO_2 emissions related to its production. The only emissions present in the process are the ones linked to the transportation of hydrogen that could be with pipelines or road transport to market which is estimated to be 1.09 kg CO_2 per kg of hydrogen, but present for all types of hydrogen.[23] This latter method has a low environmental impact but requires a lot of energy: for electrolysis to occur, electricity is required to break down water into its two elements H and O. Once that it has been chemically broken down, we obtain hydrogen as energy vector and pure oxygen, which can be recovered where economically feasible in various industries that currently use it. To summarize the panoramic of this energy vector, the major methods used today to produce it are steam reforming and coal gasification: according to the International Energy Agency, the global hydrogen production is based almost exclusively on fossil fuels, i.e., 76% from natural gas and 23% from coal in 2019[24] while 62% and 19% respectively in 2022, with today associated greenhouse gas emissions of 900 million tons of CO_2 per year. There is still little room for other low-emission methods, for which production is less than 0.7%, or 1 mega ton (Mt), almost all from blue hydrogen but where green hydrogen has had an encourages 20% increase over 2020. To conclude the overview, today's forecasts for 2030 predict the co-habitation of blue hydrogen, using carbon capture, utilization, and storage (CCUS), with green hydrogen, estimating values around 10 Mt and 14 Mt respectively if all the project currently under development will be realised, helping to achieve climate goals.[25] A very smaller amount of hydrogen is therefore produced and will be produced through the electrolysis of water, whereas other methods are in the stage of development such as reforming ethanol and sugars, water bio photolysis, photochemical water splitting and high-temperature water splitting.[26] The interest is mostly around water electrolysis due to the declining costs for having renewable energy and the technologic developments, with the opportunity to produce hydrogen from water without emitting any CO_2 at a fair price.[27]

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[22] Howarth, R., & Jacobson, M. (2021, August). How green is blue hydrogen. *Energy Science and Engineering. 9. 10.1002/ese3.956*.

[23] Cantuarias-Villessuzanne, C., Weinberger, B., Roses, L., Vignes, A., & Brignon, J.-M. (9 November 2016). Social cost-benefit analysis of hydrogen mobility in Europe. *International Journal of Hydrogen Energy*, Volume 41, Issue 42, Pages 19304-19311.

[24] International Energy Agency. (2019, June). *The Future of Hydrogen. Seizing today's opportunities.* Retrieved from IEA: https://www.iea.org/reports/the-future-of-hydrogen

[25] International Energy Agency. (2022). *Global Hydrogen Review 2022.* Retrieved from IEA: https://iea.blob.core.windows.net/assets/c5bc75b1-9e4d-460d-9056-6e8e626a11c4/GlobalHydrogenReview2022.pdf.

[26] Yue, M., Lambert, H., Pahon, E., Roche, R., Jemei, S., & Hissel, D. (2021). Hydrogen energy systems: A critical review of technologies, applications, trends and challenges. *Renewable and Sustainable Energy Reviews 146*, 111180.

[27] Ibid.

To be as sustainable as possible, the production should include only green hydrogen derived from the use of electrolysers, but they require a lot of electric power to work, opening to a strong relation between hydrogen and electricity came up already in 1977 in the Book "Hydrogen energy economy. A realistic appraisal of prospects and impacts", which stated a strong relation between the cost of hydrogen produced by electrolysis and the cost of electricity.[28] The fact that nowadays the cost of the main renewable energy technologies like photovoltaics and wind turbines is declining creates the premise and interest in investing in hydrogen production by electrolysis of water.[29] The importance of the production method is also discussed in the work done by the American economic and social theorist Jeremy Rifkin in 2002 "The Hydrogen Economy: The Creation of the Worldwide Energy Web and the Redistribution of Power on Earth", which opens to an analysis of an establishment of a new economy based on the exploitation of hydrogen. In his book, he also sees the rise and the fall of civilizations linked to the availability of "energy", in a broader sense as the employment of resources of all kinds: historically, energy has been used to expand a territory, the number of inhabitants and the need for energy to be met increase, and if the energy spent on expansion is not repaid by the resulting energy resources here is where the territory collapses. Therefore, energy is the key and hydrogen according to him could play a role on the redistribution of power on earth if it is produced with methods that do not produce environmental damages.[30]

Since now the production of hydrogen is made by using methods that pollute, and with the question of using nuclear energy still on the table, the focus should be on green hydrogen. It could replace grey hydrogen used in the chemical industry and petroleum refinery and it could be used to replace fossil fuels in the industries characterized by the need of high temperature heat like the productions of cement, steel, and glass, and where renewable energy is difficult to use directly, as suggested by Enel Green Power. It is important to consider that aspect because the production of green hydrogen requires lots of energy derived from renewables, which is why there are sectors in which investing in hydrogen is reasonable and not for others. It could be not efficient to power cars since the electrification can directly arrive, or to heat houses considering the benefits of the heat pumps[31], but for heavy industries that produce steel and concrete for example, which need high amounts of energy that

[28] Dickson, E. M., Ryan, J. W., & Smulyan, M. H. (1977). *Hydrogen energy economy. A realistic appraisal of prospects and impacts.* United States: National Science Foundation New York.

[29] Abdinab, Z., Zafaranlooa, A., Rafieed, A., Méridab, W., Lipińskic, W., & Khalilpouraef, K. R. (March 2020). Hydrogen as an energy vector. *Renewable and Sustainable Energy Reviews*, Volume 120.

[30] Rifkin, J. (2002). *The Hydrogen Economy: The Creation of the Worldwide Energy Web and the Redistribution of Power on Earth.* United States: Polity Press.

[31] Armaroli, N., & Barbieri, A. (2021). The hydrogen dilemma in Italy's energy transition. Nature Italy. 10.1038/d43978-021-00109-3. Retrieved from:
https://www.researchgate.net/publication/354513834_The_hydrogen_dilemma_in_Italy's_energy_transition.

electrification can't cope, hydrogen could be a reasonable alternative to fossil fuels.[32] That is because we are dealing with the loss of efficiency by producing hydrogen from renewable energies: we consume more energy than the one obtained with hydrogen. A surplus of renewable energies is then required, it exists in certain places of the world very favorable to wind and sun which can produce more energy than they can store, but it is not simple to achieve on aggregate given the growing demand. The geographical and geopolitical considerations play a crucial role and strong institutions with international partnerships are necessary to guarantee an equal distribution of resources. In the following chapter, we start to consider the main limitations and benefits of hydrogen implementation to get an idea of how long we will have to wait before we see it in our daily lives.

[32] Monforti-Ferrario, A., Cigolotti, V., Ruz, A., Gallardo, F., Garcia, J., & Monteleone, G. (March 2022). Role of Hydrogen in Low-Carbon Energy Future. In G. Graditi, & M. Di Somma, *Technologies for Integrated Energy Systems and Networks* (pp. 71-104). Wiley-VCH GmbH. DOI:10.1002/9783527833634.

Chapter 2 – Hydrogen appraisal

2.1 Foreword to the analysis

We are conscious of the new opportunity provided by the green hydrogen; it is important to assess whether its implementation is a goal to be pursued or not[33], when it could be convenient, and in which sectors it could become the energy driver. We condense the main limitations and benefits that occurs with the production and the use of hydrogen, to see if its market could thrive in the future. A series of cost-benefit analyses on its implementation in specific sectors have already been made, as we will observe for the case of fuel cells vehicles, but our analysis does not evaluate a specific project even if it is touching the steps of a project appraisal suggested by the EU Guidelines of 2014[34], as shown in Figure 11.

	EU GUIDELINES 2014	*OUR REVIEW*
1.	Description of the context	Economies, energy sources, and pollution
2.	Definition of objectives	Reducing pollution, finding clean energy
3.	Identification of the project	Green hydrogen as energy vector
4.	Technical feasibility & Environmental sustainability	Electrolysis of water with renewable energies
5.	Financial analysis	Financial Costs and Benefits
6.	Economic analysis	Social Costs and Benefits
7.	Risk assessment	Hydrogen risks and PPP

Figure 11 - Steps for appraisal from EU Guidelines of 2014 and our review in comparison.

Indeed, the first three points are explained in Chapter 1 with the identification of green hydrogen as energy vector to use for a clean alternative to fossil fuels, the technical feasibility is described by the available technologies that can produce green hydrogen, such as electrolysers, and the environmental sustainability and the following points will be analysed within the evaluation of costs and benefits and in the Chapter 3 related to the topic of Public-Private partnerships (PPP).

[33] Dickson, E. M., Ryan, J. W., & Smulyan, M. H. (1977). *Hydrogen energy economy. A realistic appraisal of prospects and impacts.* United States: National Science Foundation New York.

[34] European Commission, Directorate-General for Regional and Urban policy. (2014). *Guide to Cost-benefit Analysis of Investment Projects - Economic appraisal tool for Cohesion Policy 2014-2020.* Luxembourg: Publications Office of the European Union.

2.2 Costs of hydrogen as energy vector

2.2.1 First limitations

Hydrogen is not a source that we found by digging into natural underground deposits or does not come by harnessing natural energy such as sun or wind; it must be produced in a process that requires energy, and that could potentially increase pollution if petrol, carbon, or gas are used having a negative impact on the environment, while it is minimum if based on clean energy sources like solar, wind, and hydroelectric. However, the energy needed to produce hydrogen is more than the one provided by it[35], thus the carrier suffers a loss in energy efficiency, making it more costly in energy terms than the electricity or fuels used to produce it. In fact, the production of hydrogen with a standard electrolysis process requires 50 to 65 kWh of energy[36], even though there are techniques being tested that could decrease this energy expense like the one made by the Italian National Centre of Research (CNR) in 2014 which allows the consumption of just 18.5 kWh.[37] Nevertheless, considering the stage of converting electricity into hydrogen, the transport, the storage, and the subsequent conversion back into electricity in a fuel cell to be used, there is a loss of energy that may be as large as 30%.[38] A further limitation to consider is that hydrogen in its pure state is a highly flammable gas, it is lighter than air thus it can dissipate very quickly in open surroundings in case of leakages but it remains potentially dangerous when stored in large quantities in closed containers.[39] The disaster of LZ 129 Hindenberg Zeppelin in 1937 was testimony to this, where hydrogen used as an alternative to helium exploded, and it was later abandoned just due to its risky behaviour.[40] Moreover, hydrogen is not a toxic gas, but if released in confined environments can result in under-oxygenated atmospheres with the associate risk of asphyxiation.[41] However, they are manageable risks considering the final usage of hydrogen and comparing it with the use of sources like gas and petrol; for hydrogen, precautionary measures are required, having that a hydrogen-fuelled system could be equally or even safer than modern systems.[42]

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[35] *Hydrogen*. U.S. Energy Information Administration: https://www.eia.gov/energyexplained/hydrogen/ [August 25, 2022]

[36] Gallandat, N., Romanowicz, K., & Züttel, A. (2017). An Analytical Model for the Electrolyser Performance Derived from Materials Parameters. *Journal of Power and Energy Engineering*, 34-49. DOI: 10.4236/jpee.2017.510003.

[37] See: https://www.cnr.it/it/comunicato-stampa/5841/l-idrogeno-ecologico-ed-efficiente [October 23, 2022]

[38] International Energy Agency. (2019, June). *The Future of Hydrogen. Seizing today's opportunities.* Retrieved from IEA: https://www.iea.org/reports/the-future-of-hydrogen

[39] Office of Energy Efficiency & Renewable Energy. (2022, September 10). *Safe Use of Hydrogen*. Retrieved from Energy.gov: https://www.energy.gov/eere/fuelcells/safe-use-hydrogen

[40] See: https://www.history.com/this-day-in-history/the-hindenburg-disaster. Last update: (2022, May 3)

[41] H2 Obiettivo Idrogeno. *L'idrogeno: proprietà chimico-fisiche*. [August 25, 2022] http://idrogeno.assogastecnici.federchimica.it/portale_idrogeno/home.nsf/0/8BB24BE1C69B1B66C125734E0032D48C?OpenDocument#:~:text=In%20rapporto%20al%20volume%2C%20la,di%20quella%20del%20gas%20naturale

[42] Kruse, B., Grinna, S., & Buch, C. (2002, February 13). *Hydrogen Status og muligheter - Bellona rapport nr. 6.* Oslo: The Bellona Foundation.

2.2.2 Storage and usage

There are three forms of hydrogen: gaseous, liquid, and bounded in solid components. Supposing we have produced hydrogen in gaseous form, the problem is where to store it as the content of energy per unit of volume is low, requiring a considerable space and large tanks.[43] To reduce the space issue, hydrogen could be compressed at 350-700 bar or brought to a liquid state, optimizing in this way the space needed since the volume in liquid form is significantly less, but the temperature below which hydrogen is present in liquid form is equal to -252.8°C at one atmosphere pressure, which is a costly temperature to maintain[44], which require a consumption of electricity on average about 10 kilowatts per kilogramme (kWh/kg).[45] Other ways to store it which does not consider the space are the underground storage of hydrogen[46] in caves, salt domes and depleted oil and gas fields for example, or the storage on the surfaces or within solids through absorption before other techniques, but in this way we have material-based hydrogen which is not directly usable instead of physical-based.[47] Figure 12 summarizes forms of storage along with fuel cells, the electrochemical devices that makes it possible to obtain electricity directly from hydrogen and oxygen, without any thermal combustion process taking place, as a way to store and directly use hydrogen in a process described as follow: $2H_2 + O_2 \rightarrow 2H_2O$ + Electricity + Heat.[48]

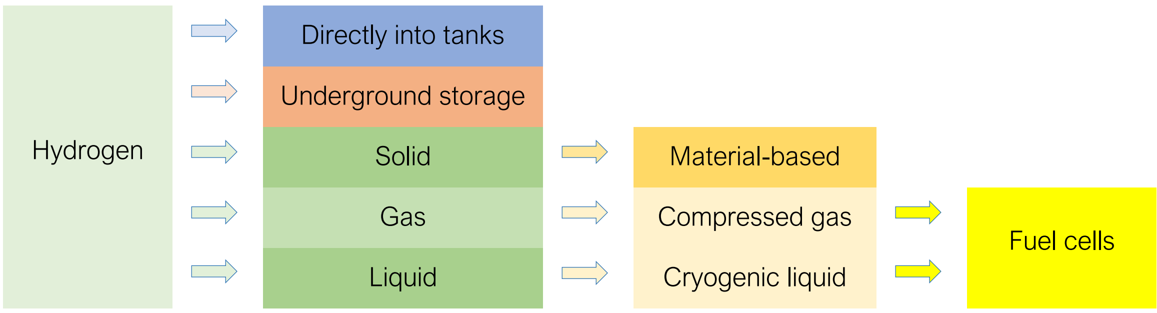

Figure 12 - Hydrogen storage forms.

[43] Kruse, B., Grinna, S., & Buch, C. (2002). *Hydrogen Status og muligheter - Bellona rapport nr. 6.* Norway: The Bellona Foundation.

[44] Office of Energy Efficiency & Renewable Energy. *Hydrogen Storage*. Retrieved from Energy.gov: https://www.energy.gov/eere/fuelcells/hydrogen-storage [September 5, 2022]

[45] International Energy Agency. (2022). *Global Hydrogen Review 2022.* Retrieved from IEA: https://iea.blob.core.windows.net/assets/c5bc75b1-9e4d-460d-9056-6e8e626a11c4/GlobalHydrogenReview2022.pdf.

[46] Yue, M., Lambert, H., Pahon, E., Roche, R., Jemei, S., & Hissel, D. (2021). Hydrogen energy systems: A critical review of technologies, applications, trends and challenges. *Renewable and Sustainable Energy Reviews 146*, 111180.

[47] Office of Energy Efficiency & Renewable Energy. *Hydrogen Storage*. Retrieved from Energy.gov: https://www.energy.gov/eere/fuelcells/hydrogen-storage [September 5, 2022]

[48] Yue, M., Lambert, H., Pahon, E., Roche, R., Jemei, S., & Hissel, D. (2021). Hydrogen energy systems: A critical review of technologies, applications, trends and challenges. *Renewable and Sustainable Energy Reviews 146*, 111180.

The volume issue however remains one strong limitation for its common use since its energy by volume is much less than other fuels even if its energy per mass is substantially greater. As we can see in Figure 13, the comparison for some fuels of specific energy given by energy per mass, called gravimetric density, and energy density given by energy per volume, called volumetric density, reveals that hydrogen has the greatest energy related to its weight, with more than 30 kWh/kg, but storing a kilogramme of hydrogen requires more space than the other fuels since its density is just 0.0838 kg/m^3 while is 0.668 kg/m^3 for Methane, 1.87 kg/m^3 for Propane, 791 kg/m^3 for Methanol and 751 kg/m^3 for Gasoline.[49]

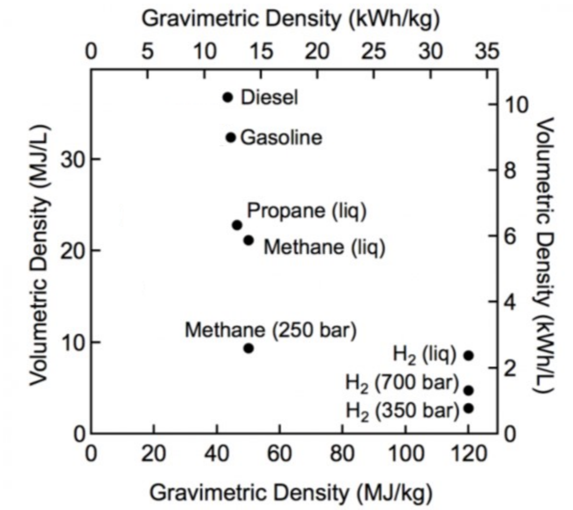

Figure 13 - Energy per mass (Gravimetric Density) and energy per volume (Volumetric Density) of conventional fuels. [50]

According to the U.S. Department of Energy, taking as example a 500 kilometres driving range, a fuel cell vehicle would need about 5 kg of hydrogen to complete the entire travel and with a compression pressure of 700 bar the storage system would require a volume of about 200 litres, which is equal around 3-4 times the volume of gasoline tanks that we observe in modern cars. There is also a cost issue regarding the technologies that help the process of storage and use of hydrogen in fuel cells for electric vehicles: a fuel cell depends for 31% on the amount and high costs of carbon fiber composite materials and for 25% on the supporting components required to deliver energy. The aim of the Department is to reach a cost of 8 dollars per kilowatt hour ($/kWh) for fuel cells technology starting from a cost projection of 15 $/kWh in 2016. What research is still working on, concerns the ability to store enough hydrogen in a vehicle while allowing for a competitive range, on-board space, and fuel storage comparable to today, including high-pressure compressed storage technologies and material-based storage technologies.[51]

[49] *See:* https://h2tools.org/hyarc/hydrogen-data/comparative-properties-hydrogen-and-other-fuels [October 6, 2022]

[50] Fuel Cells Technologies Office. (March 2017). *Hydrogen Storage DOE/EE-1552.* United States: U.S. Department of Energy - Energy Efficiency & Renewable Energy.

[51] Ibid.

2.2.3 Transportation and infrastructure

Once hydrogen has been produced, we need to consider what are the methods of its transport. For the gaseous form there are studies on the transportation of hydrogen, for which a special equipment and procedures are required to handle it since it is smaller than natural gas and can escape and spread without obvious detection through connectors or trimmings, and also putting various materials like iron and steel pipes at risk.[52] The issue of having the right infrastructure to bring hydrogen where it is needed is the most crucial since think about new dedicated hydrogen pipeline network for storage and exploitation could bring a massive cost issue.[53] Nowadays, we still have the investments on methane pipelines to consider, which have amortized cost over time and have yet to return from their expenses, but someone suggests that we could use those pipelines to transport hydrogen instead of gas; SNAM, a leading firm operating in natural gas transport and storage, is promoting this strategy trials on energy mix of hydrogen and methane gas in the current pipelines.[54] The Italian Ministry of Ecological Transition (MITE) itself, in 2021, confirms the estimates regarding the possibility of transporting hydrogen in current pipelines with a current compatibility of more than 70%.[55] However, limits are observed since the hydrogen damage on pipelines is known, several coatings can be used to diminish corrosion but they do not stop the leakages yet.[56] Also, there are ongoing studies related to the consequences of the mixtures in pipelines, and the chemical differences between methane and hydrogen such as density and viscosity lead to safety concerns regarding to possible accidents along the pipelines. For the short-term, the structure seems to have no particular degradation to compromise its use, but for long-term effects, further assessments will need to be made for pipeline conservation.[57] Although it remains complex, the possibility of such infrastructure should not be excluded as there is experience with the use of hydrogen on industrial scale in dedicated distribution pipelines, with site-specific protocols for safe management[58], like in the U.S. to deliver hydrogen to large oil refineries and chemical plants; these pipelines, though,

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[52] International Energy Agency. (2019, June). *The Future of Hydrogen. Seizing today's opportunities.* Retrieved from IEA: https://www.iea.org/reports/the-future-of-hydrogen

[53] Rifkin, J. (2002). *The Hydrogen Economy: The Creation of the Worldwide Energy Web and the Redistribution of Power on Earth.* United States: Polity Press.

[54] See: https://www.snam.it/it/transizione_energetica/idrogeno/snam_e_idrogeno/ [October 19, 2022]

[55] Italian Ministry of Ecological Transition. (July 2022). *La Situazione Energetica Nazionale Nel 2021 .* Energy Department. Retrieved from: https://dgsaie.mise.gov.it/pub/sen/relazioni/relazione_annuale_situazione_energetica_nazionale_dati_2021.pdf.

[56] Shaik, K., & Shiladitya, P. (2022). Inspection of Coated Hydrogen Transportation Pipelines. *Applied Sciences. 12(19):9503. https://doi.org/10.3390/app12199503*.

[57] Mahajan, D., Tan, K., Venkatesh, T., Kileti, P., & Clayton, C. (2022). Hydrogen Blending in Gas Pipeline Networks - A Review. *Energies. 15(10):3582. https://doi.org/10.3390/en15103582*.

[58] International Energy Agency. (2019, June). *The Future of Hydrogen. Seizing today's opportunities.* Retrieved from IEA: https://www.iea.org/reports/the-future-of-hydrogen

have a total length of about 2 575 kilometres, a very small sum when one considers the more than 482 800 kilometres for the transport of methane gas.[59] Overall, the main methods for transporting hydrogen are gaseous pipelines and pressurised tube trailers for hydrogen gas, and cryogenic tankers for hydrogen in liquid form.[60] We can also distinguish the methods for terrestrial transportation, like roads and pipelines, with a predominance of liquefied and compressed hydrogen delivery, and for maritime transportation, with ships that could transport liquefied hydrogen. To choose the right method it is fundamental to consider: the amounts of hydrogen that one wants to transport and the supply chain conditions of production and delivery routes.[61] Pipelines have the higher initial investment that could mainly concern governments[62], but once completed they are the most economical way to deliver large quantities of hydrogen gas at low pressure, while is better to use tankers for liquefied hydrogen, more dense and with high energy content, only when pipelines are not available and the costs of liquefaction permit it, requiring up to 30% of the hydrogen energy content.[63] Instead, pressurised tubular trailers are more efficient for the transports over relatively short distances, estimated not to exceed 320 kilometres from the point of production, transporting compressed hydrogen gas by road at pressures of 200-500 bar. The higher the pressure, the higher the energy density, but this will increase costs due to compression and the safety requirements of high-pressure equipment. In the European Union for instance, as stated in the European Directive on the Deployment of Alternative Fuels Infrastructure, which refers to the technical specification ISO/TS 20100 Gaseous Hydrogen Refuelling Stations, the standardised storage pressure is equal to 350 bar and 700 bar, with the first prevailing in the case of buses and the latter for passenger cars. There would be another possibility, which is the direct production and distribution at the site of use, producing hydrogen directly at sites that require it or at refuelling stations, thus eliminating the costs of transporting hydrogen. However, a trade-off between transport and production costs must be taken into account, as there would not be the same production efficiency as in the case of a single large production plant, which entails higher delivery costs but also lower production costs due to economies of scale.[64] The entire supply chain with the different types of transportation is summarized in Figure 14.

[59] Fuel Cells Technologies Office. (March 2017). *Hydrogen Delivery DOE/EE-1551.* United States: US Department of Energy - Energy Efficiency & Renewable Energy.

[60] Ibid.

[61] Martinez-Garcia, G. (1 July 2017). *Cost-benefit analysis of a hydrogen supply chain deployment case for fuel cell vehicles use in Midi-Pyrénées region.* Barcelona: Projecte Final de Màster Oficial, UPC, Escola Tècnica Superior d'Enginyeria Industrial de Barcelona.

[62] Robles, J. O., Azzaro-Pantel, C., Martinez-Garcia, G., & Lasserre, A. A. (2020). Social cost-benefit assessment as a post-optimal analysis for hydrogen supply chain design and deployment: Application to Occitania (France). *Sustainable Production and Consumption, 24*, 105-120.

[63] Fuel Cells Technologies Office. (March 2017). *Hydrogen Delivery DOE/EE-1551.* United States: US Department of Energy - Energy Efficiency & Renewable Energy.

[64] Ibid.

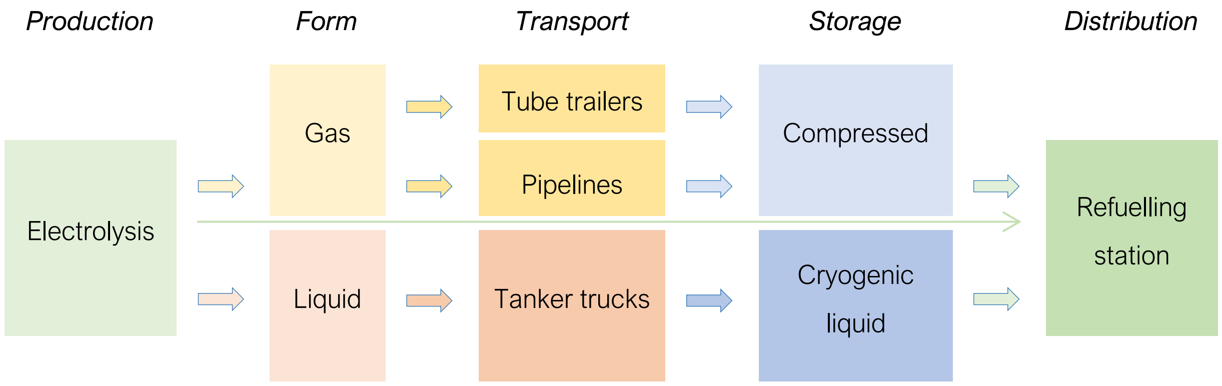

Figure 14 - Green Hydrogen from production to distribution.

Regarding hydrogen transport infrastructure, recent studies from the University of Cambridge and Reading highlight possible environmental consequences of hydrogen leakage in the infrastructure, directly related to the emission of H_2. The study is an analysis on atmospheric implications of increased hydrogen use[65], it recognises the importance of hydrogen as energy carrier for the strategy to reduce the use of fossil fuels, reducing related emissions such as carbon dioxide CO_2, methane CH_4, volatile organic compounds VOCs, and oxides of nitrogen NO_x, leading to an improvement in air quality, but the authors fear the release of hydrogen into the atmosphere, which would have a broader impact on the composition of the atmosphere that may offset the benefits of the hydrogen transition. Because air also contains quantities of other gases such as carbon dioxide and methane, the authors fear a reaction of hydrogen with these gases; thus, most doubts stem from the uncertainty on natural atmospheric hydrogen equilibrium, so more work will be needed in the future. One observation that can be made about this concerns the fact that in the European Union is valid of the precautionary principle, adopted in 2000 and laid down in Article 191 of the Treaty on the Functioning of the European Union (TFEU), according to which it is better to prevent dangerous environmental behaviour even in the absence of certain information, due to scientific shortcomings, about the actual occurrence of a harmful event. Consequently, if the hydrogen economy is currently being financed and implemented in the EU, it means that not only is there not enough scientific evidence of possible environmental damage, but the risk is also decidedly small and does not require any preventive stance; Europe, as a matter of principle, guarantees a high level of environmental protection.[66]

[65] Warwick, N., Griffiths, P., Keeble, J., Archibald, A., Pyle, J., & Shine, K. (April 2022). *Atmospheric implications of increased Hydrogen use.* London: Crown.

[66] See: https://eur-lex.europa.eu/legal-content/IT/TXT/?uri=LEGISSUM:precautionary_principle [October 25, 2022]

2.2.4 Water consumption

Water is a critical resource that in the future must be managed as well as possible to cope with the increasingly frequent periods of low availability; when we talk about water, we mean fresh, potable water, which measures only 2.5% of all water on our planet.[67] This resource is also present when we talk about hydrogen: because water is needed in the production phase of electricity and it is the raw material to run the electrolysis process from which hydrogen can be generated. The first consideration regards the use of water to obtain the electricity needed in the process, and in specific we can report a work about its usage in thermoelectric power plants fuelled by coal and oil, made in 2007 by Michael E. Webber, associate director at the Centre for International Energy and Environmental Policy at the University of Texas at Austin. According to his results, producing hydrogen with that method leeds to excess consumption.[68] In addition, he estimated how much water our society would need if we were to focus on hydrogen, as advocated by Rifkin, providing an initial analysis of total water needs with data for a transitional hydrogen economy in the fossil-driven United States. In Webber's analysis, the water intensity of the hydrogen transition economy is examined by quantifying the direct and indirect water requirements for the annual production of 60 billion kilograms of hydrogen, partly by thermoelectric electrolysis. Total water withdrawals for thermoelectric cooling will increase from the current 195 000 million gallons per day by 27% to 97% especially depending on the overall efficiency of the electrolysers that will be installed, and the portion of hydrogen produced by thermoelectric electrolysis. As we can see in Figure 15, the production of hydrogen is strictly related to the efficiency of electrolysers and therefore the electricity and water consumption.

Electrolyzer efficiency	Electricity required for electrolysis (kWh kg^{-1})	Portion of hydrogen that is produced by electrolysis					
		35%	45%	55%	65%	75%	85%
Ideal	39.4	827	1064	1300	1537	1773	2009
90%	43.8	920	1183	1445	1708	1971	2234
80%	49.3	1035	1331	1627	1923	2219	2514
75%	54.0	1134	1458	1782	2106	2430	2754
70%	56.3	1182	1520	1858	2196	2534	2871
60%	65.7	1380	1774	2168	2562	2957	3351
		Annual electricity requirements to electrolytically produce hydrogen (billion kWh)					

Figure 15 - Annual electricity input requirement to produce 60 billion kg of hydrogen for a varying fraction that is produced by electrolysis and a range of electrolyser efficiencies. (M.E. Webber, 2007)

[67] *Thirst for Power: Energy, Water and Human Survival | Michael Webber | Talks at Google*. December 2016, YouTube: https://www.youtube.com/watch?v=3DDTOk6jQ-s [August 27, 2022]

[68] Webber, M. E. (20 September 2007). The water intensity of the transitional hydrogen economy. *Environmental Research Letters*, Volume 2, Number 3.

Therefore, to resort to thermoelectrically powered electrolysis using an electrolyser with 75% efficiency, an average of about 1100 gallons of cooling water would have to be taken and 27 gallons of water would have to be consumed as feedstock and coolant for every kilogram of hydrogen produced. According to the author, water withdrawals have remained constant for decades, and this increase in water use would represent a potentially significant impact of the hydrogen economy on a critical resource such as water, and it is consequently relevant to determine the best strategy for hydrogen production. If minimizing water resource impacts is a priority and electrolysis becomes a widespread method of hydrogen production, hydrogen production will have to come from pathways that do not use much water, e.g. from wind or solar, setting up a radical decentralization supported by electricity provided by renewables.[69] Water is used for driving hydroelectric turbines, steam turbines and cooling power plants for example, and the availability is given by the hydrologic cycle which can give us a lot of water but in the wrong place, time, and form. Moreover, there are trends that hinder sustainable consumption: the population growth will lead to a higher demand for energy and water, the economic growth will increase the per capita demand, and the severe weather events brought by the climate change like rainfalls, snowmelt, droughts will make water management more difficult. In this context, driving toward less water-intensive energies could change the usage of the resource as illustrated in Figure 16, which reports a slide from the Webber's lecture "Thirst for Power: Energy, Water and Human Survival" of 2016[70], where the relation between the usage of water by several energy sources and the environmental impact measured by CO_2 emissions related to them shows how solar and wind energy will noticeably minimize the usage of water, further reinforcing the argument that green hydrogen is the preferable one.

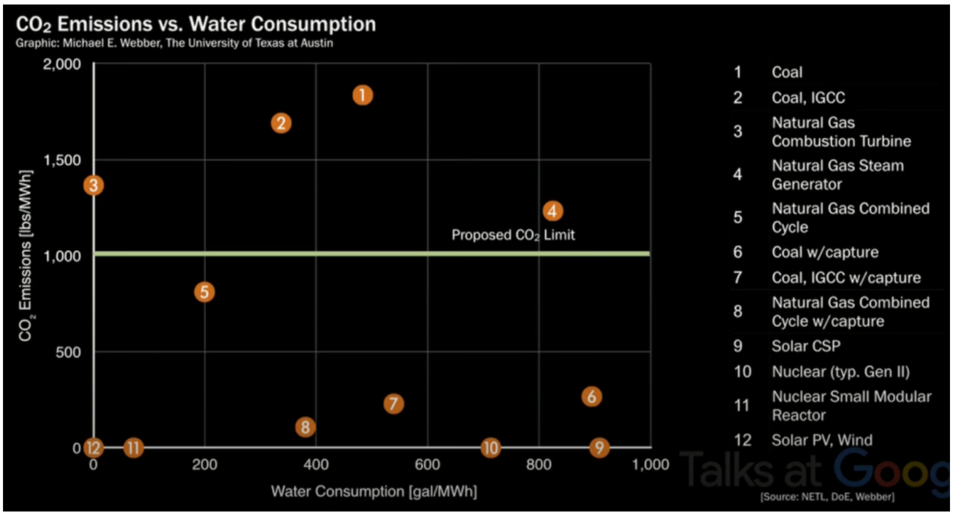

Figure 16 - CO_2 Emissions and Water Consumption of different source of energy. (M.E. Webber, 2016)

[69] Webber, M. E. (20 September 2007). The water intensity of the transitional hydrogen economy. *Environmental Research Letters*, Volume 2, Number 3.

[70] *Thirst for Power: Energy, Water and Human Survival | Michael Webber | Talks at Google*. December 2016, YouTube: https://www.youtube.com/watch?v=3DDTOk6jQ-s [2022, August 27]

Water is a necessary element, together with electricity powered by renewable sources, to power the electrolysis process, and therefore its consumption should be sustainable. To consider the direct use of water for green hydrogen production we can look at data from the Dutch company Lenntech Water Treatment Solutions for which 1 kg of hydrogen requires 9 litres (l) of water as input by the electrolysis process but, due to some inefficiencies in the process, the ratio may vary between 18 l and 24 l [71], confirmed by the literature[72], with more optimistic estimates that reach 11.1 l [73]. Furthermore, the company shows a comparison with the current consumption of fresh water for thermal power plants: with a water consumption of 20 l per kg of H_2 produced and a large 1 GW electrolyser operating at 75% efficiency for 8 000 hours per year is considered, the annual hydrogen production would be 0.15 million tonnes using 3 million m^3 of water. This annual consumption would be equal to the water consumption of a small town of about 70 000 inhabitants considering an average water consumption per inhabitant of 45 m^3. This is a figure that makes one think about the use of water, as it is necessary to locate the plant in a place with plenty of water. Thus, it is important to consider that the volumes of water needed could be significant for water-stressed regions, and the source and type of water used for large-scale hydrogen production should accordingly be emphasised in hydrogen strategies. Looking at the global level, in the International Renewable Energy Agency (IRENA) Global Renewables Outlook of 2020[74], to highlight the investment options for a safe climate, about 160 million tonnes of green hydrogen are expected in 2050, for which it is estimated that about 3 billion m^3 of water per year will be needed. These results are consistent and proportional to those calculated by Lenntech, probably with a slightly lower assumption of water consumption per kilogram of hydrogen produced due to projected improvements on technologies throughout the time horizon. The amount estimated is equivalent to about 0.08% of current global freshwater consumption and is still lower than the 5.8 billion m^3 of water estimated in 2030 for the American thermal power plants, suggesting that water consumption is not a sufficiently critical argument to give up on hydrogen. However, dependence on water remains an element of risk since hydrogen production is linked to its availability and this makes water a limit not for its consumption in general but for its availability in the surrounding area. Indeed, as the company also suggests, it will be important to individually assess the local impact where the projects will be implemented.[75]

[71] *Hydrogen*. Retrieved from Lenntech - Water treatment: https://www.lenntech.com/applications/hydrogen.htm [August 27, 2022]

[72] Mehmeti, A., Angelis-Dimakis, A., Arampatzis, G., McPhail, S., & Ulgiati, S. (2018). Life cycle assessment and water footprint of hydrogen production methods: From conventional to emerging technologies. *Environments*, 5(2), 24.

[73] Yue, M., Lambert, H., Pahon, E., Roche, R., Jemei, S., & Hissel, D. (2021). Hydrogen energy systems: A critical review of technologies, applications, trends and challenges. *Renewable and Sustainable Energy Reviews 146*, 111180.

[74] See: https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Apr/IRENA_GRO_Summary_2020.pdf?la=en&hash=1F18E445B56228AF8C4893CAEF147ED0163A0E47 [August 27, 2022]

[75] *Hydrogen*. Retrieved from Lenntech - Water treatment: https://www.lenntech.com/applications/hydrogen.htm [August 27, 2022]

As an alternative, the impact of hydrogen production on freshwater availability could be reduced if desalinated seawater is assumed to be used, and desalination in the areas with water shortages could be the key option that guarantee a sustainable use of the resource. However, the costs related to this process must be considered: for the desalination of 1 m^3 of water, the cost of electricity ranges between $0.7 and $2.5, which is believed to have little influence on the total cost of hydrogen production.[76] Which is true if we take into account that 1 m^3 of water is equivalent to 1 tonne of water, i.e. 1 000 kg, and the total cost of producing (green) hydrogen per kilogram today exceeds 4 $/kg, depending on location and the cost of the energy used to produce it, according to the International Energy Agency (IEA) report "The future of hydrogen".[77] There is also an environmental cost to consider related to desalination, because it produces 1.5 litres of brine from one litre of water, which is industrial slag for disposal.[78] It follows that the choice of desalinating water must be considered when evaluating the individual project, since as mentioned above, for some areas such as coastal areas, it may be more convenient to desalinate it. The research could lead to new solutions in the direct use of salt water, which alone damages the electrolyser anode very quickly. As discovered in research published in March 2019 by Stanford University, a kind of nickel-based foam coated with other chemical compositions of iron and nickel slows corrosion of components by allowing direct use of salt water to make green hydrogen from electrolysis.[79] However, the research does not show the costs associated with this method; it is just one case of the continuing research in the hydrogen field.

[76] Yue, M., Lambert, H., Pahon, E., Roche, R., Jemei, S., & Hissel, D. (2021). Hydrogen energy systems: A critical review of technologies, applications, trends and challenges. *Renewable and Sustainable Energy Reviews 146*, 111180.

[77] International Energy Agency. (2019, June). *The Future of Hydrogen. Seizing today's opportunities.* Retrieved from IEA: https://www.iea.org/reports/the-future-of-hydrogen

[78] See: Armaroli, N. (2021, July 9). Tutto quello che avresti sempre voluto sapere sull'idrogeno e sull'elettrificazione. (M. Montemagno, Interviewer)

[79] See: https://news.stanford.edu/press-releases/2019/03/18/new-way-generateen-fuel-seawater/ [October 5, 2022]

2.3 Benefits of hydrogen as energy vector

2.3.1 First advantages

Given the main limitations of implementing hydrogen as energy vector, we now move on to the main advantages that this element could bring. First and foremost, the advantage of being able to transport and store energy over time is not so obvious; moreover, this energy is considered a "clean" fuel which does not emit pollutants during its use and strictly obtained with energy from renewable sources. As previously mentioned, the production of hydrogen requires more energy than it produces, but according to the International Energy Agency, if there were no energy supply limits and as long as greenhouse gas emissions are evaluated, the main obstacle would be more economic than in terms of the efficiency of the entire hydrogen value chain. Just consider how hydrogen can be used more efficiently than other energy sources and without producing CO_2, as in the case of a hydrogen fuel cell in a vehicle, for which it has an efficiency of about 60% versus the 20% of gasoline internal combustion engine.[80] Additionally, Figure 17 shows how hydrogen used in fuel cells emits only pure water and heat, making it essentially an engine that with its use does not pollute.[81] Hydrogen not only has no impact on the atmosphere if correctly managed, but it has a significantly reduced impact on the health and safety of people and environment compared to conventional energies, not only in the use of fuel cells but also to more widespread production plants.[82]

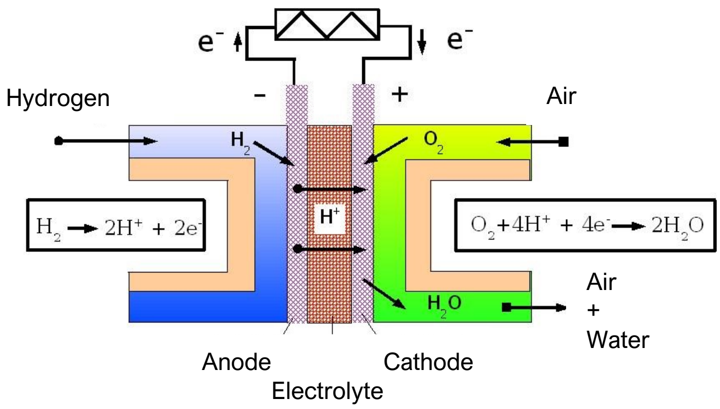

Figure 17 - Energy production from hydrogen: at the end of the cycle, energy and pure water are produced. [83]

[80] International Energy Agency. (2019, June). *The Future of Hydrogen. Seizing today's opportunities.* Retrieved from IEA: https://www.iea.org/reports/the-future-of-hydrogen

[81] ACEPER impresa green. (April 2021). *Il racconto di un mondo che si rinnova, Numero 2.* Chivasso (TO), Italy: https://www.flipbookpdf.net/web/site/70c8cd00e0b0d224e0468a91d1737bf286768b14FBP21250185.pdf.html#page/2.

[82] *Idrogeno*. Enel Green Power. https://www.enelgreenpower.com/it/learning-hub/energie-rinnovabili/idrogeno [August 8, 2022]

[83] Image adapted from Wikipedia: https://it.wikipedia.org/wiki/Pila_a_combustibile [September 13, 2022]

As mentioned in the limits, hydrogen has a low energy density per unit volume, which means that there must be larger volumes of hydrogen to meet the same energy demands as other fuels, and for this reason, hydrogen can be compressed, liquefied, or transformed into hydrogen fuels that have a higher energy density. Despite this, hydrogen contains more energy per unit mass than natural gas or petrol making itself attractive as a transport fuel; indeed, of all fuels and combustibles, regardless of volume, hydrogen has the highest energy density where 1 kg of hydrogen contains the same energy as 2.1 kg of natural gas or 2.8 kg of petrol[84], with 33.33 kWh energy per kilo for hydrogen compared to 12 kWh for petrol[85]. This energetic power of hydrogen shows the potential benefit as energy vector in sectors like aviation, naval transport, buses, but also for energy-intensive industries such as steel or chemical, and heating, where the limitation of space is relative compared to the amount of energy required. In Figure 18 is presented an indicative scheme, with the use of the data from the Italian Institute for High Performance Computing and Networking - ICAR CNR"[86], to clarify from where green hydrogen begins and where it can end.

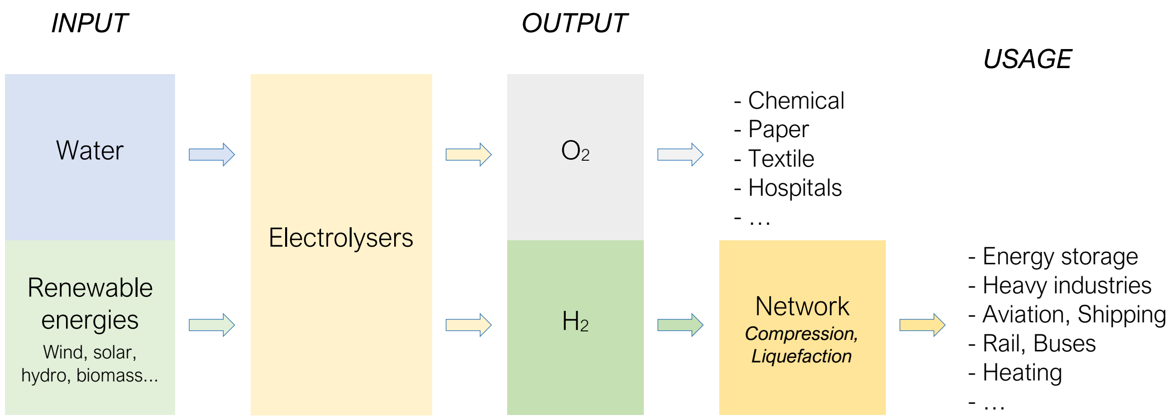

Figure 18 - Scheme of Green Hydrogen Energy.

As mentioned in the introductive chapter, another benefit regards the opportunity to avoid dependencies on other energy sources that comes from foreign countries, gaining self-sufficiency productions, with the extension of renewable energies, especially today where the geopolitical situation brought up the theme of energy supply in the foreground. This benefit derives from an assessment of the risk associated with dependence on resources that can be influenced by third parties, i.e., situations that do not depend directly on the actions of those who consume those resources.

[84] H2 Obiettivo Idrogeno. *L'idrogeno: proprietà chimico-fisiche*. [August 25, 2022] http://idrogeno.assogastecnici.federchimica.it/portale_idrogeno/home.nsf/0/8BB24BE1C69B1B66C125734E0032D48C?OpenDocument#:~:text=In%20rapporto%20al%20volume%2C%20la,di%20quella%20del%20gas%20naturale.

[85] Yue, M., Lambert, H., Pahon, E., Roche, R., Jemei, S., & Hissel, D. (2021). Hydrogen energy systems: A critical review of technologies, applications, trends and challenges. *Renewable and Sustainable Energy Reviews 146*, 111180.

[86] See: https://www.icar.cnr.it/notizie/conservare-ed-utilizzare-lenergia-senza-produrre-co2-un-obiettivo-possibile-con-lidrogeno/ [September 13, 2022]

2.3.2 Shadow prices

The scientific community and institutions are very clear and convinced that human activities are increasing the emissions of the CO_2 gas, which has a known greenhouse effect. Following the Global Energy Perspective 2019 of McKinsey[87], the fossils were responsible of 83% of the total emissions of CO_2, where the only production of energy with carbon counts for 36%, and it consequently invites action to avoid these emissions by finding alternatives that generate energy without using fossils. Humanity is facing the greenhouse effect, recognizing that the anthropogenic activity increases it which rises the global temperatures, bringing increasingly violent and frequent phenomena such as floods, droughts, and hurricanes. The United Nations Environment Programme pointed out in its "Emissions Gap Report 2021" that current climate commitments are insufficient to mitigate the projected global temperature rise of 2.7°C by the end of the century, which would be a catastrophic increase for human life on earth. As a result, the impact that some human activities have should be more severely assessed because greater emission reduction efforts will be needed by the next decade to keep global warming within the 1.5°C set in the Paris Agreement.[88] Producing CO_2 emissions has an environmental cost which is not only difficult to measure but is difficult to see with the eyes since is colourless, and in a society based on images it is a huge problem. We could suggest considering the costs related to the variation of damages generated by the increasingly violent and visible natural phenomena as imputable to the increase in emissions, although it is difficult to have an exact estimate since the damages are also related to the kind of prevention measures implemented. We could relate the price of emissions directly to these measures, to see by how much we should improve prevention to offset the impacts of the additional destructive phenomena. A similar road is estimating the optimal level of environmental protection, focusing on the demand curves based on the estimation of consumer's willingness to pay, that can be made with two methods: by using creative pricing, where consumer preferences are revealed through the demand for goods and services directly related to an environmental good, for instance a comparison between the house price in a non-polluted or safe area and a house next to a pollutant firm or in a risky zone, or by using the contingent valuation method, asking directly to consumers through a market survey their willingness to pay for the protection from the pollution.[89] Alternatively, the shadow price can be seen in the abatement value of the CO_2 kg production from natural gas and petrol, measured for example from the European EU Emissions Trading System, also used in a work that we will elaborate on later

[87] McKinsey & Company. (2019). *Global Energy Perspective 2019.* McKinsey Global Institute. https://www.mckinsey.com/industries/oil-and-gas/our-insights/global-energy-perspective-2019.

[88] UNEP, UNEP Copenhagen Climate Centre (UNEP-CCC). (26 October 2021). *Emissions Gap Report 2021.* United Nations Environment programme. https://www.unep.org/resources/emissions-gap-report-2021.

[89] Itskos, G., Nikolopoulos, N., Kourkoumpas, D.-S., Koutsianos, A., Violidakis, I., Drosatos, P., & Grammelis, P. (2016). Chapter 6 - Energy and the Environment. In N. Katsoulakos, M. Loukas-Moysis, I. G. Doulos, & V. Kotsios, *Environment and Development* (pp. Pages 363-452). Elsevier.

where the future carbon prices in the EU-28, the work of 2017 included Great Britain, are considered to compute the abatement value.[90] The price of carbon dioxide could be here seen as a waste for the economic activities, to manage by adopting compensative strategies such as buy rights to pollute or investing in protection measures, believing that they can still pollute or prevent certain phenomena. Therefore, CO_2 should not be considered as waste to manage or as a good to buy, but as a bad to avoid.

The effects of the reduction of emissions are not only environmental for nature and biosphere, but they also impact on health improvement and years of live gained considering the premature deaths for stroke, heart attacks, cancers, respiratory and cardiovascular diseases linked to pollution.[91] Moreover, the noise abatement related to road traffic and industrial activities when hydrogen is implemented is just as relevant with regard to public health[92], and eventually, the willingness to be self-sufficient rather than being subjected to a resource managed by governments in which they are not represented, as a shadow price for dependence. All of this, summarised in Figure 19, must be included in the assessment of hydrogen, and an appropriate estimation of the shadow prices should be made.

Benefits	*Shadow price measure*	*Considerations*
CO2 abatement	- Emission cap price for firms	CO_2 considered as a source to pay for consume it
	- Variation of disruptive events	CO_2 considered as a source to avoid for preventing
	- Consumers' willingness to pay	CO_2 considered as a source to avoid for preventing
Health improvement	- Treatment cost savings	Cost reduction in related hospitalizations
	- Consumers' willingness to pay	Social value of risk reduction of premature death
Noise reduction	- Consumers' willingness to pay	Social value of living in a quieter area
Dependencies avoidance	- Resource cost savings	Zeroing the cost of importing fossil fuels
	- Consumers' willingness to pay	Social value of having autonomous resources

Figure 19 - Guidelines for hydrogen-related shadow prices on benefits.

[90] Martinez-Garcia, G. (1 July 2017). *Cost-benefit analysis of a hydrogen supply chain deployment case for fuel cell vehicles use in Midi-Pyrénées region.* Barcelona: Projecte Final de Màster Oficial, UPC, Escola Tècnica Superior d'Enginyeria Industrial de Barcelona.

[91] See: https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health [September 14, 2022]

[92] Martinez-Garcia, G. (1 July 2017). *Cost-benefit analysis of a hydrogen supply chain deployment case for fuel cell vehicles use in Midi-Pyrénées region.* Barcelona: Projecte Final de Màster Oficial, UPC, Escola Tècnica Superior d'Enginyeria Industrial de Barcelona.

2.3.3 Storehouse of energy: hydrogen power-to-gas

Starting from the energy needed to produce hydrogen, the observation to make is that the energy sources, the renewables, are naturally replenishing and theoretically inexhaustible in duration but are "flow-limited in the amount of energy available per unit of time."[93] In the electric power sector the electricity that can be generated corresponds to a relatively fixed quantity over short periods of time and fluctuates depending on periods and time of day, not necessarily following the demand path for electricity. This leads to a necessary accumulation of energy, stored in some technologies which allows enough energy to be available later to meet the demand when necessary. One must therefore think of electrical energy storage devices that accumulate the energy produced during peaks of intensity, thus more than the demand, and that can distribute it at times of low production; for intermittent sources such as wind and solar, when the wind does not blow, the sun does not shine, and the energy demand is high.[94] One the one hand, new energy storage technologies are already being worked on and various projects are being financed, such as research into storage batteries at national laboratories, through to more targeted investments in start-ups like the Energy Department of the USA is doing; on the other hand, the strategy could be to use the energy not stored to produce hydrogen to generate a reserve of energy.

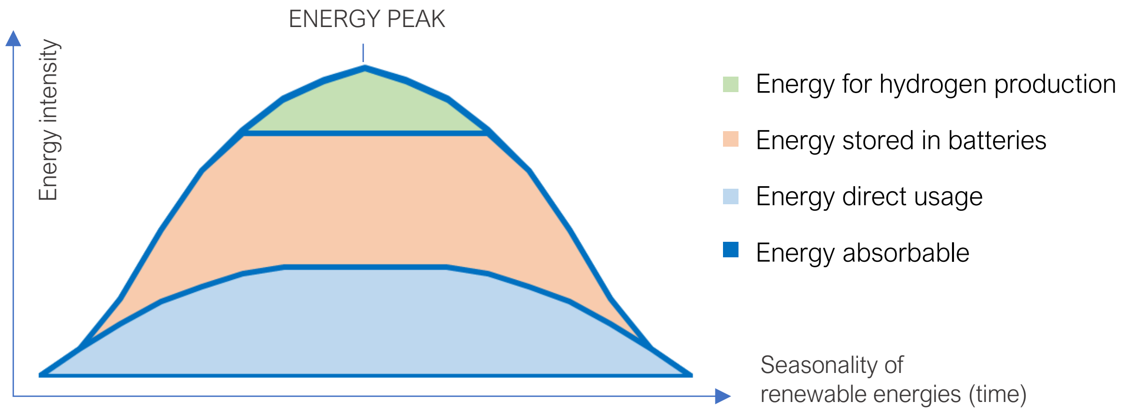

Figure 20 - Total theoretical absorbable energy with respect to hydrogen production.

As presented in Figure 20, total absorbable energy can be described by an energy intensity characterized by a more or less constant seasonal pattern, derived from fluctuating renewable energy. This intensity can be used directly to power various services or industries, can be stored in planned storage batteries, or used to power electrolysis from which hydrogen can be produced. The latter option could be considered when a surplus of energy is present, i.e., when there is a residual portion that the

[93] *Hydrogen*. (2022, January 20). Retrieved from U.S. Energy Information Administration: https://www.eia.gov/energyexplained/hydrogen/

[94] American Energy Department. *Energy Storage Office of Electricity*. ENERGY.GOV: https://www.energy.gov/oe/energy-storage [August 28, 2022]

entire system of the renewable cannot absorb or store. This process of converting the residual renewable energy, or rather the surplus, into hydrogen is known by the term Power-to-Gas, in which hydrogen is defined as a seasonal energy storage option, linked in fact to intermittent energy sources, thus allowing the potential of renewables to be exploited to the maximum in their absorption peaks, consequently responding better to energy demand.[95]

In some countries, hydrogen is already produced to absorb peak production typical of renewables as in the case of Germany, where the company Enertrag AG commissioned in 2011 the first power plant capable of storing the energy surplus produced by wind farms in the form of hydrogen, aiming to improve the supply balance of the electricity grid. As far as hydrogen is concerned, the power plant mainly consists of three 2.3 megawatt (MW) wind turbines connected with a 600 kilowatt alkaline water electrifier, capable of producing 120 nm^3 of hydrogen in one hour, and a hydrogen storage tank with a capacity of 1350 kg of hydrogen at 42 bar pressure.[96] Two other German companies, Amprion and Open Grid Europe, with their project called *Hybridge*, are also planning a large-scale power-to-gas plant to convert up to 100 MW of electricity into hydrogen, with commissioning scheduled during 2023.[97] Other examples can be found in Canada with the company FireWater Fuel Corp., which has developed an innovative system that uses cheap catalysts to produce hydrogen from the surplus energy of wind and photovoltaic plants, and in this way, the energy produced during peak hours is redistributed into the grid when electricity demand increases. However, companies make it clear that the costs of such process do not allow for the large-scale implementation, but they are looking for new ways to cut costs such as the development of new catalysts to produce clean hydrogen.[98]

A project coordinated by the professor Marcello Baricco, from the Department of Chemistry of the University of Turin, called *HyCARE*, aims at developing a hydrogen storage tank, capable to store 50 kg of hydrogen at 30/50 bar, with the technique of absorption, to store it in a solid-state, with a total round trip energy efficiency equal to 70%.[99] In addition, a research from the University of Oregon has shown how the design of new catalysts can affect the cost and efficiency of clean hydrogen production,

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[95] Linssen, J., & Hake, J.-F. (2016). Hydrogen Research, Development, Demonstration, and Market Deployment Activities. In D. Stolten, & B. Emonts, *Hydrogen Science and Engineering : Materials, Processes, Systems and Technology* (pp. 57-84). Germany: Wiley-VCH Verlag GmbH & Co. KGaA.

[96] R. Fischer, U., Wenske, M., Tannert, D., & Krautz, H.-J. (2016). Hydrogen Hybrid Power Plant in Prenzlau, Brandenburg. In D. Stolten, & B. Emonts, *Hydrogen Science and Engineering : Materials, Processes, Systems and Technology* (pp. 1033-1052). Germany: Wiley-VCH Verlag GmbH & Co. KGaA.

[97] *Hybridge Project*. (2022, August 28). Retrieved from Hybridge - convert electricity from renewable energy sources into hydrogen: https://www.hybridge.net/Project/Plan/ [August 28, 2022]

[98] FireWater Fuel Corp. (2022, August 28). *Catalyst Development for Clean Hydrogen Production*. Retrieved from Mitacs: https://www.mitacs.ca/en/partner/firewater-fuel-corp [August 28, 2022]

[99] Details on: https://hycare-project.eu/ [September 17, 2022]

therefore it can be produced with much higher efficiency and lower cost than is possible with current commercially available catalysts. With the use of new materials, hydrogen could be produced at 1$/2$ per kg, which would be less expensive for industries than current fuels, ensuring in this way the achievement of the zero emissions target. These data are in line with the U.S. Department of Energy's Office of Hydrogen and Fuel Cell Technologies ambitions of reducing the cost of clean hydrogen by 80%, from 5$ to 1$ per kg by 2030[100], but it is important to remember that now they remain ambitions rather than predictions, and we will reason on those later. However, a large part will be played by renewables themselves: a 2020 study considering the Western U.S. power system shows that seasonal hydrogen storage with a discharge duration of up to 1 week could be cost-effective soon if power capital costs are 1.5 $/kWh or less and energy capacity costs are 1.8 $/kWh or less by 2025.

In conclusion, storage systems like hydrogen could be cost-competitive soon if renewables increase their capacity or significantly reduce their capital costs, or if revenues from additional services or new markets that incentivise hydrogen production are monetised.[101] Energy storage is essential to cope with the seasonality and variability of renewable resources and to take full advantage of them, and consequently the potential benefit of hydrogen storage must be considered when evaluating policies for its implementation.

[100] Oregon State University. (2021, December 10). *Researchers develop advanced catalysts for clean hydrogen production*. Retrieved from ScienceDaily: https://www.sciencedaily.com/releases/2021/12/211210140714.htm

[101] Guerra, O. J., Zhang, J., Eichman, J., Denholm, P., Kurtz, J., & Hodge, B.-M. (2020). The value of seasonal energy storage technologies for the integration of wind and solar power. *Energy & Environmental Science*, Issue 7.

2.3.4 Sustainability

Economics is about managing the use of scarce resources, and the sustainable use of these resources should feature more prominently in the process of management. The most quoted definition of sustainability regards the development and was made in 1987 by the UN World Commission on Environment and Development[102]: "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Hydrogen is proposed as an energy alternative to make energy production more sustainable and limiting harmful effects on the environment, but it is important to check whether hydrogen production is sustainable or not. To answer, we start by looking at the relation between environment, economy, and equity, shown in Figure 21, and how hydrogen impacts on each of them, as presented by the University of California.[103]

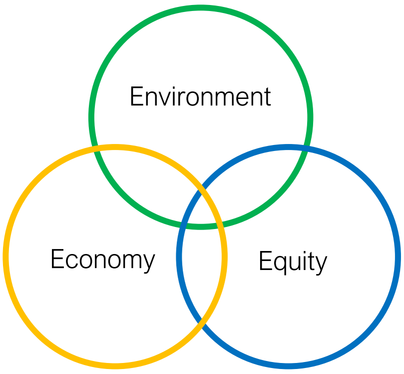

Figure 21 - Relation of the three "E".

The impact of hydrogen on the environment, not considering its leakages, is clearly positive for the compensation on energy usage from pollutant sources, and we are reaching, if it has not already been reached, the limit of economic development using them. The impact on economy at the beginning could be negative due to the dismission of obsolete plants, but new ones for hydrogen would be built potentially compensating losses, in a macroeconomic context it would bring cleaner industries for a healthier population, and also it could probably slow down the consumption of energy in the short-term since it cannot compensate alone the phase-out of fossil fuels. For equity, Rifkin considers hydrogen as an opportunity to "democratize" energy and give to everyone the same rights on energy if we reach a more autonomous production and consumption, with a sort of Worldwide Energy Web to share the energy as a community, making its impact positive for the balance of society.[104]

[102] See: https://eur-lex.europa.eu/EN/legal-content/glossary/sustainable-development.html [September 1, 2022]

[103] University of California. (2022, August 28). *What is Sustainability?* Retrieved from UCLA Sustainability: https://www.sustain.ucla.edu/what-is-sustainability/ [August 28, 2022]

[104] Rifkin, J. (2002). *The Hydrogen Economy: The Creation of the Worldwide Energy Web and the Redistribution of Power on Earth.* United States: Polity Press.

The issue of using energy from renewable sources is brought to the forefront of the sustainability assessment: the production of hydrogen is incredibly dependent on surplus renewable energy, given the impossibility of using other environmentally harmful sources. According to the International Energy Agency[105], the share of renewables in the global electricity supply reached 28.6% in 2020. In Figure 22, to reach Net Zero Emission by 2050 (NZE), the total energy produced must reach 25 000 terawatt hour (TWh), which means reaching more than 60% share by 2030, and we can see that the almost linear trend of previous years does not favour the achievement of this objective.

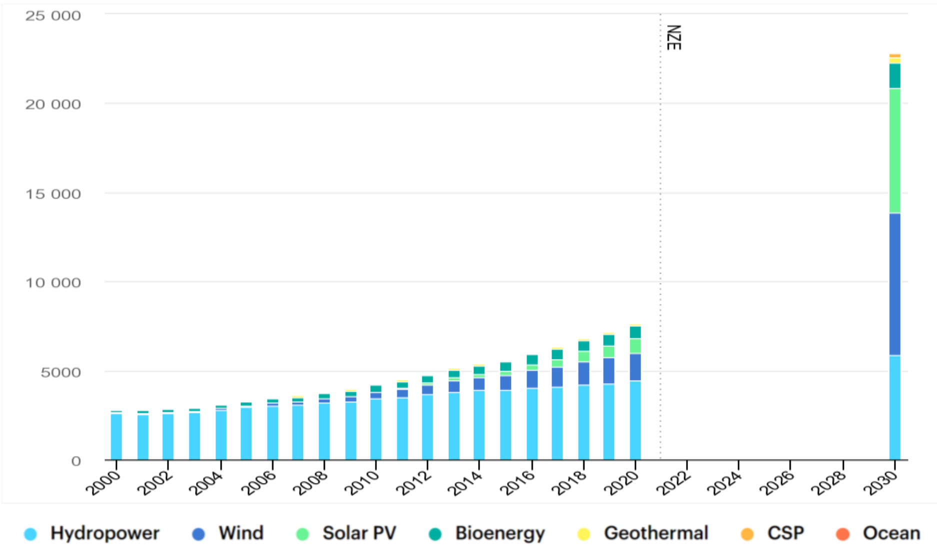

Figure 22 - Renewable power generation in TWh by technology, historic and in the Net Zero Scenario, 2000-2030. (IEA)

Therefore, the production of hydrogen cannot slow down the growth of these energy resources, but it can be a player when these energies cannot be stored or directly used, as previously said. There are areas in which the renewables are even too many, as in the case of several Italian regions like Valle d'Aosta, Trentino-Alto Adige/Südtirol, and Basilicata: data from the Italian National Institute of Statistics (ISTAT) show that in these regions the electricity consumption is totally covered by renewable energies production and the surplus, since it cannot be stored, is given to other regions.[106] Following the Directive 2009/28/EC, which bounded Italy to cover 17% of gross final energy consumption by 2020 with renewable energy sources, we have that in 2020 the share was already 20.4% and growing respect to the 18.2% of 2019.[107] At the European level, Norway has the capability to produce green hydrogen through its abundant clean energy sources, where the 99% of the electricity production is given by renewables, letting also produce hydrogen at a competitive price with respect to other fuels such as

[105] International Energy Agency. (2021, November). *Renewable Power - Tracking report*. Retrieved from IEA: https://www.iea.org/reports/renewable-power

[106] ISTAT. (2022). *Noi Italia in breve, 100 statistiche per capire il Paese in cui viviamo Edizione 2022.* Italy: Istituto Nazionale di Statistica. https://www.istat.it/it/files//2022/06/Noi-Italia-in-breve-2022.pdf.

[107] Ibid.

gasoline.[108] Consequently, during projects evaluation, when more renewable energy production is possible and if the technologies to store energy are not available, hydrogen presents itself as a sustainable solution without necessarily compromising the use of renewables.

Another consideration regards the use of finite sources together with renewable sources, such as the use of water and other raw materials related to hydrogen. For water consumption, we have dedicated an entire paragraph in which we already answered considering the amount of water used nowadays in other energy plants and compared by the amount needed to produce an equivalent amount of hydrogen. A last concern should be made for the use of platinum as raw material for fuel cells: the final cost of a fuel cell is related to it, which could be enough expensive and insufficient to stop the commercialization of vehicles powered by hydrogen. Currently, the platinum supply is about 200 metric tons, but the total amount needed in the EU could reach 600 metric tons by 2050. However, the fuel cell today requires on average 30/49 grams of platinum with future innovations that could guarantee a reduction up to 10/15 grams per unit by 2050[109], and the improvement of its recycling rate, already present in industries such as electronics and chemical industry, could compensate the shortage of supply.[110] What would be needed then is the study of hydrogen technology development that would reduce the use or even replace the use of materials such as platinum in the production of fuel cells and electrolysers.[111] There is an additional risk to be assessed because these minerals are found in high concentrations only in particular geographic locations, like for platinum where 80% of it is found in South Africa, which places a great deal of weight on the world geopolitical situation. Consequently, as suggested by Olivier Vidal of CNRS-University of Grenoble, there is still a need to use this resource rationally and to study material recycling strategies from the outset. In this regard, mention should be made of the *PLATIRUS* project[112] coordinated by Dr. Amal Siriwardana from Tecnalia and funded by the European Union, started in 2016 and completed in 2021, which aimed at the stable supply of platinum in Europe. The results were to obtain technologies for material recovery from products such as spent catalysts, mining, and electronic waste.[113]

[108] Kruse, B., Grinna, S., & Buch, C. (2002, February 13). *Hydrogen Status og muligheter - Bellona rapport nr. 6.* Oslo, Norway: The Bellona Foundation.

[109] Martinez-Garcia, G. (1 July 2017). *Cost-benefit analysis of a hydrogen supply chain deployment case for fuel cell vehicles use in Midi-Pyrénées region.* Barcelona: Projecte Final de Màster Oficial, UPC, Escola Tècnica Superior d'Enginyeria Industrial de Barcelona.

[110] Cantuarias-Villessuzanne, C., Weinberger, B., Roses, L., Vignes, A., & Brignon, J.-M. (9 November 2016). Social cost-benefit analysis of hydrogen mobility in Europe. *International Journal of Hydrogen Energy*, Volume 41, Issue 42, Pages 19304-19311.

[111] Ibid.

[112] See: https://www.platirus.eu/the-project/ [October 11, 2022]

[113] See: https://cordis.europa.eu/article/id/436236-a-sustainable-bridge-for-the-gap-between-supply-and-demand-of-valuable-metals/it [April 27, 2022]

2.4 Economic Feasibility

2.4.1 Variability of the cost per energy provided

The cost of producing energy through hydrogen is a potential barrier for the implementation. Indeed, there is a difference between the cost that private actors assume and the social cost related to hydrogen, where the former is the one related only to the cost of obtaining the resource, which is what is looked at most, while the latter includes the social benefits related to switching from fossil fuels to non-polluting energy, including the social willingness that should influence private actors. The obstacle is therefore how to employ photovoltaic, wind, hydroelectric, geothermal, and other renewable energies to feed the electrolytic process with the lack of low-cost hydrogen production and conversion technologies.[114] In many scientific publications we can find different estimated prices related to hydrogen production depending on the source of energy, the technology used and the location of production. Assuming the conversion between dollars and euro constant and equal to one, according to the IEA the cost today to produce hydrogen is around 1.4 €/kg but may also be greater than 4 €/kg depending on the source of energy used[115], and this interval between lower and higher price is a significant obstacle in the comparison with other fuels. Moreover, these estimates seem to be very optimistic: taking the case study of Robles[116], in their Region of production, the price, which includes the costs of production, transport, and storage of the hydrogen, is around 8.41 €/kg with a prevision of 6.76 €/kg reachable in 2030. However, the investors should not stop their analysis on the price per kilogram since the amount of energy stored in one kg of hydrogen is higher than the other fuels. In fact, the perception changes taking data from the Italian Ministry of Economic Development (MISE)[117]: while for methane we have an energy of 12.3 kWh/kg, for hydrogen we have 33.33 kWh/kg, and therefore taking the highest value obtained by Robles, we get that for hydrogen the price per energy provided is around 0.25 €/kWh. These results are consistent with another study conducted by Ajanovic[118] in 2018: as showed in Figure 23, this study brings different prices depending on the quality of the electrolysers, like for large-size ones which can give a cost below 0.15 €/kWh.

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[114] Abdinab, Z., Zafaranlooa, A., Rafieed, A., Méridab, W., Lipińskic, W., & Khalilpouraef, K. R. (March 2020). Hydrogen as an energy vector. *Renewable and Sustainable Energy Reviews*, Volume 120.

[115] International Energy Agency. (2019, June). *The Future of Hydrogen. Seizing today's opportunities.* Retrieved from IEA: https://www.iea.org/reports/the-future-of-hydrogen

[116] Robles, J. O., Azzaro-Pantel, C., Martinez-Garcia, G., & Lasserre, A. A. (2020). Social cost-benefit assessment as a post-optimal analysis for hydrogen supply chain design and deployment: Application to Occitania (France). *Sustainable Production and Consumption, 24*, 105-120.

[117] See: https://carburanti.mise.gov.it/ospzSearch/confontare [October 17, 2022]

[118] Ajanovic, A., & Haas, R. (2018). Economic prospects and policy framework for hydrogen as fuel in the transport sector. *Energy Policy 123, Elsevier*, 280-288.

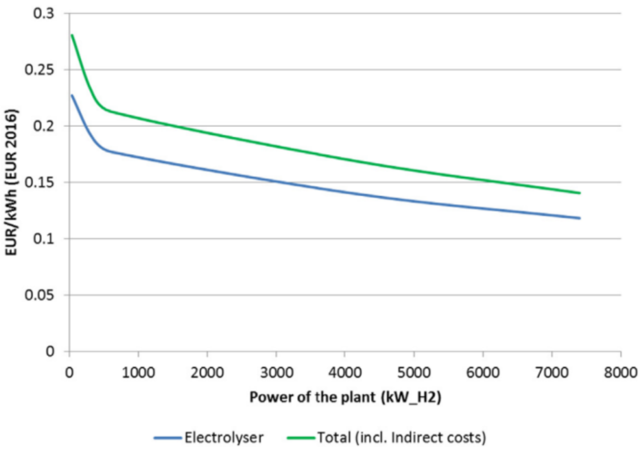


Figure 23 - Cost of hydrogen depending on the power of electrolyser. (Ajanovic et al., 2018)

One important element is the investment on the electrolysers, which are costly nowadays, where IEA estimates a range of capital expenditure, to buy and maintain an alkaline electrolyser, of 500 $ up to 1 400 $ per kilowatt efficient.[119] Thus, the price for having hydrogen, due to the technologies to be used, remains disheartening and it is a constraint for the mass use; but for a long-term perspective, the trends of lower costs on one hand and the rising energy competitors prices on the other lead us to make interesting forecasts. The data for both hydrogen and methane gas are in fact highly variable and, rather than trying to reach a general conclusion, they should be analysed in specific projects such as the case studies in the literature. In the case of methane as the natural gas, indeed, the data provided by Autogas Italia Srl[120] indicate that one standard cubic metre of methane corresponds to 11 kWh, and applying the conversion whereby 1 m^3 of methane, equals to 0.671 kg, the content in one kg will be 16.4 kWh, while from the conversion table of the Italian municipality of Bologna the same quantity corresponds to 13.1 kWh per kilogramme.[121] This difference in results indicates the complexity in this area to identify a precise value, as it is difficult to assign an equal value valid for all production and supply conditions. In terms of prices, the Italian Energy Networks and Environment Regulatory Authority (ARERA) helps to have a reference on natural gas, for which a spot price was measured at the end of 2021 in the main European hubs above 230 €/MWh, or 0.23 €/kWh. Since it is a market price, though, it is highly variable and with a volatility that remains high to this day.[122]

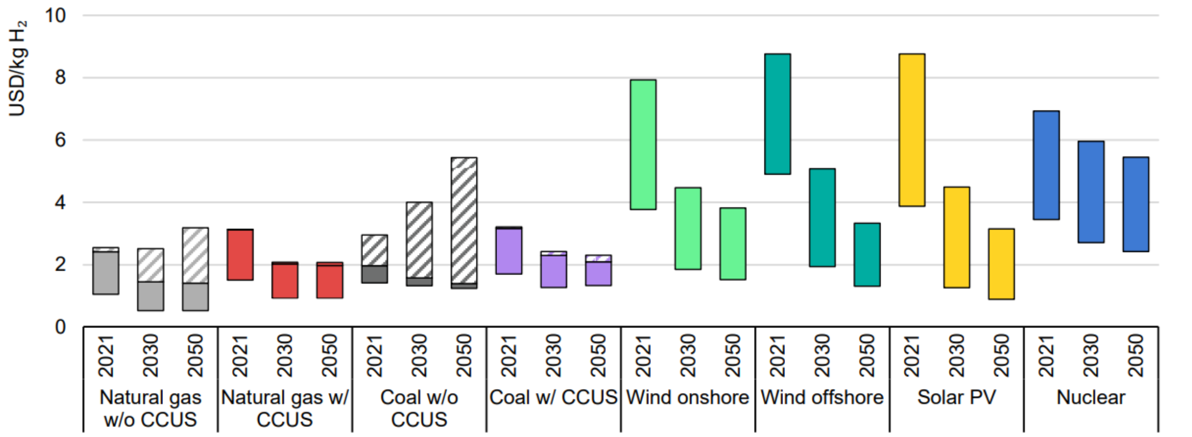
[119] International Energy Agency. (2019, June). *The Future of Hydrogen. Seizing today's opportunities.* Retrieved from IEA: https://www.iea.org/reports/the-future-of-hydrogen

[120] See: https://www.autogasitalia.it/it/faq/metano/a-quanti-metri-cubi-corrisponde-un-kg-di-metano/ [October 8, 2022]

[121] See: https://www.cittametropolitana.bo.it/imprese/Engine/RAServeFile.php/f/BDOA/allegatoC.pdf [October 8, 2022]

[122] See: https://www.arera.it/it/com_stampa/22/220330cs.htm [October 8, 2022]

Even for hydrogen the total cost is extremely variable with respect to the technology of production used and, according to the last review made by the IEA[123], it is currently between 4 and 9 €/kg (remembering the assumption of the euro/dollar exchange rate constant and equal to one) using electricity from renewables to power the electrolysis process. Interesting to notice are the cost for the blue hydrogen, represented in purple and red in Figure 24, which is currently competitive with the other sources, and the perspective on the future costs for green hydrogen that will be competitive too, helped by the increase of CO_2 price and by the efficiency and expansion of technologies since in 2030 the cost to produce green hydrogen will be around 2 and 4 €/kg so just 0.06 and 0.12 €/kWh.



Notes: Ranges of production cost estimates reflect regional variations in costs and renewable resource conditions. The dashed areas reflect the CO_2 price impact, based on CO_2 prices ranging from USD 15/tonne CO_2 to USD 140/tonne CO_2 between regions in 2030 and USD 55/ tonne CO_2 to USD 250/ tonne CO_2 in 2050.
Sources: Based on data from McKinsey & Company and the Hydrogen Council; Council; IRENA (2020); IEA GHG (2014); IEA GHG (2017); E4Tech (2015); Kawasaki Heavy Industries; Element Energy (2018).

Figure 24 - Levelized cost of hydrogen production by technology in 2021 and in the Net Zero Emissions by 2050 Scenario, 2030 and 2050. (IEA)

[123] International Energy Agency. (2022). *Global Hydrogen Review 2022.* Retrieved from IEA: https://iea.blob.core.windows.net/assets/c5bc75b1-9e4d-460d-9056-6e8e626a11c4/GlobalHydrogenReview2022.pdf.

2.4.2 Price issue: methane and hydrogen

Due to the several fields of implementation, it is difficult to assess its general economic feasibility in general, but several argumentations can be made; it is interesting to understand where it makes sense to use it as energy vector and to understand how the situation will evolve over the coming years. In the Transforming Energy Scenario made by the IRENA[124], the electricity could satisfy just half of the total energy demand in 2050, and therefore the direct use of renewables cannot cover all the demand, making alternative such as hydrogen more important in sectors where electricity will not be able to play a major role. A first comparison may be made between methane and green hydrogen; according to ARERA[125] the price of natural gas in Italy in September 2022 had an average of 0.42992 €/kWh, and for the values from January to September of this year the average can be calculated obtaining a value equal to 0.32293 €/kWh, which is higher than the cost of hydrogen IEA's 4-9 €/kg corresponding to 0.12-0.27 €/kWh, and therefore we could say that there is already an economic advantage of hydrogen with respect to methane. However, one must also consider the sector that leads to the use of hydrogen, and if we take as reference the fuels for transportation, the price noted by Transport & Environment and Legambiente[126] for hydrogen light transport, which is 13.7 €/kg equal to 0.41 €/kWh, will be unaffordable at first glance when compared to the prices of other fuels measured by the MISE.[127] In Figure 25 are presented the personal calculations regarding the arithmetic average prices for the transport sector made with prices of the first two quarters 2022 including all passenger car segments, using the observations measured by the MISE[128], in order to compare the current prices of the available fuels.

[124] International Renewable Energy Agency. (2020). *Global Renewable Outlook - Summary 2020.* Retrieved from https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Apr/IRENA_GRO_Summary_2020.pdf?la=en&hash=1F18E445B56228AF8C4893CAEF147ED0163A0E47

[125] See: https://www.arera.it/it/consumatori/placet.htm#econom [October 9, 2022]

[126] Tritto, C., & Poggio, A. (April 2021). *Il ruolo dell'idrogeno nel trasporto terrestre.* Transport & Environment, Legambiente. https://www.legambiente.it/wp-content/uploads/2021/05/ruolo-idrogeno-nel-trasporto-terrestre_2021.pdf.

[127] See: https://carburanti.mise.gov.it/ospzSearch/confontare [October 9, 2022]

[128] Computations made from: https://download.mise.gov.it/osservaprezzicarburanti/documenti/Comparazione%20basata%20sulla%20percorrenza%20di%20100%20KM_%20annualit%C3%A0%202022.pdf [October 9, 2022]

Fuel	Energy content	Average unit cost	Average cost in kWh
Gasoline	8.88 (kWh/l)	1.873 €/l	0.21 €/kWh
Diesel	10 (kWh/l)	1.774 €/l	0.18 €/kWh
Natural gas (CNG)	12.3 (kWh/kg)	1.825 €/kg	0.15 €/kWh
LPG	6.6 (kWh/l)	0.831 €/l	0.13 €/kWh
Hydrogen	33.33(kWh/kg)	13.7 €/kg	0.41 €/kWh

Figure 25 - Average fuel cost: arithmetic average prices first two quarters 2022 including all passenger car segments. (Own calculations and data from MISE)

What we should consider in addition is the economic or social price that the use of natural gas has; for an environmental point of view, the emission of natural gas can be exploited by the CO_2 equivalent measure. Following data from Italian Agency for Newrisks Technologies, Energy and Sustainable Economic Development (ENEA)[129], 369.6 are the grams of CO_2 per kWh of methane and considering that the price of one ton of carbon-dioxide now is about 90 €, while for 2021 was 30 €, we can estimate the environmental cost of natural gas by making a proportion where if one ton of CO_2 costs 90 €, 369,6 grams will cost 0.03326 €/kWh of methane in 2022, and 0.01108 €/kWh in 2021. There remains much variability in the estimates depending on the method for shadow price computation; however, by comparing the results in Figure 26, we can get an idea of how the price of hydrogen per energy provided now may be cheaper than methane if used directly in industry, whereas for other sectors such as transport, due to technologies requirements, the most relevant shadow price in this case related to the CO_2 must really increase to compensate the difference in the market, to reach hydrogen's economic competitiveness. The trend in Figure 27 suggests that with a further increase of the price, together with the increase of gas price and the development of cheaper technologies for hydrogen, the two resources of gas and hydrogen would be comparable also for the transport sector in terms of prices.

	Market price	Environmental cost (CO_2 shadow price)	Total
Methane *for transport* (2022)	0.15 €/kWh	0.03326 €/kWh	0.18 €/kWh
Hydrogen *for transport* (2022)	0.41 €/kWh		0.41 €/kWh
Methane (2021)	0.23 €/kWh	0.01108 €/kWh	0.24 €/kWh
Methane (2022, until Sept.)	0.32 €/kWh	0.03326 €/kWh	0.35 €/kWh
Methane (2022, only Sept.)	0.43 €/kWh	0.03326 €/kWh	0.46 €/kWh
Hydrogen (2022)	0.12-0.27 €/kWh		0.27 €/kWh

Figure 26 - Economic values of Methane and Hydrogen. (Own calculations and data from ARERA)

[129] See: http://kilowattene.enea.it/KiloWattene-CO2-energia-primaria.html [October 4, 2022]

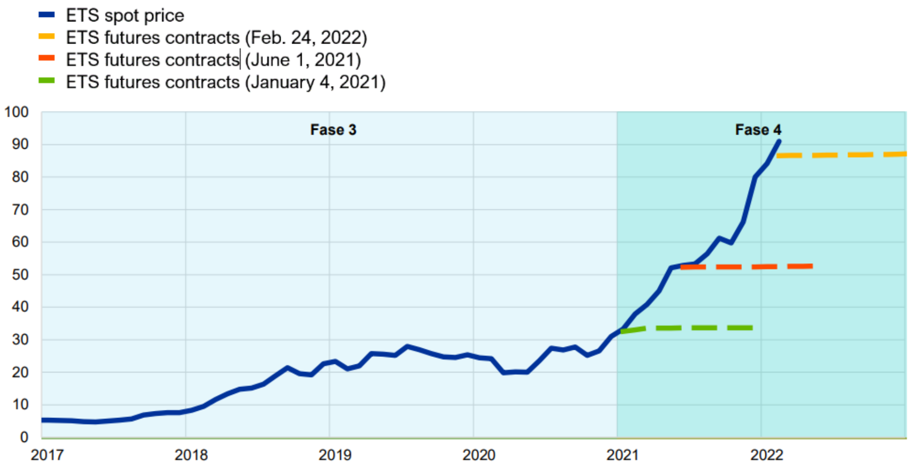


Figure 27 - Spot and futures contract prices (€/ton of carbon) on the ETS system. [130]

Moreover, the result of a research published in the International Journal of Hydrogen Energy[131] shows that hydrogen could become a widespread alternative as early as 2030, supported by a long-term CO_2 cap increase, while in the business-as-usual scenario the share of hydrogen, produced with low-carbon technologies and electrolysers absorbing electricity during periods of high availability of renewables, in the final energy consumption of the transport and industry sectors would reach only 5% and 6% of the total by 2050. As a result, for industry, since the amount of energy needed is not easy to be given directly by renewable sources, hydrogen can be a possible alternative with respect to gas, given the favourable price variability. Eventually, for heavy industry in which hydrogen is already used, it is of vital importance to focus hydrogen production on sustainable energy, completely ceasing the use of fossil fuels, where their prices will no longer be cost-effective, and the cost of green hydrogen will decrease by up to 30% by 2030 due to the decreasing costs of renewable energies.[132] The processes for creating hydrogen using fossil sources must be limited, which although cost-effective lead to significant environmental impacts, keeping as the main method of production to use the electrolysis of water, considered to be the most promising technology[133] and the most suitable for the long-term goals.[134]

[130] Image adapted from: https://www.bancaditalia.it/pubblicazioni/bollettino-eco-bce/2022/bol-eco-3-2022/bolleco-BCE-3-2022.pdf [October 4, 2022]

[131] Sgobbi, A., Nijs, W., De Miglio, R., Chiodi, A., Gargiulo, M., & Thiel, C. (5 January 2016). How far away is hydrogen? Its role in the medium and long-term decarbonisation of the European energy system. *International Journal of Hydrogen Energy, Elsevier*, Volume 41, Issue 1, Pages 19-35.

[132] ACEPER impresa green. (April 2021). *Il racconto di un mondo che si rinnova, Numero 2.* Chivasso (TO), Italy: https://www.flipbookpdf.net/web/site/70c8cd00e0b0d224e0468a91d1737bf286768b14FBP21250185.pdf.html#page/2.

[133] Thengane, S. K., Hoadley, A., Bhattacharya, S., Mitra, S., & Bandyopadhyay, S. (23 September 2014). Cost-benefit analysis of different hydrogen production technologies using AHP and Fuzzy AHP. *International Journal of Hydrogen Energy*, Volume 39, Issue 28, Pages 15293-15306.

[134] Italian Ministry of Ecological Transition. (July 2022). *La Situazione Energetica Nazionale Nel 2021 .* Energy Department. Retrieved from: https://dgsaie.mise.gov.it/pub/sen/relazioni/relazione_annuale_situazione_energetica_nazionale_dati_2021.pdf.

2.4.3 The case of transport sector

2.4.3.1 For vehicles, electric is leading the way

Delving the light transport sector, the current petrol car tends to be inefficient not only from an energy point of view, since most of the energy is just heat, but also from an economic point of view considering the increasing environmental cost of its use. A solution is therefore needed: according to Armaroli[135], direct electrification is a more efficient solution and already has mature and suitable technologies, while hydrogen is evaluated as a little alternative. An important fact to bear in mind is that investing in electrification in these markets and making engines more efficient can also be advantageous due to the circularity of electric cars. The recycling of raw materials, such as lithium, makes this system better than a hydrogen car in its current state. However, the potential of compression and liquefaction have not stopped some realities that have thought about hydrogen as a potential transportation fuel, complementing electricity and biofuels. Cars and trains are already a reality, thanks to the European company Alstom with the Coradia iLint train using fuel cell technology that can reach speeds of up to 140 kilometres per hour by emitting steam and water and without making noise.[136] In the automotive sector, Asian companies Toyota, Honda, and Hyundai are already introducing their hydrogen car models to the market, and developing the hydrogen supply chain by increasing the stations and fuel cell vehicle market share will bring to a reduction of the gap between the conventional fossil fuel vehicle market and the fuel cell vehicle market.[137] It should be pointed out that this is also thanks to the governments' contribution: in Japan, there are substantial incentives to reach the State goal of producing 6.2 million hydrogen fuel cell cars and building an infrastructure based on at least 1 200 refuelling stations by 2040.[138] However, these figures are small compared with those of the electric car: in Germany for instance, the number of active charging points is 60 698, including 10 767 fast charging points, and currently has more than 500 000 full electric vehicles on the road in 2021.[139]

[135] Armaroli, N., & Barbieri, A. (2021). *The hydrogen dilemma in Italy's energy transition.* Nature Italy. 10.1038/d43978-021-00109-3. Retrieved from: https://www.researchgate.net/publication/354513834_The_hydrogen_dilemma_in_Italy's_energy_transition.

[136] ACEPER impresa green. (April 2021). *Il racconto di un mondo che si rinnova, Numero 2.* Chivasso (TO), Italy: https://www.flipbookpdf.net/web/site/70c8cd00e0b0d224e0468a91d1737bf286768b14FBP21250185.pdf.html#page/2.

[137] Martinez-Garcia, G. (1 July 2017). *Cost-benefit analysis of a hydrogen supply chain deployment case for fuel cell vehicles use in Midi-Pyrénées region.* Barcelona: Projecte Final de Màster Oficial, UPC, Escola Tècnica Superior d'Enginyeria Industrial de Barcelona.

[138] ACEPER impresa green. (April 2021). *Il racconto di un mondo che si rinnova, Numero 2.* Chivasso (TO), Italy: https://www.flipbookpdf.net/web/site/70c8cd00e0b0d224e0468a91d1737bf286768b14FBP21250185.pdf.html#page/2.

[139] Motus-E. (December 2021). *Le Infrastrutture di Ricarica Pubbliche in Italia - Third edition.* https://www.motus-e.org/pubblicazioni-motus-e.

As the trend in Figure 28 suggests, the numbers of stations are set to increase due to increasing investment and technological improvements in vehicle autonomy and power, leaving little room for the entry of hydrogen at least for the upcoming years.

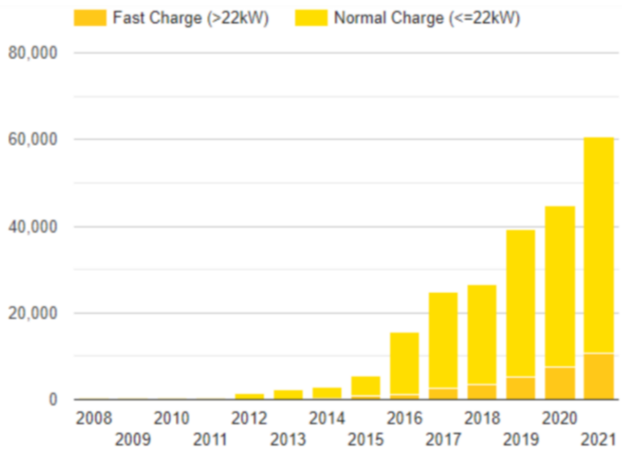


Figure 28 - Germany number of public stations for the recharging of electric vehicles. (Motus-E)

Indeed, if we look at the current refuelling stations for hydrogen, we have that in 2010 were just 10 and in 2017 were 90 active charging points across the whole Europe[140], which is an outstanding situation with respect to electric. Also Italy, public charging infrastructures for electric vehicles confirm the growth trend: on 31 December 2021, 26 024 charging points and 13 233 infrastructures, stations or columns, were installed in 10 503 publicly accessible locations in Italy[141], while for hydrogen, there are currently two filling station: one in Bolzano, where the cost of hydrogen is around 13.7 €/kg, with a full tank of, say, a Hyundai Nexo or a Toyota Mirai costing between 70 and 80 €, enough to cover over 600 km[142] (nowadays according to SNAM, with 1 kg of hydrogen it is possible to run a car for 130 km[143]), and a new one in Mestre opened by ENI this year.[144] Then, the price would be competitive with today's petrol and diesel engines, also supported by ENEL X estimations where the average cost to run 100 km on a petrol car in 2017 was around 12.5 €[145], which equals to 75 € for 600 km, and with the increases we are seeing this year in fuel prices, therefore, it is visible the potential economic advantage.

[140] Atanasiu, M. (2019). *Public-Private Partnership on hydrogen - A European success story - #H2020Energy info days.* FCH Joint Undertaking. This document is available at: https://ec.europa.eu/inea/sites/default/files/june26-presentation_9.pdf.

[141] Motus-E. (December 2021). *Le Infrastrutture di Ricarica Pubbliche in Italia - Third edition.* https://www.motus-e.org/pubblicazioni-motus-e.

[142] ACEPER impresa green. (April 2021). *Il racconto di un mondo che si rinnova, Numero 2.* Chivasso (TO), Italy: https://www.flipbookpdf.net/web/site/70c8cd00e0b0d224e0468a91d1737bf286768b14FBP21250185.pdf.html#page/2.

[143] See: https://www.snam.it/it/hydrogen_challenge/idrogeno_transizione_energetica [September 2, 2022]

[144] ENI. (2022, September 2). *Mobilità sostenibile*. Retrieved from Eni.com: https://www.eni.com/it-IT/mobilita-sostenibile/stazione-servizio-idrogeno.html [September 2, 2022]

[145] Enel X. *Quanto costa il pieno di un'auto elettrica?* https://www.enelx.com/it/it/faq/quanto-costa-fare-un-pieno [September 2, 2022]

However, the lack of the adequate infrastructure for recharging hydrogen vehicles makes it almost impossible to use these vehicles today. Interesting is that the active recharging station in Bolzano, opened in 2014 and managed by the Institute for Technological Innovation, not only distributes green hydrogen, but also produces and stores it, with 180 normal cubic meters of H_2 per hour for a total per year of over 1.5 million normal cubic meters of clean fuel, thanks to the hydro-electric plant of Cardano (BZ). This distributor can supply almost 15 coaches per day, with a range of 200-250 km, or alternatively up to 700 cars, where the significant saving is not in money, but rather on environment, amounting to approximately 525 000 litres of gas or 440 000 litres of diesel prevented annually. However, these corresponds to about 1 200 000 kg of carbon dioxide not emitted into the atmosphere, which equates to a shadow price of just 108 000 € in a year. These numbers do not deter the Brenner Motorway's long-term goal of creating a distribution network with filling stations approximately every 100 km[146], but there are critics since significant cost improvements beyond those predicted by experts are required.[147]

[146] Autostrada del Brennero SpA. *Hydrogen*. Retrieved from Autobrennero: https://www.autobrennero.it/en/sustainability/hydrogen/ [August 23, 2022]

[147] Sgobbi, A., Nijs, W., De Miglio, R., Chiodi, A., Gargiulo, M., & Thiel, C. (5 January 2016). How far away is hydrogen? Its role in the medium and long-term decarbonisation of the European energy system. *International Journal of Hydrogen Energy, Elsevier*, Volume 41, Issue 1, Pages 19-35.

2.4.3.2 Cost-benefit analyses on hydrogen fuel cells vehicles

A recent study[148] states that hydrogen is not implemented in the transport sector today due to its prohibitive costs of production and usage, and it is true since hydrogen is not economically feasible yet, but the long-term energy problems, such as availability of resources, variability of prices and energy storages will be particularly fundamental in choosing to invest on it. Several analyses were conducted particularly in this sector, which, in 2015, was responsible for 25.8% of total EU-28 greenhouse gas emissions, to evaluate the introduction of hydrogen fuel cells vehicles.[149] For example, the work of Martinez-Garcia aims to determine if the hydrogen deployment in the French Midi-Pyrénées region can increase enough the social welfare in order to compensate its actual costs, and the method used is the Cost-Benefit Analysis, the standard tool for projects' evaluations that involves environmental and social issues.[150] The analysis is conducted using a specific social discount rate equal to 5% to find the present values of costs and benefits of future periods and using shadow prices to valuate externalities affecting the project. The Net Present Value (NPV), the sum of the difference between benefits (B) and costs (C) discounted (i) for each period (t) of the project duration (n), is often considered the key indicator to make a decision, considering that the project is viable only if the NPV is positive.

$$NPV = \sum_{t=0}^{n} \frac{(B_t - C_t)}{(1+i)^t}$$

The case study of Martinez-Garcia is part of a larger work published later together with Robles, Azzaro-Pantel, and Lasserre in 2020 to determine the best supply chain for hydrogen and to test whether the introduction of hydrogen mobility sufficiently increases social welfare.[151] In the supply chain configuration presented in Figure 29, we can state the cost of hydrogen equal to 10.14 €/kg in 2020, or 0.30 €/kWh which is a bit higher but in line with respect to precedent measurements. The choice of the hydrogen supply chain configuration that is selected and proposed for analysis is made through a multi-criteria decision-making process called TOPSIS, Technique for Order of Preference by Similarity to Ideal Solution, a method that deals mainly with engineering problems with the advantage of having few parameters involved, making the analysis as objective as possible.

[148] Ajanovic, A., & Haas, R. (2018). Economic prospects and policy framework for hydrogen as fuel in the transport sector. *Energy Policy 123, Elsevier*, 280-288.

[149] Robles, J. O., Azzaro-Pantel, C., Martinez-Garcia, G., & Lasserre, A. A. (2020). Social cost-benefit assessment as a post-optimal analysis for hydrogen supply chain design and deployment: Application to Occitania (France). *Sustainable Production and Consumption, 24*, 105-120.

[150] Martinez-Garcia, G. (1 July 2017). *Cost-benefit analysis of a hydrogen supply chain deployment case for fuel cell vehicles use in Midi-Pyrénées region.* Barcelona: Projecte Final de Màster Oficial, UPC, Escola Tècnica Superior d'Enginyeria Industrial de Barcelona.

[151] Robles, J. O., Azzaro-Pantel, C., Martinez-Garcia, G., & Lasserre, A. A. (2020). Social cost-benefit assessment as a post-optimal analysis for hydrogen supply chain design and deployment: Application to Occitania (France). *Sustainable Production and Consumption, 24*, 105-120.

Year	2020	2030	2040	2050
Demand (t per day)	7.90	59.43	138.79	198.17
Number of total production facilities	*25*	*62*	*92*	*110*
Number of total storage facilities	*12*	*66*	*150*	*214*
Capital cost				
Plants and storage facilities (10^6 €)	304.47	401.53	263.71	43.44
Operating cost				
Plants and storage facilities (10^3 € per day)	43.44	307.15	708.68	1013.16
Total daily cost (10^3 € per day)	80.12	489.34	1036.96	1446.56
Cost per kg H_2 (€)	*10.14*	*8.23*	*7.47*	*7.30*
Production facilities (t CO_2-eq per day)	8.27	61.35	142.51	201.91
Storage facilities (t CO_2-eq per day)	5.56	41.84	97.71	139.51
Total GWP (t CO_2-eq per day)	13.73	103.18	240.22	341.42
kg CO_2-eq per kg H_2	*1.74*	*1.74*	*1.73*	*1.72*

Figure 29 - Hydrogen supply chain configuration. (Robles et al., 2020)

There are mainly two points of view to consider: the social perspective, in which the Total Cost of Ownership (TCO), a financial procedure that estimates all costs associated with an activity which in this project corresponds to the investment costs of the introduction of fuel cells vehicles, and the governmental perspective, where instead of having the TCO there are a series of government policies such as subsidies and taxes, while for both situations the externalities remain the same. Assumed by the authors an increase in the total number of fuel cells vehicles from 32 000 of 2020 to 789 000 of 2050, the CO_2 abatement is the most significant externality, counting a reduction of 21 billion kg from 2020 to 2050 representing an external social benefit of 42.22 million € in 2050, followed by air pollution abatement, characterised by the reduction of other gases such as nitrogen oxides NO_x, carbon monoxide CO, and hydrocarbons HC, and platinum depletion that reduces the benefits gained from previous abatements as a precious raw material to use.[152] The results presented in Figure 30 shows that the Net Present Value for both perspectives is positive only in the single measure of 2050, while for the entire interval 2020-2050, taking as reference the more optimistic governmental perspective visible in Figure 31, the value of the NPV is still negative, leading to an unfavourable scenario and a non-viability choice for the project.[153] It is interesting to state, though, that CO_2 abatement, air pollution and noise abatement externalities are on aggregate offsetting 25.3% of the TCO, and for the governmental perspective up to 28% of the total investment, suggesting how a more stringent assessment of positive externalities can significantly affect the final value.[154]

[152] Robles, J. O., Azzaro-Pantel, C., Martinez-Garcia, G., & Lasserre, A. A. (2020). Social cost-benefit assessment as a post-optimal analysis for hydrogen supply chain design and deployment: Application to Occitania (France). *Sustainable Production and Consumption, 24*, 105-120.

[153] Ibid.

[154] Martinez-Garcia, G. (1 July 2017). *Cost-benefit analysis of a hydrogen supply chain deployment case for fuel cell vehicles use in Midi-Pyrénées region.* Barcelona: Projecte Final de Màster Oficial, UPC, Escola Tècnica Superior d'Enginyeria Industrial de Barcelona.

			2020	2030	2040	2050
NPV economic comparison	TCO	M€ in year	-110,34	-168,61	-63,81	50,80
NPV with externalities	CO_2	M€ in year	2,44	19,36	40,23	42,22
	Platinum depletion		-16,78	-10,16	-6,17	-3,05
	Air pollution		0,96	3,39	4,86	4,32
	Noise		0,17	0,79	1,13	0,99
	SNPV	M€ in year	-123,55	-155,23	-23,76	95,28

			2020	2030	2040	2050
NPV subsidy policies	Subsidy for HRS	M€ in year	-2.43	0.00	0.00	0.00
	Subsidy for FCVs		-474.45	-222.13	-92.77	-15.26
	Taxes on FCV purchase		-59.05	12.77	11.89	8.48
	Taxes on hydrogen		-10.14	0.00	0.00	0.00
NPV externalities	CO_2 abatement	M€ in year	2.44	19.36	40.23	42.22
	Platinum depletion		-15.58	-8.30	-4.25	-1.81
	Air pollution abatement		0.96	1.15	4.18	5.93
	Noise abatement		0.17	0.79	1.13	0.99
NPV_{SCBA} with subsidy policies		M€	-566.24	-193.15	-37.83	39.82

Figure 30 - Social NPV (above) and NPV for the government perspective (below). (Robles et al., 2020)

			2020-2030	2020-2040	2020-2050
Net economic comparison	Subsidized HRS	M€	-20.67	-20.67	-20.67
	Subsidies for FCVs		-1,968.71	-3,025.27	-3,352.30
	Taxes on FCV purchase		0.18	88.13	166.63
	Taxes on hydrogen		-10.14	-10.14	-10.14
Net externalities	CO2 abatement	M€	104.94	421.65	854.72
	Platinum depletion		-75.72	-130.59	-164.27
	Air pollution abatement		23.23	66.72	114.05
	Noise abatement		5.17	15.41	26.32
Governmental net present value		**M€**	**-1,941.71**	**-2,594.76**	**-2,385.66**

Figure 31 - Governmental NPV results. (Martinez-Garcia, 2017)

A second result interesting to point out concerns the calculation of the year of socio-economic conversion, which corresponds to the first year when the benefits exceed the costs; computed to the year 2045 for the social perspective, after that year, the sum of social benefits offsets the costs, generating profits[155], whereas the Total Cost of Ownership is expected to be fully recovered in 2068. Since for the governmental perspective the NPV is higher, it can be expected that the year of governmental-economic conversion will come sooner, as in fact is calculated in 2043, with the year when all costs are recovered foreseen in 2069, one year later than the social perspective.[156] We can see from this research how the time horizon for the economic conversion changes depending on the parameters taken as a reference: as described in Figure 32, the time needed to have the benefits exceed

[155] Martinez-Garcia, G. (1 July 2017). *Cost-benefit analysis of a hydrogen supply chain deployment case for fuel cell vehicles use in Midi-Pyrénées region.* Barcelona: Projecte Final de Màster Oficial, UPC, Escola Tècnica Superior d'Enginyeria Industrial de Barcelona.

[156] Ibid.

the costs is the longest without governmental subsidies and externalities, while if we consider externalities the time needed shortens, and it gets shorter and shorter if we also consider subsidies, government aid provided mainly at the beginning of the project as we can notice for the drastic initial rise of the curve, which anticipate the time horizon by almost 5 years.[157]

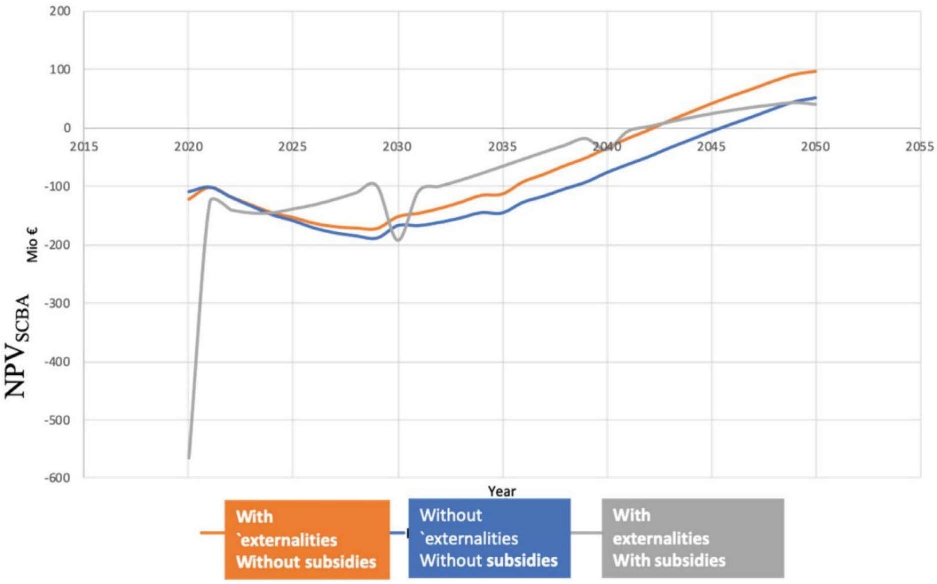


Figure 32 - Different time of economic conversion for different perspectives. (Robles et al., 2020)

Previous researches that estimate the socio-economic conversion period were made, like the one by Cantuarias-Villessuzanne, which estimated the social costs and benefits to arrive at the time required to convert from gasoline combustion engine vehicles to fuel cell vehicles, obtaining a more distant year of convergence equal to 2049 with an optimistic scenario and 2054 with a conservative scenario.[158] These periods seem very long, but with a 50 year time horizon are projects that have an affordable time of recovery considering the really high investment cost, relevance, and impact.[159] Furthermore, the authors emphasise that including the externalities can really encourage the transition to hydrogen-powered vehicles in Europe[160], as it can already be seen here that the time horizon of the socio-economic conversion is shrinking over time helped by the greater weight provided by non-monetary impacts.

[157] Robles, J. O., Azzaro-Pantel, C., Martinez-Garcia, G., & Lasserre, A. A. (2020). Social cost-benefit assessment as a post-optimal analysis for hydrogen supply chain design and deployment: Application to Occitania (France). *Sustainable Production and Consumption, 24*, 105-120.

[158] Cantuarias-Villessuzanne, C., Weinberger, B., Roses, L., Vignes, A., & Brignon, J.-M. (9 November 2016). Social cost-benefit analysis of hydrogen mobility in Europe. *International Journal of Hydrogen Energy*, Elsevier, Volume 41, Issue 42, Pages 19304-19311.

[159] Martinez-Garcia, G. (1 July 2017). *Cost-benefit analysis of a hydrogen supply chain deployment case for fuel cell vehicles use in Midi-Pyrénées region.* Barcelona: Projecte Final de Màster Oficial, UPC, Escola Tècnica Superior d'Enginyeria Industrial de Barcelona.

[160] Cantuarias-Villessuzanne, C., Weinberger, B., Roses, L., Vignes, A., & Brignon, J.-M. (9 November 2016). Social cost-benefit analysis of hydrogen mobility in Europe. *International Journal of Hydrogen Energy*, Elsevier, Volume 41, Issue 42, Pages 19304-19311.

2.4.4 Summary of limitations and benefits

Eventually, we can provide a scheme of the main drawbacks that regard hydrogen, as presented in Figure 33. First, the cost of hydrogen's production needs to be well considered. Bearing in mind that green hydrogen is at concern, the use of electrolysers is of paramount importance and its costs are currently significant, with the prospect that they may become cheaper. In addition, the literature indicates that the catalysts will also become more efficient, lowering their cost relative to production, and compensating the loss of energy efficiency. There are no particular risks associated with the use of electrolysers other than the need to have the raw materials required for their use, which, while the forecasts seem to be manageable, are not without risk of being depleted or managed inefficiently given the necessary increase in demand for electrolysers. Dependence on raw materials to build the necessary technologies may not be a major problem at present, however, in the future due to the increasing demand for materials, efficient and effective management of supply and consumption, with related international agreements, will be crucial. Still regarding production, water consumption as previously analysed can be managed without actual risk, although it is still a delicate resource with an uncertain future that would merit further investigation. As a solution, the use of salt water could be opted for, but specific situations would have to be analysed since it is an energy-intensive process. Instead, the use of renewable energy is not and will not be a problem given the growing trends of such technologies. As far as hydrogen storage is concerned, the solutions are to compress or liquefy it with processes that require some cost and energy input certainly to be considered and that are unlikely to be efficient over time. Hydrogen transport, on the other hand, is characterized by means of transport such as trucks and ships, which would have a cost comparable to that of current fossil fuel or gas transport systems, to which the powering of such means would have to be considered, since hydrogen could itself serve as fuel. This type of transportation is obviously not risk-free as it is not currently, it can be assumed that if the number of vehicles carrying hydrogen increases the likelihood of accidents will be greater but still comparable to those of current tankers, with consequences that should not be underestimated given the energy power of hydrogen. Or, a larger and more widespread infrastructure will be used, highly expensive to build but cheaper once built on which only maintenance costs depend, but with lower risks given the possibility of better management of the network, and in addition, the possibility of converting the current gas network to supply hydrogen cannot be ruled out. It must, of course, be considered that hydrogen is highly dangerous as a gas and although it is highly controlled and still comparable to current fuels, an increase in its use is not without risks, particularly those concerning potential leaks in the grid. Finally, it cannot be ruled out how financial returns derived from previous investments in non-hydrogen projects are negatively impacting hydrogen deployment, many projects related to the natural gas facility for instance have already been initiated, with financial returns that have yet to occur, citing the Nord Stream 2 project as an example. This can be a significant hurdle for governments and firms to overcome, limiting the possibility of immediate investment in large hydrogen-related projects, and more in-depth studies should be done on the subject even if it is only a question of time. As in the case for the renewable energies, the question should be seen in detail since the economic resources are now aiming at their implementation rather than the direct production of hydrogen, however they should be treated together since a higher renewable energy centre could directly create the hydrogen energy storage during its periods of peaks.

						Interest		
	Limits against hydrogen implementation	Actual weight	Future weight	Actual Risk	Future Risk	Economic	Environmental	Social
1	Production costs							
	electrolyser	high	medium	very low	low	X		
	raw materials	low	medium	low	high	X	x	x
	water consumption	low	low	very low	medium	x	X	X
	cost and waste of desalinization	medium	medium	very low	low	X	x	
	renewable energy	low	very low	very low	very low	x	X	
2	Storage cost							
	compression	medium	medium	low	low	X		
	liquefaction	high	high	low	low	X		
3	Transport							
	tank trucks or cargo ships	low	low	very low	medium	X	x	
	pipelines infrastructure	very high	medium	very low	low	X		
4	Dangerous gas							
	flammability and asphyxiation	low	low	very low	medium		x	X
	environmental impacts of H2 leakages	?	?	very low	?		X	x
5	Running projects on other fuels							
	investments recovery	medium	low	medium	very low	X		
	investments on renewables	high	low	high	medium	X		x

Figure 33 - Limitations and their risks related to hydrogen implementation.

Moving on to the benefits summarized in Figure 34, hydrogen is potentially an infinite producible and storable resource with limits only regarding space and maintenance cost for storage which is something that electricity suffer more with the issue of storage batteries, although there are technological advances in that field as well. Producibility is a feature that should not be underestimated considering the fact that currently most of our energy system is powered by energies that, in the long run, will reach depletion. The associated risks are not present, just think of the current use of hydrogen, the future prospect concerns the uncertainty in the use of hydrogen in large quantities. The storage capacity is also highlighted in the literature since hydrogen can retain energy potential even after its production and the current risks associated are not present; however, one can foresee how the storage of large quantities of hydrogen is not risk-free, since it remains a flammable gas as current fossil fuels and natural gas are. First among all the benefits is the environmental one, i.e., the drastic reduction in CO_2 emissions that is critical and is likely to play a significant role along with growing renewables. This benefit poses no risks either in the short run or in the long run, as does the benefit on the health of the population, whereas pollutants' illnesses and hospitalizations would be reduced, and of the noise impact of any production plants and means of transportation when compared to current systems. Ultimately, a major benefit relates to breaking away from current limits regarding energy imports, thus decreasing dependence on finite resources from third parties. Indeed, hydrogen is presented as an infinite resource, the price of which will not be determined by seller and buyer, but rather will be tied solely to production technologies. Consider for instance the current cost of renewable energy such as photovoltaics instead of gas: the cost of energy consumption could not depend on the prices of a resource, but rather on the technology used. That is why Rifkin noted an energy democratization, since the moment technologies are available energy can be distributed and consumed by individual citizens as economic agents.

						Interest		
	Benefits for hydrogen implementation	Actual weight	Future weight	Actual Risk	Future Risk	Economic	Environmental	Social
1	Clean energy							
	CO_2 abatement	very high	very high	very low	very low	X	X	X
	health (air quality, noise)	medium	medium	very low	very low	x	X	X
2	Potentially unlimited resource							
	abundant and inexhaustible	low	medium	very low	low	X	x	
	storage capacity	high	medium	very low	medium	X	x	
3	Dependences							
	from other sources	very high	high	high	medium	X		X
	democratic resource	low	medium	very low	low			X

Figure 34 - Benefits and their risks related to hydrogen implementation.

Among all these benefits, we would like to emphasize the impact of CO_2 abatement; more attention should be paid to how the social cost is calculated, as the consequences are not only environmental and social but also purely economic. Neglecting the market price imposed for emissions, there is a difficulty in including the economic costs derived from non-routine weather phenomena in the assessment of carbon-dioxide abatement. Climate protection, as a result, avoids monetary consequences that while difficult to quantify are well in place and increasingly internalized by people. In calculating the shadow price, the cost given by the CO_2 market has been considered; however, in a broader assessment, in which hydrogen is financed, the cost that environmental disasters are causing and will cause in the coming decades, if unsustainable sources continue to be used, should be considered. A global estimate is presented in the EM-DAT database from CRED[161], indicating an economic damage of approximately $252.1 billion for the year 2021 alone, an amount higher than the average of the previous decade, suggesting that the trend is increasing. Accordingly, one could consider the impact in each region when going to analyse a specific project, to include this impact in the assessment. As Figure 35 shows, the disasters and the economic losses related can be taken for each zone of the world, keeping in mind that the number of disasters occurred in 2021 were 432 against the 2001-2020 annual average of 347.

[161] CRED. (2022). *2021 Disasters in numbers.* Brussels: CRED.

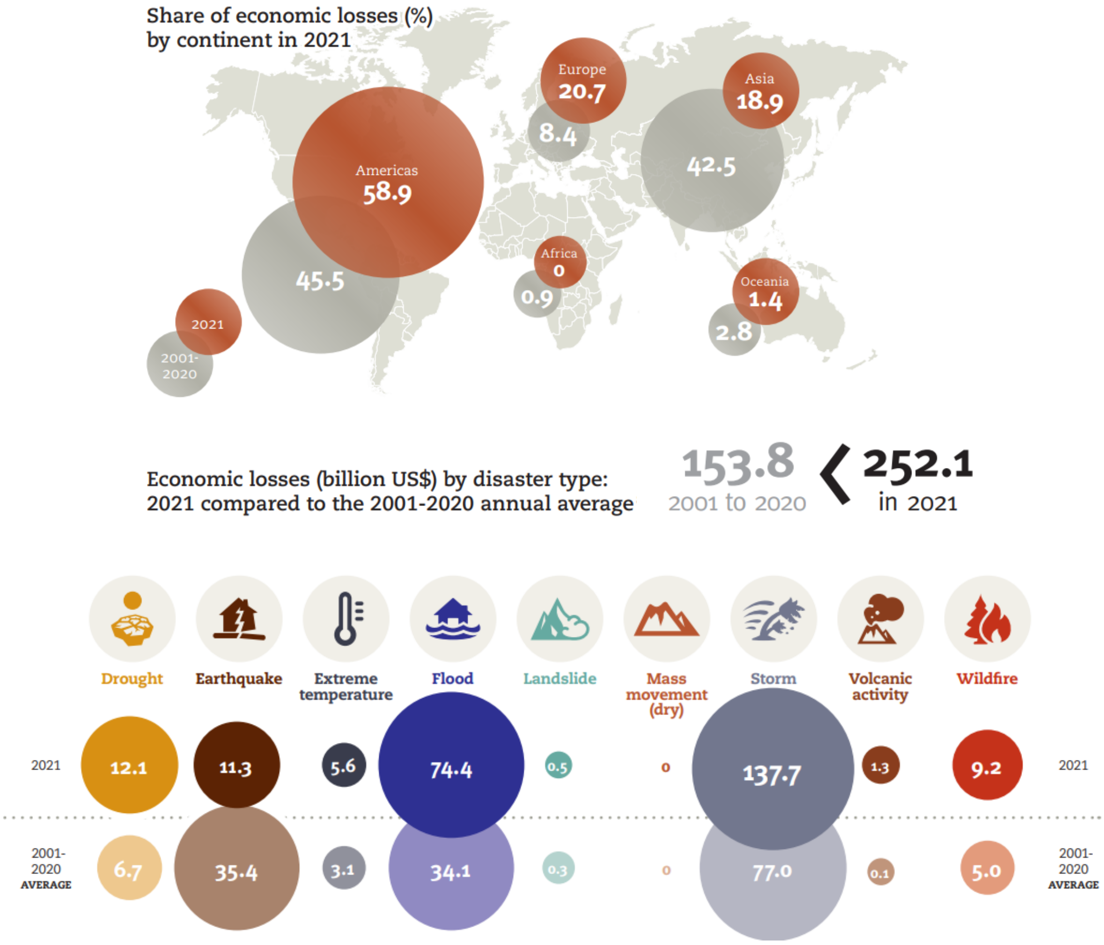


Figure 35 - Disasters' distribution and economic losses by area and by disasters type. (CRED)

In this analysis, therefore, companies and governments called to act would be interesting to understand whether they are risk takers or risk averse, as there are limits and risks regarding hydrogen, but environmental risks should be considered. In Europe, for example, 20.7% of the total 252.1 equates to an annual cost of 52.2 B$, if the same percentage was adopted for previous years in which the average was $153.8 billion, we would obtain 31.8 B$, with a variation therefore of $20.4 billion; following a production approach to find a shadow value, these money could consequently be allocated in part to financing projects that would reduce this variation in loss. For example, if we consider the annual variation of severe climate events in Europe, corresponding to $20.4 billion, and assuming it is constant, if we consider the total amount of global emissions to be about 1 billion tons of CO_2-equivalents[162] recorded in 2022 and relate it to the change in economic damages, by making a simple proportion we can see how one ton of CO_2 equivalent corresponds to $20.4. This value, however, is currently lower than what we find in the market, although it is bound to increase if the rise in temperatures is not brought under control, and as a result, alternative methods for its assessment must be found.

[162] See: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Quarterly_greenhouse_gas_emissions_in_the_EU#:~:text=Highlights&text=In%20the%20first%20quarter%20of,the%20first%20quarter%20of%202019. Data extracted in August 2022. [November 11, 2022]

2.4.5 Methodology for the evaluation of CO_2

2.4.5.1 The full cost of CO_2

Among the most significant impacts, we find the reduction in pollutant emissions due to the replacement of fossil fuels and methane of particular relevance. Valuing these emissions is very critical because it is not part of financial analysis but rather socio-economic, which requires to price something for which no market exists. Moreover, its evaluation is important when we compare prices of different fuels to measure which is the best, as we did in 2.4.2, by making the pollutant emissions a potentially crucial factor in assessing whether technologies such as hydrogen can be adopted. To put a consistent value on emissions, we can start by looking at the guidance provided by the 2014 EU Guidelines[163] in which we can find a first method so-called "Bottom-up" approach. The first step involves the estimation of the total volume of additional or reduced emissions of a given pollutant, in our case the avoided CO_2; the volumes can be recovered within the EMEP/EEA air pollutant emission inventory guidebook updated to 2019[164], which contains reference measurements for pollution volumes in different sectors. Second, we can proceed with the measurement of total CO_2-equivalent, which is not required in our case since we are focusing precisely on CO_2, but when other pollutants must be assessed is better to have uniform measures. Once we have it, we estimate the total cost associated with the volume of emissions using the unit price expressed in euros per ton of CO_2-equivalent. Therefore, the total cost of greenhouse gas emissions can be calculated through the following formula, where V_{GHG} is the change in pollutant volume reduced or increased in CO_2 equivalents and C_{GHG} is the unit shadow price in the year in which it is calculated.

$$\textit{Shadow cost of GHG emissions} = V_{GHG} \times C_{GHG}$$

Given the need to decrease these emissions, the unit price increases over time; as shown in Figure 36, in 2013 an attempt have been made by the European Investment Bank (EIB) to indicate a unit price valid at least throughout the European Union. The unit cost of greenhouse gas emissions through a CO_2-equivalent value is measured as follows and, according to these values, as of today, the unit value should correspond to 37€ per tonne of CO_2 (tCO_2), following the central scenario as was recommended by the guidelines.

[163] European Commission, Directorate-General for Regional and Urban policy. (2014). *Guide to Cost-benefit Analysis of Investment Projects - Economic appraisal tool for Cohesion Policy 2014-2020.* Luxembourg: Publications Office of the European Union.

[164] See: European Environment Agency - EMEP/EEA air pollutant emission inventory guidebook 2019 http://efdb.apps.eea.europa.eu/?source=%7B%22query%22%3A%7B%22match_all%22%3A%7B%7D%7D%2C%22display_type%22%3A%22tabular%22%7D [November 3, 2022]

Scenarios	Value 2010 (€/ton-CO_2 equivalent)	Annual adders from 2011 to 2030	Value 2022 (€/ton-CO_2 equivalent)
High	40	2	64
Central	25	1	37
Low	10	0.5	16

Figure 36 - Unit cost of GHG emissions computed in 2013 by the EIB and own calculation for 2022.

It is interesting to note that today the situation is very different about the unit price, considering that in our comparison of price per energy content between methane and hydrogen we had taken as reference the current CO_2 price on the Emission Trading System (ETS), which is around 90€, so far above the 37€ estimated in 2013. Since then, the EU ETS price related to emissions has increased faster only recently, plus, it is risky to think that this reference value is sufficient to assess CO_2 emissions. Therefore, although it may give a rough indication, the use of a cost-plus pricing method to estimate the total value of hydrogen could lead to inaccurate and underestimated results of the shadow cost, mainly due to the fact that the market price has a mutable behaviour, is not always timely in providing information and does not represent the entire pool of possible participants presenting a reduced competitiveness.[165] For this reason, in the EIB Group Climate Bank Roadmap 2021-2025 of 2020[166], the unit cost of GHG emissions, in specific the shadow cost of carbon, has been updated as:

"The full cost to the economy of saving or emitting a tonne of carbon"

What is suggested is the fact that one should not stop at models in which a single instrument is considered, such as may be the EU ETS or a carbon tax, but should also include other instruments, e.g. the introduction of technical standards to be met, incentives to use clean energy, and other incentives that are more influential on participants' behaviour. Thus, there is a difference between the cost associated with the ETS instrument and the shadow cost of carbon; as shown in Figure 37, although the market price of CO_2 can be used as a benchmark for the shadow price as a sort of market analogy, the total cost includes all the actions that must be taken to achieve in time an emission targets, and that is why the price of carbon is linked to the desire to reduce emissions. Indeed, if there were no urgency to reduce emissions their value would be reasonably low, while it is logical to expect an increase in the value the closer we get to the deadline. Consequently, the shadow cost of CO_2 depends on the targets that governments set and relative annual values presented in the figure have been calculated based on the goals of containing global warming to within 1.5°C and having zero emissions in 2050.

[165] Zheng, L., Wang, J., Yu, Y., Li, G., Zhou, M., Xia, Q., & Xu, G. (2022). On the Consistency of Renewable-to-Hydrogen Pricing. *CSEE Journal of Power and Energy Systems, 8(2), 392-402. DOI: 10.17775/CSEEJPES.2021.05630*.

[166] European Investment Bank. (2020). *EIB Group Climate Bank Roadmap 2021-2025.* Luxembourg: European Investment Bank. DOI 10.2867/503343.

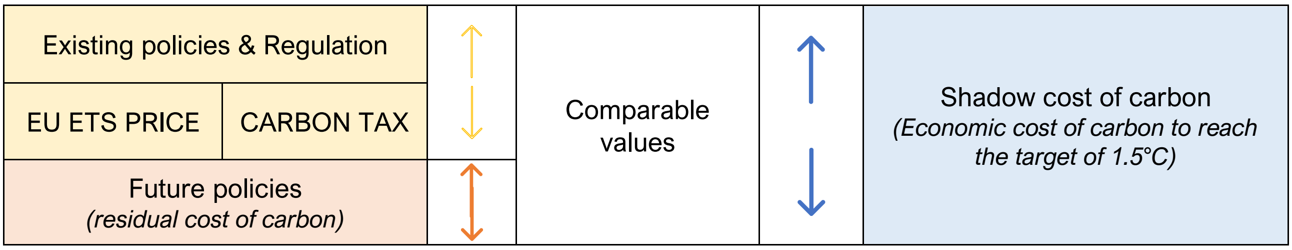


Figure 37 - Shadow cost of carbon and wider supportive policies. (EIB)

To obtain values for the shadow cost of carbon, the EIB started by looking at the Integrated Assessment Models (IAMs), which are quantitative models of the economy and climate systems, taking eight world frameworks of the Integrated Assessment Modelling Consortium (IAMC) database containing the full set of policies including the future ones as the residual cost of carbon. They made a set of scenarios, where the values reported in Figure 38 are presented in orange for the median cost derived from all the models and in blue for the variability related to different scenarios; on one hand we have the 25th percentile with policies that evaluate less the shadow cost of carbon and on the other the 75th highest percentile, which they reveal a quite large gap of about 300€/tCO_2 in 2030 and 800€/tCO_2 up to 2050 depending on technological developments, specificity of each region, consumer preferences and political behaviours.

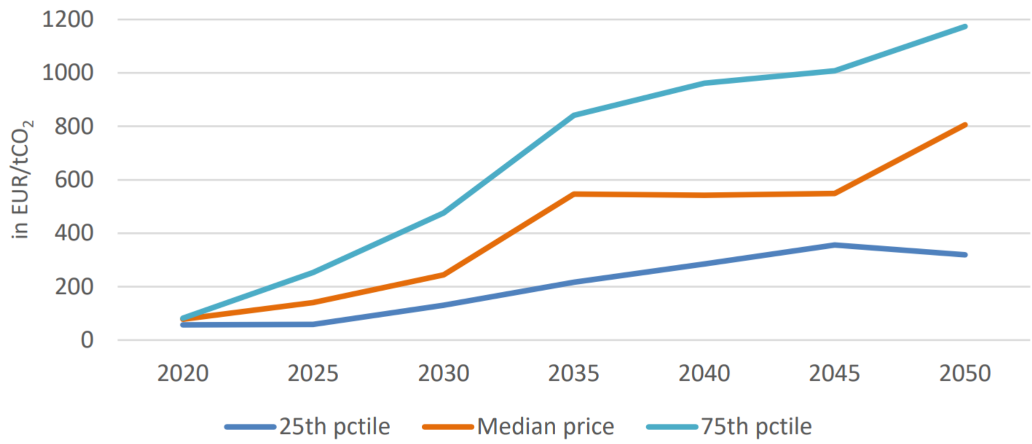


Figure 38 - Review of IAMC database with values in €$_{2016}$/tCO_2-equivalent. (EIB)

The variability of these results means that from an efficiency point of view, as stressed by the literature, individual manoeuvres i.e., taxation or ETS market, are more certain than an all-encompassing assessment value for emissions explaining the cost clearly[167], but they are still dependent on the framework in which we are evaluating. The literature also presses on this point, where CO_2 abatement is evaluated differently depending on location; reduction potentials are different among regions as the

[167] IPCC. (2018). *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change,.* sustainable development, and efforts to eradicate poverty. [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani,: Cambridge University Press, Cambridge, UK and New York, NY, USA, 616 pp. https://doi.org/ 10.1017/9781009157940.

environmental policies, and to be considered where the specific project is based.[168] What EIB proposes, then, is an intermediate baseline reported in Figure 39, in which we round up the median estimates for each decade and interpolate linearly for intermediate years, yielding a shadow cost of carbon of 80€ in 2020, as of today it is expected to have exceeded 100€, while it is equal to 250€ in 2030, to 525€ in 2040, and up to a value of 800€ per tonne in 2050.

	2020	2025	2030	2035	2040	2045	2050
Value (€/ton-CO2 equivalent)	80	165	250	390	525	660	800

Figure 39 - Recommended aligned EIB shadow cost of carbon (€2016/tCO2e) for the period 2020-2050. (EIB)

The Intergovernmental Panel on Climate Change (IPCC), with its report "Global Warming of 1.5 °C"[169], shows the connection between the price of carbon and the containment of rising temperatures; the price is higher in the scenario in which temperatures remain below 1.5°C while more likely are the scenarios in which temperatures rise by approximately 2°C. As noticed in Figure 40, according to the EIB's 2030 and 2050 forecasts values of 250€/ton and 800€/ton, respectively, the predicted scenario is near the S1[170], between 1.5°C and 2°C global temperature increase.

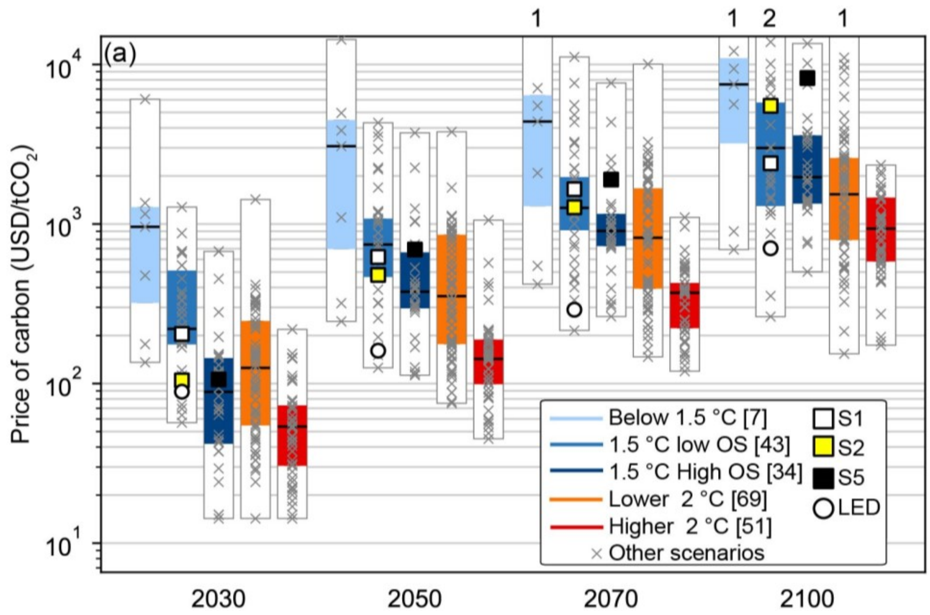


Figure 40 - Global price of carbon emissions consistent with mitigation pathways. (IPCC)

[168] Qunli, W., & Huaxing, L. (2019). Estimating Regional Shadow Prices of CO2 in China: A Directional Environmental Production Frontier Approach. *Sustainability*, 11. 429. 10.3390/su11020429.

[169] IPCC. (2018). *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change,.* sustainable development, and efforts to eradicate poverty. [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani,: Cambridge University Press, Cambridge, UK and New York, NY, USA, 616 pp. https://doi.org/ 10.1017/9781009157940.

[170] In Figure 40: S1 is a sustainability-oriented scenario, S2 is a middle-of-the-road scenario, and S5 is a fossil-fuel intensive and high energy demand scenario. LED is a scenario with particularly low energy demand.

Comparing the prices with those in the EU ETS market, we immediately see that the current value is significantly higher; the same is true in the United States, where a study[171] confirms the increase in the shadow price of CO_2 from 2010 to 2017, referring to coal-fired power plants during the implementation of five regulatory provisions, and notes how the market allowance prices have remained relatively lower than the full cost of carbon. It is then suggested how society could benefit most when the government raises these market prices to bring them closer to the real value of the issues as measured by the shadow price. Moreover, the literature confirms that these shadow prices, in addition to increasing over time, are significantly higher in states with climate targets and higher than the rates of the main taxation or cap-and-trade emission mechanisms worldwide.[172] As a result, the European CO_2 market price should be more closely adapted to shadow price, including all climate mitigation policies and strategies, to make carbon prices explicit as a prerequisite for further improving shared carbon abatement policies and accurately assessing energy transition projects.[173]

To summarize, the method that EIB proposes is to use IAMs and rely on an emission reduction pathway indicated by the scientific community to hold the temperature rise to 1.5°C, defining the level of emissions to be reduced and the model to get there. In addition to the CO_2 market, there are technical standards and other strategies to consider, i.e. the emission level for new vehicles, regulations, and the mandatory percentage of renewables, which all of them have a cost. IAMs containing these costs within detailed economic and climate models. They are integrated assessment models that evaluate economic-environmental strategies, considering, e.g., energy demand, efficiency potentials, consumers behaviour, technological innovation, and uncertainty, as well as systems integration and resource constraints, preparing different scenarios to achieve emissions containment. An IAM evaluates the impact of each scenario in a cyclical order of emissions, climate change, damage, policy response, emissions reduction, economic model, emissions, and so on. It is therefore a broader method and an alternative to the approaches usually used for estimating non-market values, i.e. market analogy and utility approach, which is closer to the production approach seen as the evaluation of costs to eliminate and prevent a certain non-market damage, i.e. CO_2. Given the great uncertainty about the elements contained in the models, the EIB proposes to use the median values, which are consistent with the IPCC scenario calculations. This result, consequently, corresponds to the shadow cost of carbon.

[171] Shirong, Z., & Guangshun, Q. (2022). The shadow prices of CO2, SO2 and NOx for U.S. coal power industry 2010–2017: a convex quantile regression method. *Journal of Productivity Analysis. 57. 10.1007/s11123-022-00629-0*.

[172] Kuosmanen, T. (2022). Lurking in the shadows: The impact of CO2 emissions target setting on carbon pricing in the Kyoto agreement period. *Energy Economics. 10.1016/j.eneco.2022.106338*.

[173] IPCC. (2018). *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change,.* sustainable development, and efforts to eradicate poverty. [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani,: Cambridge University Press, Cambridge, UK and New York, NY, USA, 616 pp. https://doi.org/ 10.1017/9781009157940.

2.4.5.2 Carbon switching price

A narrowly related concept is the carbon switching price, which is the price a project decision maker is willing to pay, or receive, for being indifferent between the option of continuing to use fossil sources or replacing them with sustainable sources.[174] From an article published for ENEA in 2018[175], we can derive a formula for calculating the switching price, having a situation in which if the price of CO_2 in the European ETS market was higher than this theoretical price, one would have a situation in which producing energy with hydrogen would be cheaper.

$$\text{Switching price} = \frac{\text{hydrogen cost (€/MWh)} - \text{competitor cost (€/MWh)}}{\text{competitor } CO_2 \text{ intensity } (tCO_2/MWh) - \text{hydrogen } CO_2 \text{ intensity } (tCO_2/MWh)}$$

To estimate the costs at the numerator, we can refer to the document prepared by the Italian Ministry for Ecological Transition to extract indicative prices in euros per MWh for hydrogen competitors in the Italian market, represented in Figure 41.[176]

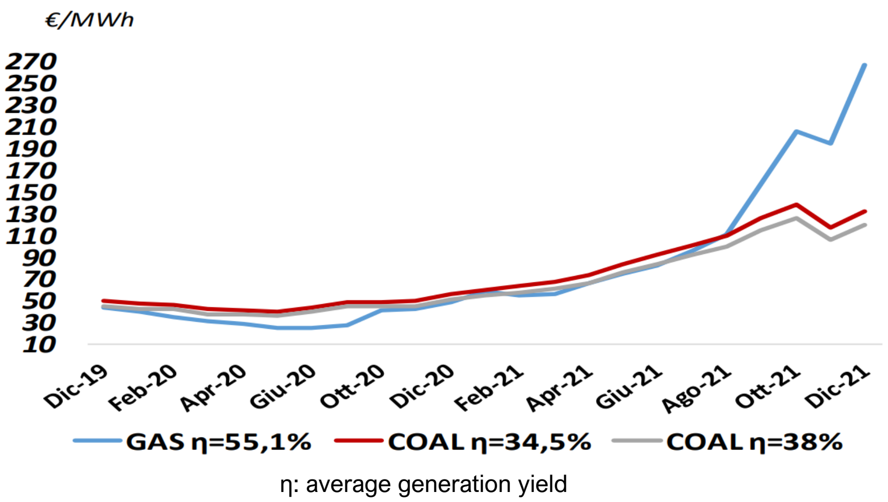


Figure 41 - Generation cost trend 2021 for different sources in Italy. (MITE: SNAM elaboration on ICIS data)

For data on emission factors at the denominator instead, we rely on IPCC data that indicate the amount of CO_2 corresponding to one MWh for each resource, for which we have 201.96 $kgCO_2/MWh$ for natural gas and 403.2 $kgCO_2/MWh$ for coal.[177] Bearing in mind that the cost of hydrogen production has as a

[174] European Commission, Directorate-General for Regional and Urban policy. (2014). *Guide to Cost-benefit Analysis of Investment Projects - Economic appraisal tool for Cohesion Policy 2014-2020.* Luxembourg: Publications Office of the EU.

[175] Aiello, S., & Fratini, M. (2018). Nuove regole nel Sistema Europeo di Scambio di quote di emissione di CO2. *Energia, ambiente e innovazione. DOI 10.12910/EAI2018-036*, 58-63.

[176] Italian Ministry of Ecological Transition. (July 2022). *La Situazione Energetica Nazionale Nel 2021* . Energy Department. Retrieved from: https://dgsaie.mise.gov.it/pub/sen/relazioni/relazione_annuale_situazione_energetica_nazionale_dati_2021.pdf.

[177] Our World In Data: https://ourworldindata.org/grapher/carbon-dioxide-emissions-factor. Data from: IPCC — Intergovernmental Panel on Climate Change [November 5, 2022]

reference the value of 0.27€/kWh, or 270€/MWh, we can proceed with an estimate of the switching price that could be obtained during 2021. The results shown in Figure 42 confirm the current competitiveness of hydrogen over natural gas, with a switching price from a value of 990 at the beginning of 2021 to a value equal to zero at the end of the year, while for coal it would be necessary to have a CO_2 market price of at least 347€ to make switching from coal to hydrogen worthwhile considering the value of emissions, a price that as seen above to date is around 90€ per ton of CO_2 emitted.

	Emissions factor (tCO2/MWh)	Indicative prices early 2021 (€/MWh)	Indicative prices late 2021 (€/MWh)
Hydrogen	0	270	270
Natural Gas	0.202	70	270
Coal	0.403	50	130
Switching price (Hydrogen - Gas)		990	0
Switching price (Hydrogen - Coal)		546	347

Figure 42 - Computation of the estimates for switching prices in Italy, 2021. (Own elaboration with IPCC and MITE data)

What we did was to consider local Italian prices, but we know that the situation can depend a lot on the area where these prices are calculated; indeed, if we take average European prices, we notice that the value for natural gas is still low to have a switching price equal to zero, taking the values previously cited by ARERA in 2.4.2, the average stood at 230 MWh. In addition, taking data from Eurostat[178] we can observe how the price is not as high as estimated in the Italian case, but considering the whole Europe is lower and stands at 65€/MWh for non-household consumers. In this case then, the value of the switching price is well above the previous value and, using the same formula, equal to 1015€. The trend, however, follows the one seen in the Italian case so we should expect in the future a reduction in the switching price in this case as well, but it is necessary to reiterate the fact that it is advisable to carefully evaluate the conditions of the place where one wants to develop a project and how the same parameters calculated under different conditions can give significantly different results.

Another method to derive the cost of CO_2 is the use of willingness to pay; however, while this tool can include the non-financial costs involving psychological factors, time and effort to undertake a change, it is subject to the characteristics with which its estimation is made. In fact, surveys and questionnaires are the most commonly used methods to derive willingness to pay through the so-called "Utility" approach, where preferences are stated and not observed in markets. The definition of questions is essential in this case, since it is a question of asking the maximum price that a private individual is willing to pay in a market equilibrium situation, pointing out that the latter situation is very rare in everyday

[178] Eurostat. (2022, October). *Natural gas price statistics*. Retrieved from Eurostat: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Natural_gas_price_statistics#Natural_gas_prices_for_non-household_consumers

life and consequently makes a reliable estimate that corresponds to the shadow price difficult.[179] Other limitations relate to the difficulty of having an appropriate audience of subjects to ask the question, who may not have all the information to make an informed judgement, also leading to an inconsistency between the answers and the behaviour of individuals and possible "strategic" responses to obtain benefits. Willingness to pay may in fact underestimate the importance of certain prices, especially those necessary to achieve climate goals. For example, a study conducted in the aviation sector shed light on the fact that the willingness to pay to reduce emissions was drastically lower than the prices that can be observed in the European Emissions Trading Scheme[180], highlighting the limitations of both methods because while on one hand we have a high market price but not involving the majority of actors, on the other hand we have greater involvement but with a much lower price level if not zero, i.e. situations where people are not willing to pay a single cent to reduce emissions.

In conclusion, by summarizing the different approaches to estimating the value of CO_2, currently market prices and climate damages do not fully reflect the value of emissions. In the economic analysis, however, it is crucial in estimating the benefit that would result from the use of hydrogen; so, its estimation is the biggest challenge for those who want to address this issue, and as we have seen, the way to its calculation is not one way. The most comprehensive approach is the one that EIB prepared; its analysis estimates the median value of different economic and environmental policies of various systems arriving at a value consistent with the observations made, that is, higher than what is currently visible in the European CO_2 market. The suggestion here is to use values closer to those representing the locality in which the projects are analysed, since the difference in estimates, especially in the long run, is very marked depending on the policies adopted to achieve the climate goals of containing temperatures.

To take a further step, we suggest an action that could be taken from a governmental perspective, which is to set a tax, if the polluter-pays principle is to be followed, or an incentive in the form of voucher or bonus, or else a mixed system, to be allocated firstly to companies that generate energy with fossil fuels and then directly to citizens equal to the value that would make the switching price between hydrogen and fossil fuels null. In this way, the company is faced with the condition of being able to switch energy sources by zeroing out emissions, thus bringing out that value in €/MWh measured and updated every year which represents the emissions that are permanently abandoned.

[179] Li, H., Sun, Q., Zhang, Q., & Wallin, F. (February 2015). A review of the pricing mechanisms for district heating systems. *Renewable and Sustainable Energy Reviews. https://doi.org/10.1016/j.rser.2014.10.003*, Volume 42, Pages 56-65.

[180] Berger, S., Kilchenmann, A., Lenz, O., & Schlöder, F. (March 2022). Willingness-to-pay for carbon dioxide offsets: Field evidence on revealed preferences in the aviation industry. *Global Environmental Change. Volume 73, 102470. https://doi.org/10.1016/j.gloenvcha.2022.102470*.

2.5 Towards the role of financiers

To conclude this chapter, there are other examples in the literature[181] that pointed out that the current cost of the hydrogen supply chain is not yet competitive for the introduction of hydrogen on a large scale, and consumption of rare materials such as platinum is making people discuss its development as an issue of sustainability. Several breakthroughs are required soon concerning research and development of approaches to reduce costs and increase the efficiency of technologies, to obtain lower values for the TCO. However, we are talking about huge and immediate investments to get benefits in the long term, and the time horizon indicates that the investments must be taken now if society requires an energy transition as soon as possible. None of the studies cited adopted an incremental approach with respect to the specific alternative of hydrogen like petrol or gas, probably because for an economic point of view it would be a failure seeing the prices or because putting a weight to the environmental question is still difficult and debatable, resulting in a more political matter even if the economic consequences that changing environment brings are clear. A key role will be played by the entities who will make available the economic resources that would go into financing projects related to hydrogen production and distribution. Therefore, the focus will shift to who can finance the energy transition that includes in part the use of hydrogen as an energy carrier; each entity, a company, a region, a state, must look at its own resources and exploit the potential, utilising and sharing it. Serving all of today's energy with hydrogen is clearly not feasible and the analysis must evaluate it as part of the energy mix, to get the energy we need through energies that are considered clean. A big question that we are going to analyse is what the potential of institutions and private multinational firms is to cope with the costs of production and usage, understanding if common economic resources could overcome extreme costs that little actors would never afford.

[181] Yue, M., Lambert, H., Pahon, E., Roche, R., Jemei, S., & Hissel, D. (2021). Hydrogen energy systems: A critical review of technologies, applications, trends and challenges. *Renewable and Sustainable Energy Reviews 146*, 111180.

Chapter 3 – Public-Private Partnerships on hydrogen

3.1 The importance of the governments

In the previous chapter, we understood how the evaluation of hydrogen is related to several factors which make difficult a judgment on the general viability of our energy vector, but it was seen that the trend of energy competitors' prices, hydrogen's production costs and technologies, and environmental burden, lead to a progressive positive verdict of it. As certain programs suggest to us[182], there are climate goals to be achieved by 2030 and 2050 and strategies directed at these extremely urgent targets are underway, including hydrogen's initiatives, and therefore the awareness of the need for action from the outset is present. To date, hydrogen has not entered the daily lives of citizens despite being a winning technology for the sustainability objectives; there should be a social choice that leads to the use of it rather than other fuels, but with what economic resources can a project, that from the economic point of view suffers great limitations, be realized? In addition to large companies, the main players in mobilizing large monetary sums are governments; while the former, those associated with natural gas and oil production and distribution, are still economically tied to fossil sources, and defend their interests accordingly, the latter are the ones who can decree guidelines and allocate funds where they see fit. Large companies linked to non-sustainable energy sources are aware of the climate issue, yet some remain tough; as indicated by the outlook of McKinsey[183], the supply of natural gas is the most resilient of fuels, which will only reach its peak in 2037. For the most optimistic, like Rifkin, that peak should have already arrived, as in fact would be desirable, but if we take ENI as a reference, we note that at least until 2025 gas will not cease to increase, and as far as its own production is concerned gas in 2050 will still account for 85% of its total production.[184] It is not trivial to say that an important issue for a company is to remain competitive in the market, and often this can only be done by maintaining a certain level of energy production and consumption while minimising costs. It is precisely here that the role of government, the public sector, can play a particularly important role; letting the market operate independently risks losing or slowing down goals that are perceived as unprofitable. Research[185] and independent reports[186] confirm that the prospect of hydrogen depends essentially on the political framework and governmental choices as well as the costs of the technologies, and that although efforts

[182] European Green Deal: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en [October 10, 2022]

[183] See: https://www.mckinsey.com/industries/oil-and-gas/our-insights/global-gas-outlook-to-2050 [October 10, 2022]

[184] See: https://www.bnnbloomberg.ca/italian-giant-eni-sees-oil-peak-just-six-years-away-1.1397243 [February 28, 2020]

[185] Ajanovic, A., & Haas, R. (2018). Economic prospects and policy framework for hydrogen as fuel in the transport sector. *Energy Policy 123, Elsevier*, 280-288.

[186] DNV. (2022). *Energy Transition Outlook 2022 - A global and regional forecast to 2050.* Oslo: DNV.

to improve these technologies are of paramount importance for companies, political support is required to achieve hydrogen competitiveness, thus shining a spotlight on the potential of policy makers to promote the transition to sustainable development.[187]

For a hydrogen-oriented economy we will have to wait until at least 2030 according to the European outlook[188], the year in which the hydrogen infrastructure, which requires considerable amounts of investment, will be more widespread. The same stumbling block is perceived in the United States of America, where low-cost technology development is currently focusing on innovative materials, more efficient and less expensive liquefaction, and integration of production and distribution points, to create a national supply infrastructure.[189] Among the main reasons for this distant prospect is the lack of coordinated actions by stakeholders, such as car companies and fuel distribution companies in the case of the transport sector, which slow down the investments and with the fact that they have very long-time horizons. In addition, there is also the fact that there has been no clear and binding emission reduction target in recent years, which has somehow left time to wait before acting.[190] Progress has, however, been made by governments around the world in reducing emissions from their economies, one could think about the COP21 in Paris; still, the challenge is to find ways to reduce emissions while ensuring competitiveness and ability to meet energy needs,[191] although each industry and institution has a different vision that emphasises more or less the use of hydrogen in the future energy system.[192]

[187] Yue, M., Lambert, H., Pahon, E., Roche, R., Jemei, S., & Hissel, D. (2021). Hydrogen energy systems: A critical review of technologies, applications, trends and challenges. *Renewable and Sustainable Energy Reviews 146*, 111180.

[188] See: https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen_en [October 11, 2022]

[189] Fuel Cells Technologies Office. (March 2017). *Hydrogen Delivery DOE/EE-1551.* United States: U.S. Department of Energy - Energy Efficiency & Renewable Energy.

[190] Ajanovic, A., & Haas, R. (2018). Economic prospects and policy framework for hydrogen as fuel in the transport sector. *Energy Policy 123, Elsevier*, 280-288.

[191] Brandon, N. P., & Kurban, Z. (2017). Clean energy and the hydrogen economy. *Phil. Trans. R. Soc. A 375: 20160400.*

[192] Linssen, J., & Hake, J.-F. (2016). Hydrogen Research, Development, Demonstration, and Market Deployment Activities. In D. Stolten, & B. Emonts, *Hydrogen Science and Engineering : Materials, Processes, Systems and Technology* (pp. 57-84). Germany: Wiley-VCH Verlag GmbH & Co. KGaA.

3.2 International standards and EU's vision

Standards and legal framework are well defined by the governments, as in the case of the European Union, and they should be useful all around the world for having standardized requirements to produce and trade hydrogen. There are international guidelines made by the International Organisation for Standardisation, which is an independent non-governmental international organization, detached from the jurisdiction of a state. The first standard on hydrogen dates to March 1999 and was the ISO 13984:1999 Liquid hydrogen - Land vehicle fuelling system interface, made by the technical committee "ISO/TC 197 - Hydrogen technology". Currently, there are ISOs under development such as the ISO/AWI 14687 Hydrogen fuel quality - Product specification, ISO/WD 19884 Gaseous hydrogen - Cylinders and tubes for stationary storage, and ISO/WD 19887 Gaseous Hydrogen - Fuel system components for hydrogen fuelled vehicles. It is interesting to compare the published, under development, withdrawn or deleted standards related to hydrogen and other fossil fuels; the results of our research form the official website[193], reported in Figure 43, show that typing-in "hydrogen" we get fewer standards than "natural gas" and "petroleum" for each category. This difference shows that there is still a need to develop appropriate standards for the large-scale introduction of hydrogen; in particular, there is no standard that specifically addresses clean or green hydrogen. In addition, looking at the ratio of the number of published standards to those that have not been published, i.e., withdrawn, it can be inferred how many attempts are needed before an agreement that satisfies everyone can be found; the results for hydrogen do not differ much from those for other fuels, suggesting how the decision-making process, while remaining less involved in terms of number of publications probably due to the fact that the hydrogen energy system is relatively new, is no more difficult to finalize.

International standards (ISO)				
Keyword	Under development	Published	Withdrawn + deleted last year	Rate Published/Withdrawn
Natural gas	64	374	334	1.12
Methane	2	7	1	7.00
Petroleum	82	496	406	1.22
Gasoline	4	13	12	1.08
Hydrogen	27	89	85	1.05
Green hydrogen	0	0	0	0.00
Gaseous hydrogen	14	28	22	1.27
Liquid hydrogen	1	3	1	3.00
Hydrogen energy	0	3	2	1.50
Electric vehicles	36	109	132	0.83
Hydrogen vehicles	8	28	25	1.12

Figure 43 - International standards for different searches by keyword. (Own elaboration from ISO)

[193] Retrieved from: https://www.iso.org/advanced-search/x/ [October 24, 2022]

Data show that the standards currently being worked on are greater in number for natural gas and oil than for hydrogen, suggesting how the focus is still primarily on those energy sources. For the light transport in particular, the results display that standards on hydrogen vehicles are being made, but less than for electric vehicles, demonstrating that the international interest is focused on the latter. Faced with this additional regulatory challenge, governments are not standing still, and as far as Europe is concerned, we have for example the EIHP project, the European Integrated Hydrogen Project, which worked collaboratively between government agencies and automotive companies to develop regulations for hydrogen-powered vehicles.[194] The European Commission continues to define a set of binding laws for climate and energy targets, which foresee that the use of sustainable hydrogen energy will reduce greenhouse gas emissions by around 20% compared to 1990, to regulate hydrogen-powered cars subject to legal requirements, such as the end of life vehicles waste prevention and limitation requirement to ensure the proper recovery and recycling of components whenever possible. The policy objectives define climate and sustainability regulations and requirements for the development of hydrogen energy, demonstrating how the public sector is crucial and in some cases it is the driving force for change, and the speed with which it acts is of utmost importance especially because of its self-imposed goals.[195] It was as early as 2002 that the European Commission was moving toward hydrogen: in that year, Rifkin was an adviser to Romano Prodi, the then-president-in-office of the Commission, and drew up a strategic plan to make the European Union a green hydrogen economic centre. A coordinated long-term plan was announced in October of that year to break away from fossil fuel dependence and move to be the first hydrogen-based superpower, strongly supported by President Prodi himself, but it took years to see the beginning of the realization of that vision.

"At the current pace, Europe's oil import dependency is set to grow from around 50 per cent today to 70 per cent or more in 2025. Current trends are clearly unsustainable. We have to act now in order to change them. Our objective is a fully integrated hydrogen economy, based on renewable energy sources, by the middle of the century. These efforts will be successful only if national and European resources, both public and private, are pulled together in a coordinated way."

Romano Prodi, 2002.[196]

[194] Kruse, B., Grinna, S., & Buch, C. (2002, February 13). *Hydrogen Status og muligheter - Bellona rapport nr. 6.* Oslo, Norway: The Bellona Foundation.

[195] Cantuarias-Villessuzanne, C., Weinberger, B., Roses, L., Vignes, A., & Brignon, J.-M. (9 November 2016). Social cost-benefit analysis of hydrogen mobility in Europe. *International Journal of Hydrogen Energy*, Volume 41, Issue 42, Pages 19304-19311.

[196] See: https://cordis.europa.eu/article/id/21474-hydrogen-is-the-way-forward-says-prodi. Last update: 21 January 2004.

3.3 Looking at Public-Private Partnerships

3.3.1 What is a Public-Private Partnership

"A long-term contract between a private party and a government entity, for providing a public asset or service, in which the private party bears significant risk and management responsibility, and remuneration is linked to performance"

(Internatonal Bank for Reconstructon and Development, April 27, 2017)

When we are in the presence of a cooperative institutional arrangement between actors from the private and the public sectors, we are in the presence of a Public-Private Partnership (PPP). Although it is considered a new method, the concept of cooperation in this sense is not new at all, but it is modern because it has been in practice since 1970s; it can be seen as an improvement of the previous contracting and privatizations, to combine in a better way the strong institutional power of the public and the knowhow and resources of the private, allocating the risks properly.[197] Three are the subjects: a public body interested in the implementation of some project, a private actor aiming to make profit after or during the operations, and a commission which aims to assist accession as a form of mediator.[198] PPPs are seen as a way to manage and govern organizations that produce a public service; indeed, they are seen as a tool to manage infrastructure projects, such as can be for pipelines which have a public interest of distributing hydrogen[199], resulting in services with better quality, more efficient and cost effective[200], but also to manage research projects to develop technologies that benefit all citizens, delivering products and services at a lower cost for them.[201] This instrument is particularly useful when the technologies and the scale of the project imply the need to incur substantial costs and risks; for this, the private actors involved are in general big firms with specific technologies or influence for a certain sector, but smaller firms for local projects are not excluded from the use of this tool since it is important to select the right partners among the private sector to avoid different interests that could obstacle the realisation of the PPP.[202] Governments can execute projects which for their relevance attract firms, and

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[197] Loganathan, K., & Kaushal, V. (July 2021). *Evaluation of Public Private Partnership in Infrastructure Projects.* Conference Paper - DOI: 10.1061/9780784483602.018: ResearchGate.

[198] Directorate General Regional Policy. (March 2003). *Guidelines For Successful Public-Private Partnerships.* Bruxelles: European Commission.

[199] Hodge, G. A., & Greve, C. (Jun, 2007). Public-Private Partnerships: An International Performance Review. *Public Administration Review*, Vol. 67, No. 3, pp. 545-558, Published By: Wiley.

[200] Loganathan, K., & Kaushal, V. (July 2021). *Evaluation of Public Private Partnership in Infrastructure Projects.* Conference Paper - DOI: 10.1061/9780784483602.018: ResearchGate.

[201] de Bettignies, J.-E., & Ross, T. W. (Jun, 2004). The Economics of Public-Private Partnerships. *Canadian Public Policy / Analyse de Politiques*, Vol. 30, No. 2, pp. 135-154, Published By: University of Toronto Press.

[202] Loganathan, K., & Kaushal, V. (July 2021). *Evaluation of Public Private Partnership in Infrastructure Projects.* Conference Paper - DOI: 10.1061/9780784483602.018: ResearchGate.

whereas the public is expert on the bureaucratic aspects and the wellbeing of the people bringing the social willingness, the private has innovative technologies, often a better ability to assess risks and managerial experience.[203] These skills are rewarded usually with a mechanism characterized by three different ways of payment and agreed before the start of work: the direct compensation from the government to the private, the collection of fees from the users by the private, or by a combination of these two.[204] Turning to the reasons for participating in this type of partnership, these are revealed from a survey conducted by Loganathan & Kaushal[205], involving a wide range of industrial professionals, which found that the main factors or Key Performance Indicators for choosing a PPP were the value for money, costs and time (a non-monetary good which is incredibly considered by firms and institutions), the private sector efficiency and expertise of partners better exploited, and the allocation of risks among the parties.

The Public-Private Infrastructure Advisory Facility indicates that there are different types of partnerships depending on the risk transfer, the amount of investment by the parties, and the ownership of assets both during the period of proceedings and at the end or at transfer. The most common types, rather than the Privatizations or other forms of collaboration such as Service Contracts and Build Transfers, are the Build operate transfer (BOT), Build own operate transfer (BOOT), Build own operate (BOO), and Operation and maintenance contract (O&M). BOOT and BOO can also be called ROOT and ROO when they refer to a rehabilitation of an existing facility instead of the construction of a new one. The BOOT type is part of a more general category which is the Design-Build-Finance-Operate (DBFO) since private-public partnership bundles together multiple project phases or functions, i.e. the initial concept and output requirements, the building or rehabilitation, the financing, the maintenance over the life of the contract, and the operation phase.[206] As summed up in Figure 44, the characteristics shown refer to roads and highway projects, but they fit well into the context to get a general overview of the main differences between the different kinds of partnership. The first type BOT is well suited to projects which have a relevant initial investment and operating content, financed by the government. The second, BOOT, is well suitable to projects with relevant investing and operating content, but when the public part does not have the chance to finance the project entirely due to a shortage of financial resources, which is the most used type. In the third, BOO, the private company is the main subject, the market risk may be lower if there is a demand history, and it is considered as the step before privatization; private operates independently on the project, the government does not fund the project directly but

[203] Ibid.

[204] See: https://ppp.worldbank.org/public-private-partnership/ppp-contract-types-and-terminology [October 24, 2022]

[205] Loganathan, K., & Kaushal, V. (July 2021). *Evaluation of Public Private Partnership in Infrastructure Projects.* Conference Paper - DOI: 10.1061/9780784483602.018: ResearchGate.

[206] See: https://ppp.worldbank.org/public-private-partnership/ppp-contract-types-and-terminology [October 24, 2022]

offers other financial incentives such as, for instance, concessions or exemptions from taxation. And the fourth, O&M, is a contract applied to projects after their initial development, where a deep operativity is required, letting the private efficiency and technical knowhow prevail.

'PP Modality Type	Ownership	Main Features	Risk Transfers	Access to private finance
Build Operate Transfer (BOT)	Government	Government finances the facility while private company builds the facility, operates the facility on a concession, at the end is transferred to the government.	Government bears equity risk. Private company bears the risks associated with the construction	Limited access
Build Own Operate Transfer (BOOT)	Private company until transfer	Private company finances, builds, and operates the facility on a concession, at the end is transferred to the government.	Private company bears equity risk, construction risk, and other commercial risks	Significant infusion of private capital for construction and working for operation and maintenance.
Build Own Operate (BOO)	Private company	As in BOOT, except that the facility is not transferred to the government. Common for the rehabilitation of an existing facility rather than the construction of a new one	Private company bears equity risk, construction risk, and other commercial risks	Significant infusion of private capital for construction and working for operation and maintenance.
Operation and maintenance contract (O&M)	Government	Management and operation of a public infrastructure is out-sourced to a private company. Great control of service passed to the private company	Relatively low-risk option for expanding the role of the private sector, additional risk of keeping the facility up to certain technical standards, no equity risk	Limited infusion

Figure 44 - Characteristics of the main Public-Private Partnerships on infrastructures. (PPIAF)

Most of new projects fall into the BOOT type, in which the government is the final owner but guarantees a concession for an accorded period to the private sector, which in general is a private consortium of firms. During the contract period, it can finance, build, operate, maintain, and manage the project, recovering from the investment's costs through user charge. This type of PPP allows private financing, and the allocation of risk to the private enterprise, assuming the risk that revenues will be lower than those needed to achieve the required rate of return on equity (ROE). The project is presented by the private sector and the financing parties also support it in negotiations with the commissioning government, insisting on tax or other support to make the project viable. For hydrogen-related projects, which might involve the development of pipeline infrastructure, production facilities, or research into hydrogen technologies, it is important to understand the weights that the public and private sectors assume within these partnerships.

3.3.2 Complementary tool between potentials and limitations

Partnerships are just one of the possible instruments of the government since there are other ways to boost the energy transition[207], i.e. mandatory disclosure of information about a company's pollution level, fiscal policies that penalize polluters with direct taxes or carbon pricing, or even the technology push with incentives and funding to non-polluting technologies and the establishment of technical requirements, but is perhaps the closest way to monitor and cooperate with private interests given the contractual nature of the partnership. Together with PPP, a State has the possibility to intervene on taxation, for example, which is a key instrument: the price of electricity is not exempt, taxes consequently affect potential investments in electrification, therefore exemptions or reductions of them should be also considered. Or another case, regulating the option of introducing energy from renewable sources into the grid, as found by research[208] that observed in European states a reduction in renewable energy input due to the inefficiency of distribution systems.

The role of governments is therefore of paramount importance in speeding up changes in the energy sector, otherwise much time and investment would be lost.[209] The majority of the promoters of a public-private partnership are in fact the governments themselves[210], to address specific issues and with the aim to align public and private objectives, strengthening trust and collaboration, and minimising costs along all stages of the process.[211] The authorities are interested in developing this type of cooperation because they are aware of the potential that private investments have in stimulating economic development[212], and it is also interesting to note that the larger the public entity proposing a type of partnership, the more incentive there is to create private consortia capable of supporting a large investment programme. As a result, starting from regional partnerships that can help small private entities, one can reach an audience of numerous private entities[213], which is also why these alliances can include international institutions and grouped companies rather than single operators. In addition, there can be cooperation between multiple public entities, and this makes sure that there are

[207] DNV. (2022). *Energy Transition Outlook 2022 - A global and regional forecast to 2050.* Oslo: DNV.

[208] Yue, M., Lambert, H., Pahon, E., Roche, R., Jemei, S., & Hissel, D. (2021). Hydrogen energy systems: A critical review of technologies, applications, trends and challenges. *Renewable and Sustainable Energy Reviews 146*, 111180.

[209] Ibid.

[210] Vyshnivska, B., & Kireitseva, O. (2022). Peculiarities Of Application Of Public-Private Partnership As A Mechanism For Implementation Of Innovation Activity. *Three Seas Economic Journal. 3*, 35-41. 10.30525/2661-5150/2022-1-5.

[211] Dupré, L., Cavallini, S., Bisogni, F., & Volpe, M. (2012). *EP3R 2010-2013 - Four Years of Pan-European Public Private Cooperation.* 10.2824/565581.

[212] Buranbaeva, L. (2022). Public-private partnership in the system of regional management. *Vestnik BIST (Bashkir Institute of Social Technologies)*, 48-53. 10.47598/2078-9025-2022-3-56-48-53.

[213] Demotes-Mainard, J., Canet, E., & Segard, L. (2006). Public-private partnership models in France and Europe. *Thérapie*, 61. 325-34, 313. 10.2515/therapie:2006059.

institutional, societal and economic improvements, having a positive impact on private participation[214]; moreover, the quality of the institution is positively related to the involvement of private investments.[215] Furthermore, with these partnerships the governments set a long-term perspective[216], so to have an efficient project we should have solid and lasting states, which is not so obvious if we consider that a sort of stability of nations, at least in part of Europe, was reached only after the second world war. Therefore, the quality of institutions has a direct impact on the outcome of the partnership, characterized by the quality of regulation and efficiency of the public bureaucracy, independence, and thus conflicts of interest.[217] Nevertheless, as with time the stability of governments is increased it is also increased the influence and economic power of private firms, such as multinationals that achieve revenues higher than single modern states; therefore, the public part must carefully evaluate the interests that the private partners can have.

For a partnership to be successful, it is necessary to ensure the full competitiveness of the private sector, in order to give the widest possible range of companies the opportunity to participate without losing operational ability, i.e. containing the amount of participants within a reasonable number.[218] In fact, this type of alliance does not always work perfectly; a lack of visibility and information sharing, for instance, can be a limitation, as can the lack of stability, political or economic, of the two parties given the long period of collaboration required.[219] It is therefore important to create a resilient partnership, able to adapt quickly to possible changes that may occur over the years; in addition, setting goals with clear deadlines is helpful in this regard.[220] Fundamental to the success of a partnership is the management of contractual relations to maintain stable interactions throughout the project's duration, effectively allocating remuneration and risks, which are, as emphasised by Confindustria, fundamental to make the private sector invest: to give an example, standards agreed by the parties to be followed in the event of a surprising phenomenon compromising the project ensure that the private company is not held liable.[221]

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[214] Fleta Asín, J., & Muñoz Sánchez, F. (2021). Renewable energy public–private partnerships in developing countries: Determinants of private investment. *Sustainable Development*, 29. 10.1002/sd.2165.

[215] Ibid.

[216] Hodge, G. A., & Greve, C. (Jun, 2007). Public-Private Partnerships: An International Performance Review. *Public Administration Review*, Vol. 67, No. 3, pp. 545-558, Published By: Wiley.

[217] Cui, C., & Hope, A. (April 2018). Review of studies on the public–private partnerships (PPP) for infrastructure projects. *International Journal of Project Management*, DOI: 10.1016/j.ijproman.2018.03.004.

[218] Vyshnivska, B., & Kireitseva, O. (2022). Peculiarities Of Application Of Public-Private Partnership As A Mechanism For Implementation Of Innovation Activity. *Three Seas Economic Journal. 3*, 35-41. 10.30525/2661-5150/2022-1-5.

[219] Dupré, L., Cavallini, S., Bisogni, F., & Volpe, M. (2012). *EP3R 2010-2013 - Four Years of Pan-European Public Private Cooperation.* 10.2824/565581.

[220] Ibid.

[221] Confindustria. (September 2020). *Position Paper - Piano d'azione per l'idrogeno 2020.* Rome: Confindustria. Retrieved from: https://www.confindustria.it/home/policy/position-paper/dettaglio/piano-azione-idrogeno.

3.3.3 Risk allocation

3.3.3.1 The importance of distributing responsibilities

"Any factor, event or influence that threatens the successful completion of a project in terms of time, cost or quality."

(Directorate General Regional Policy, March 2003)

As we said, the risk allocation is crucial in a PPP since it influences the financial aspect of a project and affects the value of it for the society. The public party should finance companies proportionally to the responsibilities carried by itself and them, to ensure the viability of the project, and the private participation should be weighted should be balanced to optimise risk management. Once the public sector has clarified its objectives, it can proceed to choose the type of partnership and consequently the risk allocation, deciding who is going to accept the risks of construction phase, the delivery of service and the maintenance of the project. There is a trade-off for the public between risks and payments, since the private would require more financial incentives or payments if the risks assumed are higher, and therefore the public must choose carefully what risks wants to transfer. Other ways to incorporate hazards in the financial aspect of a project, rather than the cash flows weighted to the cost of the risk, are for example the reduction of the minimum payback period and the rise of the rate of return needed. In general, the allocation should follow the principle according to which the part who can manage the risk in the most cost-effective way is chosen.[222] To mention several dangers that can follow the creation of a partnership we can have changes in regulations, inflation or currency problems, environmental liability, insolvency of one of the partner, reduction or failure of the demand for the service provided, and more general perils such as fire, flood and earthquakes, keeping in mind that risks might be related or bounded to each other.[223] This is a critical phase during the creation of a partnership because the complexity of risks and the connections among them regards the fact that they could be specific for the government, specific for the private part, or shared. The parties have then to apply in all these cases strategies to avoid, retain, control, and transfer risks and present them to the other group, to evaluate the comprehensive situation of risk management and decide the best way to develop a project.[224]

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[222] Directorate General Regional Policy. (March 2003). *Guidelines For Successful Public-Private Partnerships.* Bruxelles: European Commission.

[223] Ibid.

[224] Xu, J., & Lin, X. (2016). *The analysis of the PPP risk management under the perspective of local government.* 69. 1774-1780.

3.3.3.2 Public and private risks

Sometimes PPPs are characterized by improper risk allocation between public and private, which leads to an excessive cost of capital (the minimum rate of return or profit a company must earn before generating value, i.e. the cost that a business incurs to finance its operations to evaluate whether an investment is justified) that reduces value creation. The private sector might be represented by a consortium, rather than distinct identities, that carry out the different project phases. These consortia are also created on purpose so that project objectives can be reached; however, the government interacting with the consortium has reduced information due to the dispersion of expertise within a consortium, which leads to reduced transparency between the public and private sectors, increasing the risk of negative outcomes for the public that does not know how the private parties manage their activities. Therefore, the public must recognise well how the project phases are managed and understand what the best private participation can be, since the objective is to divide responsibilities, and consequently risks, between the parties in the most efficient way possible to achieve the defined common objectives and minimise costs.[225] In order to share responsibility while minimising costs, risks must be priced objectively and transparently, avoiding transferring risks to a party that cannot manage them. Figure 45 shows a curve of the cost of risks that finds its lowest point where the level of private sector participation is optimal; if we are on the left part of the curve, i.e. in the situation where the level of participation is low, the cost is higher because the public sector retains risks that the private sector would be better able to manage. If, on the other hand, we are on the right side of the curve, i.e. in the situation where the level of risk managed by the private sector is high, the cost will be higher because the public sector is loading the private sector with too many risks that it cannot manage and will consequently demand a higher risk premium.[226]

[225] Quiggin, J. (2004). Risk, PPPs and the public sector comparator. *Australian Accounting Review. 14. 10.1111/j.1835-2561.2004.tb00229.x.*, Pages 51-61.

[226] Stegemann, U., & Beckers, F. (2021, September 10). *A smarter way to think about public–private partnerships.* Retrieved from McKinsey & Company: https://www.mckinsey.com/capabilities/risk-and-resilience/our-insights/a-smarter-way-to-think-about-public-private-partnerships

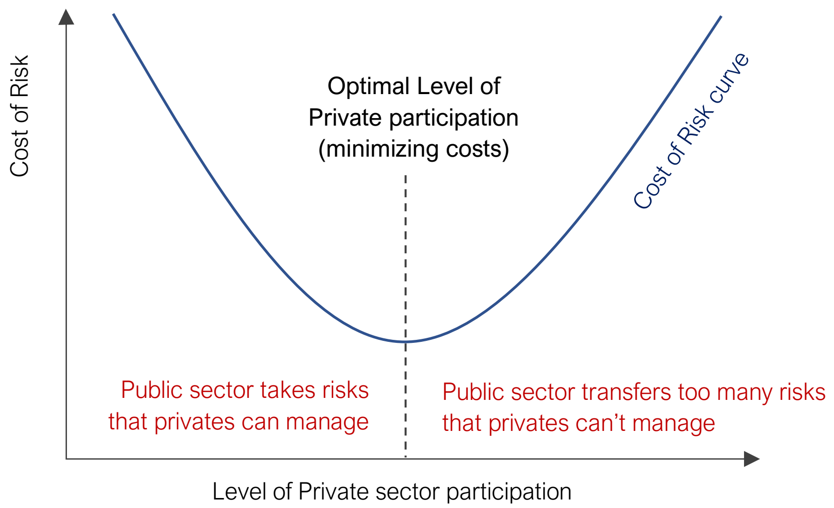

Figure 45 - Illustrative level of private-sector risk participation. (Adaptation from Symbolus Management Consultancy)

In a PPP contract, there is a tendency to allocate a risk to the party that can least dissociate itself from that risk without considering that it may be the party least capable of managing that risk[227]; for example, the management of raw material supplies cannot disregard the private sector even though there may be cases where such raw materials are public or have to be purchased from third countries in which there are trade agreements between public parties. Furthermore, one of the two parties may be more relevant in terms of knowledge, skills, financial availability, and influence, making the collaboration not entirely fair and balanced; there may be cases where individual interests prevail, eroding the results of the partnership. Thus, there can be firstly an "adverse selection", i.e. when one party is involved thinking it is appropriate whereas in reality it is not. A party have information that the other do not have; the partner's abilities are not well known due to information asymmetries and therefore participants with information might participate selectively during the project's phases, to the detriment of the other party. Secondly, a "moral hazard", when one party acts out of self-interest for its own specific goals at the expense of collaborators, again given the lack of information due to difficult monitoring between the parties; the public could obtain a low-quality product if the private party excessively reduced costs or private could obtain government subsidies if there was a conflict of interest. Moreover, it can be seen from Figure 46 that if the public were to give too much responsibility and risk to the private sector, as well as putting it at a disadvantage from any manifestation of the risks, there would be a risk of opportunistic behaviour arising from this increased responsibility, where the public fails to monitor the whole situation.[228]

[227] Shrestha, A., Tamosaitiene, J., Martek, I., Hosseini, M. R., & Edwards, D. (2019). A Principal-Agent Theory Perspective on PPP Risk Allocation. *Sustainability. 11. 6455. https://doi.org/10.3390/su11226455*.

[228] Ibid.

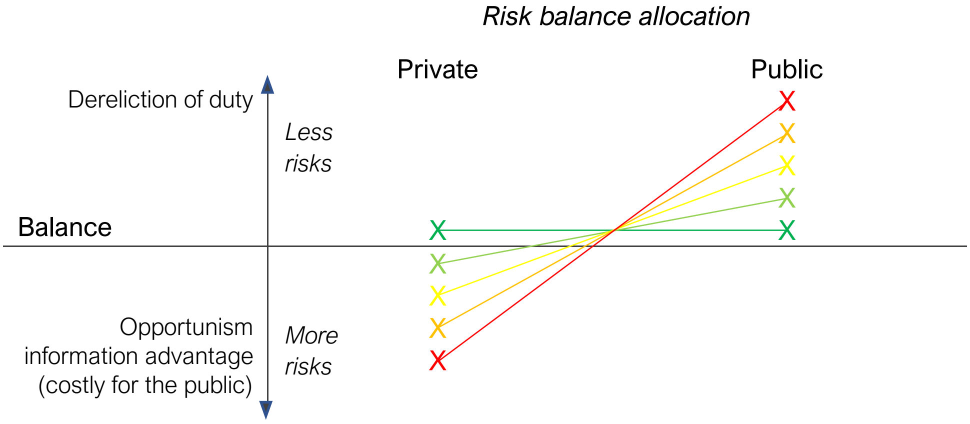

Figure 46 - Role of risk allocation to achieve a win-win balance. (Adaptation from Shrestha et al., 2019)

The general rule shared in the literature[229] is that the parties should agree on who among them best meets the following parameters to allocate a risk:

- Control: the party that has sufficient ability to reduce probability and severity of the risk.

- Information: the party that has the highest level of information regarding the risk, sharing is necessary.

- Incentive: inducing the party to exercise a high level of effort to cope with the risk.

There are several types of risks that can be encountered during the successive phases of a project; they can concern construction and operation phases, or they can be demand, regulatory and network risks. Whether it is the construction of a new piece of machinery or a large infrastructure, there will always be associated risks that can endanger the realisation of the project. Even in the operational phase, i.e. after the project has been completed, there may be risks associated with the malfunctioning of the work that may occur. Additionally, depending on the sector, for hydrogen in particular, demand is different and subject to many variations and conditions. For example, to supply industries, the demand would be dictated by energy needs, whereas in the case of the transport sector, the construction of filling stations would have to follow the quantity of hydrogen-powered vehicles in parallel and vice versa. Then, one would have to distinguish between risks related to the economy in general (systematic risk) and those related to specific demand (idiosyncratic risk). For regulatory risks, the party that is better places to deal with them is clearly the government, while for network risks, one must consider the connections that an individual project may have to the infrastructure of which it is a part. For example, in a hydrogen production plant for distribution, any risk of the whole system is potentially relevant.[230]

[229] Shrestha, A., Tamosaitiene, J., Martek, I., Hosseini, M. R., & Edwards, D. (2019). A Principal-Agent Theory Perspective on PPP Risk Allocation. *Sustainability. 11. 6455. https://doi.org/10.3390/su11226455*.

[230] Quiggin, J. (2004). Risk, PPPs and the public sector comparator. *Australian Accounting Review. 14. 10.1111/j.1835-2561.2004.tb00229.x.*, Pages 51-61.

One study[231] analysed qualitatively and quantitatively, using inferential methods and multi-criteria decision-making techniques, the relevance of the main risks that characterise the phases of a generic PPP to give an indicative hierarchical scale for prioritising risks. The most important ones are in order: economic and financing risks, i.e. having higher financing costs than expected, construction risks for the quality of performance and standards plus the lack of adequate support infrastructure and the risk of non-completion, operational risks, service changes, legal and political risks. Governments also resort to PPPs in order to decrease the input of public funds for services and innovations.[232] Risk allocation may therefore become challenging: we will take as reference a Risk Matrix of the Global Infrastructure Hub (GIH) concerning photovoltaic solar plants[233], which risks, although indicative, may refer to a possible hydrogen production facility. Some risks are specific to one of the two parties, while others are shared or involve responsibilities of one or the other depending on the cases; the latter are useful because they allow both parties to take obligations, but they can be very dangerous for the success of the partnership and for the management of the adverse event, in case it occurs, because intervention may be delayed due to a lack of clear division of responsibilities.[234]

Public Risk	Shared Risk or both	Private Risk
Land and Site	Force Majeure	Design
Social	Disruptive Technology Risk	Construction
Demand	Variations Risk	Operating
MAGA		Environmental
Change In Law		Financial Markets
Early Termination		Strategic/ Partnering
		Condition At Handback

Figure 47 - Risk allocation for a Photovoltaic Solar Plant PPP among public and private sector. (Own elaboration from GIH)

Figure 47 shows the risks to the PPP of a Solar PV plant that we may find in similar projects related to hydrogen production and we can see that the most critical, i.e. risks during construction, operation and those related to the financial part, are mostly the responsibility of the private party and it is interesting to see that environmental risks are mostly borne by the private party, except for external environmental

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[231] Jokar, E., Aminnejad, B., & Lork, A. (2021). Assessing and Prioritizing Risks in Public-Private Partnership (PPP) Projects Using the Integration of Fuzzy Multi-Criteria Decision-Making Methods. *Operations Research Perspectives. Volume 8, 100190. https://doi.org/10.1016/j.orp.2021.100190*.

[232] Quiggin, J. (2004). Risk, PPPs and the public sector comparator. *Australian Accounting Review. 14. 10.1111/j.1835-2561.2004.tb00229.x.*, Pages 51-61.

[233] Global Infrastructure Hub. (2019). *PPP Risk Allocation Tool 2019 Edition (Energy, Communications & Industrial parks) - Photovoltaic Solar Plant - Pages 20-54.* Retrieved from GIH: https://ppp-risk.gihub.org/risk-allocation-matrix/energy/photovoltaic-solar-plant/.

[234] Shrestha, A., Tamosaitiene, J., Martek, I., Hosseini, M. R., & Edwards, D. (2019). A Principal-Agent Theory Perspective on PPP Risk Allocation. *Sustainability. 11. 6455. https://doi.org/10.3390/su11226455*.

events in the hands of the public and climate change events which are shared, while for the rest i.e. obtaining environmental consents, compliance with environmental consents and laws, and environmental conditions caused by the project are the responsibility of the private party. There are risks that involve both parties which can be shared or party specific as appropriate; an example may be the case of strikes where e.g., nationwide and sector strikes are typically borne by the government, but specific strikes at the construction site or company will be a borne by the private party. The public, on the other hand, is responsible for the risks associated with the availability of the land on which construction is taking place, except for the security of the site, which is the responsibility of both, where the public safeguards the overall stability while the private partner monitors the day-to-day state. The legislative and political risks are also public's responsibility, including MAGA risks, standing for Material Adverse Government Action, that are those cases where the risks arise from specific "political" actions such as outright nationalization or expropriation. Subsequently, social risks are also managed by the public, while as far as project design is concerned, it is up to the private party to ensure on any risks related to suitability and possible changes on the design and purpose of the service.[235]

It can be seen in Figure 48 how, in absolute value, the amount of risks retained is slightly greater for the private party than for the public party and the difference is more visible in cases where the risks are expressly the sole responsibility of either party (dark yellow), while the government side holds the largest share of risks where intervention is considered residual, namely 'circumstance-dependent risks' (light yellow), which arise from specific cases that may occur and for which the government may need to provide assistance to the counterparty.

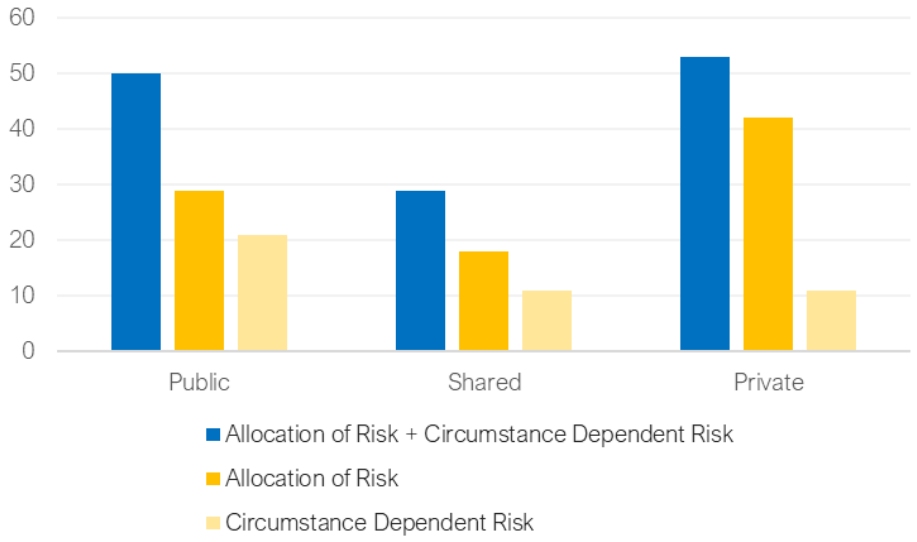

Figure 48 - Number of risks related to each part of the PPP in a Photovoltaic Solar Plant. (Own elaboration from GIH)

[235] All specific risks and their allocation can be found in Table 3 in the appendix.

Other risk matrices exist to have a guideline on which allocation can be successful in implementing a PPP project and are consistent with the results; guidance can be found from the World Bank[236] for BOOT, other types of PPP development and other cases for specific projects. In the case at hand, the risk allocation appears to lean slightly toward the private sector, particularly because of the significance of the risks it faces, where the public tends to hold wider risks and intervene when the need arises rather than as a matter of principle, but this allows to transfer risks that otherwise the public would have been hard-pressed to manage as a matter of economic resources and knowhow. In general, in the 2008 OECD publication "In Pursuit of Risk Sharing and Value for Money"[237] warns public institutions not to transfer risks to the private sector to the maximum extent, but rather to transfer those risks that the private sector is able to control and mitigate more efficiently, thus reducing the overall cost of them. Indeed, if there is too much transfer to the private sector, the higher the risk premium demanded by private players will be, thus increasing the cost to the public and to the overall project, undermining the cost-effectiveness of PPP versus traditional procurement.

To conclude, one study[238] demonstrated three key aspects: the first concerns the introduction of third-party capital financing, a funding competition that would help achieve better risk allocation, an aspect therefore that could help the success of a partnership and that would increase the information available to the public sector, decreasing the information asymmetry that characterizes the public sector and the private individuals involved. A funding competition is an initiative that is currently being used in the UK with the aim of finding lenders willing to finance debt, increasing competition and obtaining more advantageous debt financing terms. In this operation, the government selects a preferred bidder, i.e. the lead company that will co-ordinate the project, which, under government supervision, must seek the best price in the debt market to finance the project. Potential lenders receive information to assess whether to grant financing and by how much, which in turn will make offers to the preferred bidder. Subsequently, the latter proceeds to select the lenders under the supervision of the government, which must finally approve the choices and proceed with the project's implementation. These external funds can help to decrease adverse selection and moral hazards, since the interests of those who finance are aimed at making sure that the project meets the objectives that the public has promoted, so that the expected return on investment is achieved. The second concerns the management of consortia because, although its creation is useful since a single operator can never have the assets to build and

[236] See: https://ppp.worldbank.org/public-private-partnership/library/allocating-risks-public-private-partnerships [November 8, 2022]

[237] OECD. (2008). *Public-Private Partnerships: In Pursuit of Risk Sharing and Value for Money.* Paris: Organisation for Economic Co-operation and Development.

[238] Marty, F., & Voisin, A. (February 2008). *Partnership contracts, project finance and information asymmetries: from competition for the contract to competition within the contract?* Paris: Observatoire Francais des Conjonctures Economiques.

manage the project alone, there will be further allocation of private risks among participants depending on the management of the project phases. To avoid phenomena where private actors take advantage and have opportunistic behaviour, the process requires "back-to-back" contracts to link the main agreement with a relevant part of the subcontract. The third and final aspect relates to constant competitive pressure throughout the life of the project, which is useful for ensuring service quality and assessing whether performance is satisfactory, using tests such as benchmarking or market testing; though, these assessments may bring uncertainty regarding to transaction costs and they may adversely affect the charge for the public partner.

3.3.3.3 Risks added by hydrogen

In the case of a green hydrogen plant, the associated risks are very similar to those previously listed for the example of photovoltaics; those that can be added are related to the specific characteristics and requirements of hydrogen. Given the energy output, the safety of the plant will take on significantly more weight and consequently the project burden will increase, so the party taking responsibility for it will demand a higher risk premium than the one demanded with conventional energy sources. An additional element concerns the so-called "raw materials" of hydrogen, thus the availability of water for the electrolysis process and the need for specific materials to build the electrolysers and other components. The geographic location of the production site tends to be a responsibility of the public sector, where the latter can help to make the water supply more efficient, while the sourcing of materials for plant construction and machinery is usually a private responsibility. It is no small matter to have water as a necessary element for hydrogen production because it is a public good. The analysis that has been done on water consumption for hydrogen production suggests that there would be a simple change of use from the water currently used for conventional power plants in cooling processes to the water needed for hydrogen production considering the quantities of hydrogen to be produced. It is, however, a factor to be considered especially during periods when, for climatic reasons, this risk increases, possibly impacting the constant production of energy from it. However, from our perspective we consider energy production from hydrogen as a part of the whole energy mix in which renewables take the largest role and hydrogen contributes to energy needs where renewables find technological limits; consequently, the risk of having little water available is present but it is at a level where it can be managed by governments.

The public sector is therefore the one that will necessarily ensure the availability of water, while the private sector should guarantee the availability of the raw materials for the construction of the components related to the hydrogen production process; however, this responsibility should be shared with the public since what might occur is the presence of international trade agreements concerning raw materials. Indeed, the situation is different depending on whether companies purchase these resources or the state, through contracts between supplier and buyer countries. One reflection that could be made concerns the procurement of these materials and what kind of goods they are; if they were considered public goods as water, their management would be different and it would be up to governments to manage them, otherwise they are considered as goods to be purchased by private parties directly from the extracting countries. The solution could be found by analysing the size of the project and the required quantity of these resources: when the quantity is small, the risk of its procurement may be attributed to the private sector, but when it comes to large investments with a very high resource requirement, then the weight of the public sector, which tends to be greater, will place the responsibility for procurement in its hands. An important factor in this respect is the contribution that the circular economy model can make in this regard, by decreasing the need to source raw materials directly from third countries and by exploiting the recycling of materials already present or in the vicinity of the project's area. In fact, the international partnerships and industrial alliances that have been initiated will contribute to the creation of diversified supply routes capable of withstanding geopolitical instabilities.[239]

Moving on to consider the issue of security, flammability and possible asphyxiation in enclosed environments are two of the critical features that can have negative consequences on which responsibility must be taken. In this sense, it is likely to be expected that insurance related to hydrogen risks will increase, especially in the case of its direct use by citizens as well as by companies; the risk of explosion, the degradation of materials such as metal and steel in pipelines, the long steps to produce it that can interrupt production if a stage suffers problems are all cases where the greater the damage, the higher the price to pay for insuring or equipping oneself with risk mitigation strategies. These can be increased control and leakage detection along the entire hydrogen chain, improved materials and frequent maintenance of these, and diversification of production by creating multiple production lines to keep the plant running during the replacement of components in case a production chain breaks down. Usually, these risks are mainly the responsibility of the private sector; however, in the case of energy production plants and distribution, there is public sector involvement due to e.g., the form of ownership in a company as an interest holder through the ownership of shares, which makes the company not entirely autonomous. In addition, the efficient allocation of risks regarding security would involve the public sector through the establishment of strict technical standards and requirements to be met during all stages of hydrogen production and distribution. However, standards are currently scarce to efficiently regulate and manage the possible dangers derived from the nature of hydrogen, so it is believed that further governmental efforts are needed in this regard.

Finally, a brief addition can be made on how to calculate these risks: there are quantitative methods of risk analysis, involving a mathematical relationship (f) between severity (S) and probability (P) to determine the risk (R), giving $R=f(S,P)$, or qualitative methods, i.e. descriptive of the impact that may occur defining a hierarchical risk scale. For the evaluation of each risk, the severity and probability of a given event can be taken into account to derive the monetary value representing it, by multiplying the gravity of the loss and its likelihood with each other: $R=S x P$. For other useful measures, reference can be made to the "maximum possible loss", i.e. the largest loss in absolute value that can occur, and the "probable maximum loss", i.e. that loss which, although not necessarily large, will occur with the greatest probability.

[239] CEN-ENEA. (2022). *4th Report On Circular Economy In Italy.* Rome: Circular Economy Network. Retrieved from: https://circulareconomynetwork.it/rapporto-2022/.

3.3.3.4 Value-for-Money as the guiding principle

At the point when risks are optimally transferred, in addition to having that the costs associated with them is minimized, we will have that the Value-for-Money (VfM) of the project will be the highest. VfM is a concept related to a project's ability to create value, and several definitions can be found about it, e.g. the one in Treccani's 2012 Dictionary of Economics and Finance, which defines it as the optimal combination of capital and operating costs to achieve the best possible quality of goods or services.[240] Other definitions are coherent and show that VfM entirely encompasses the costs and quality throughout the partnership period to efficiently and effectively meet the objectives required by the intended users. Estimating value in this regard is currently difficult given the lack of an established procedure to measure it. For some, it may be a value that incorporates the entire portfolio while for others it may vary depending on the importance of individual activities undertaken by the participants[241]; however, it remains a useful principle to be followed when we talk about PPP. In order to create value, the best way is to achieve results rather than saving costs, since excessive savings if it does not bring results the value will be negligible; the quality of results is therefore a very important factor in the evaluation of VfM.[242] Indeed, the assessment is done not only to make an ex-ante decision, but also to monitor an ex-post situation during the operational phase, to carefully evaluate whether the results obtained are satisfactory and create value. In the case of an ex-ante evaluation, practice tends to associate the VfM with the net present value (PV) related to the PPP projects; however, the calculation of PV can be difficult and costly in terms of time and money, so it still remains a questionable method.[243] Therefore, it is not crucial to monetize it through cost-benefit analyses, although it may be feasible and useful as we shall see later, but it is good to describe it since it is a broad concept for promoting cooperation through PPPs[244] and to highlight quantitative and qualitative benefits that a project can generate.[245]

[240] Treccani. (2022, November 8). *Value for money - Dizionario di Economia e Finanza (2012)*. Retrieved from Treccani.it: https://www.treccani.it/enciclopedia/value-for-money_%28Dizionario-di-Economia-e-Finanza%29/

[241] Jackson, P. (May 2012). *Value for money and international development: Deconstructing myths to promote a more constructive discussion.* OECD Development Co-operation Directorate. The OECD Development Assistance Committee: www.oecd.org/dac.

[242] Ibid.

[243] Zhao, J., Greenwood, D., Thurairajah, N., Liu, H. J., & Haigh, R. (March 2022). Value for money in transport infrastructure investment: An enhanced model for better procurement decisions. *Transport Policy. Volume 118, https://doi.org/10.1*, Pages 68-78.

[244] Jackson, P. (May 2012). *Value for money and international development: Deconstructing myths to promote a more constructive discussion.* OECD Development Co-operation Directorate. The OECD Development Assistance Committee: www.oecd.org/dac.

[245] Zhao, J., Greenwood, D., Thurairajah, N., Liu, H. J., & Haigh, R. (March 2022). Value for money in transport infrastructure investment: An enhanced model for better procurement decisions. *Transport Policy. Volume 118, https://doi.org/10.1*, Pages 68-78.

Once responsibilities are well allocated among the parties, it is possible to achieve the goals with maximum VfM, ensuring that the private cost is less than the cost that would have been achieved compared to using a traditional public financing system[246], the same applies to the cost of the public sector so as to have the most efficient public spending possible.[247] It often happens that public and private sectors goals do not take into consideration the opinion of the citizens, e.g. during the creation of railways and roads for the market development that pass through environmentally critical areas; government, business and citizens set out the economic and social values of a given project for which a shared assessment should be found, although the weight of the first two parties is certainly greater and usually prevails.[248] The assumption made concerned the representation of citizens' interests by governments but this does not always reflect reality; the government also has specific interests, i.e. wanting to be elected again, interests that are partisan and not collective, or the fact that there is no protection of specific interests that affect the closest users, which brings us back to the issue of the quality of institutions as a prerequisite for a successful partnership.[249] Assessing the VfM is therefore not only about traditional value related to supply-side, characterized by optimization of cost, time, and quality, but also about demand-side, i.e., public participation, characterized for example by the type of service being provided, impact on the environment, equitable distribution of the product or service, social inclusion, and resilience of the project over time.[250]

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[246] Quiggin, J. (2004). Risk, PPPs and the public sector comparator. *Australian Accounting Review. 14. 10.1111/j.1835-2561.2004.tb00229.x.*, Pages 51-61.

[247] Zhao, J., Greenwood, D., Thurairajah, N., Liu, H. J., & Haigh, R. (March 2022). Value for money in transport infrastructure investment: An enhanced model for better procurement decisions. *Transport Policy. Volume 118, https://doi.org/10.1*, Pages 68-78.

[248] Ibid.

[249] Shrestha, A., Tamosaitiene, J., Martek, I., Hosseini, M. R., & Edwards, D. (2019). A Principal-Agent Theory Perspective on PPP Risk Allocation. *Sustainability. 11. 6455. https://doi.org/10.3390/su11226455*.

[250] Zhao, J., Greenwood, D., Thurairajah, N., Liu, H. J., & Haigh, R. (March 2022). Value for money in transport infrastructure investment: An enhanced model for better procurement decisions. *Transport Policy. Volume 118, https://doi.org/10.1*, Pages 68-78.

3.3.3.5 Value-for-Money in the PPP decision-making process

VfM is often measured by the public sector in deciding whether a project should be undertaken through a PPP or through other forms of private involvement, such as may conventionally be a public procurement in which the public entity remains responsible for the main risks of the project, including those associated with the design, construction, operation, and maintenance phases of the project. It should be pointed out that the methodology for estimating VfM is under continuous debate in the literature, and consequently there is no single agreed-upon method for arriving at the estimate of this value. Even, in some countries, such as Belgium and the Netherlands, its use can be safely neglected in the adoption of a PPP, where the calculation of VfM is optional, while in other states, such as France, its calculation is not only provided for but also mandatory by law; it is therefore clear that this is an emerging instrument that is currently not considered by all to be fundamental in the decision to use PPPs, but it can be computed to give an overview of the project and in some cases can support the implementation of the partnership.[251]

Some states such as France and Germany use more of a quantitative analysis to arrive at its value, while in the UK a mix of quantitative and qualitative analysis is preferred but starting with the latter. It is consequent to comment on the fact that there is a trade-off between these two approaches since if the quantitative part is less manipulable but with limited information, the qualitative part covers a more ample spectrum of information but is easily manipulated. In general, we start from the quantitative difference between costs and benefits supplemented by the assessment of associated risks and qualitative analysis. The perspective with which VfM is calculated can also vary; from those who see the authority as an individual entity assessing whether it is worthwhile to do a project or not depending on its interests, thus having a governmental perspective, i.e. France, and those who see its calculation from the perspective of citizens, thus giving a socio-economic perspective, i.e. UK.[252]

Before going into the value determination, it is interesting to look at the relationship between the cost and value of a project; two parameters that characterize the decision of implementing a project are the maximum supportable cost on one hand, hence a budget limit, and the minimum level of expected performance on the other, hence a minimum quality limit. Options that exceed the maximum budget even if they carry a very high value, along with options that are very frugal but cannot guarantee minimum quality, must be excluded; the solution that creates the most value is not always the optimal one, nor is the least expensive one. The options also may have different values depending on the discount rate that

[251] EPEC. (March 2015). *Value for Money Assessment - Review of approaches and key concepts.* Luxembourg: European PPP Expertise Centre: www.eib.org/epec.

[252] Ibid.

is used in the analysis given the long duration typical of projects related to infrastructures or new technologies; the real discount rate is used when forecasts of future cash flows are not indexed to inflation, otherwise the nominal discount rate is used, which will usually be higher since it includes inflation. Again, the rate may vary depending on the state undertaking the analysis; in the British case, the nominal discount rate that is stated in the EPEC report is fixed and equal to 6.09%, while in the French case the "market-based borrowing" rate is used by convention, and in the Belgian and Dutch cases the latter measure is complemented with a project specific risk premium rate. This different assumption of the discount rate leads to different impacts in case the market interest rate increases: in the case of the UK the private cost of capital will increase while the public discount rate will remain unchanged and equal to 6.09%, on the other hand in cases such as the French and Dutch the public discount rate, in addition to the private cost of capital, will also increase.[253]

By convention, to decide whether a PPP should be implemented, the comparison is between the option of a PPP and a conventional public procurement, to understand whether PPP generates a higher VfM with its execution. If we take the case of France, the computation of the VfM, as mentioned is by law part of the preliminary assessment, where for all states it is in any case calculated before or during the procurement phase, combines from a quantitative analysis the cash flows and risks in the two alternative options. The analysis begins with estimating the CapEx and OpEx cash flows to be taken by the authority, which are long-term and operating expenses, it continues with the risk assessment and ends with measuring the present value (PV) as benchmark of the VfM, determining the best solution between PPP and public procurement. Cash flows of the entire life cycle include design costs, construction costs, maintenance costs, financing costs, management costs, monitoring costs, operating costs, taxes (including VAT), public subsidies, and revenues from the activity when present for both options. In the case of a PPP there is a little rate that discounts these cash flows which represents a more coordinated and efficient negotiations and activities than the conventional procurement option. Next, the likelihood and impact of the risks associated with these movements are assessed; discrete probability distributions of risks can be used if the projects are small, otherwise a continuous probability distribution of risks and Monte Carlo simulations can be used in which a monetary value is estimated. Only after that, we move on to the qualitative analysis by explaining what non-monetary consequences may contribute to the VfM. Eventually, by applying the public discount rate, we compute and compare the two PV: if the current value of the PPP is higher, it is worth adopting the partnership, otherwise the option will be discarded due to the resulting higher costs and no added VfM.[254]

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[253] EPEC. (March 2015). *Value for Money Assessment - Review of approaches and key concepts.* Luxembourg: European PPP Expertise Centre: www.eib.org/epec.

[254] Ibid.

Summing up then, the Value-for-Money in the two options depends mainly on three differences:

1) Cost of private finance and public discount rate:
   If the cost of capital for the private partner is greater than the public discount rate, this will result in a cheaper and consequently more attractive conventional procurement option rather than PPP when other conditions are equal.
2) Assumed efficiency of PPP partners for the capital and operational expenditures.
3) Assumptions on the risk valuation through cashflows:
   If public can transfer risk to the private, this will result in a cheaper and more attractive PPP option rather than conventional procurement option.

The cost of financing assumption is a fundamental element for the VfM assessment; therefore, the risk assessment and the discount rate provide the main motivation for choosing between a PPP and a traditional procurement.[255] In conclusion, the choice of whether to adopt a PPP must thus be made on a case-by-case basis, but there are additional advantages that may help reward the choice of using it, answering the question that we can ask to ourselves:

Where does PPP create Value-for-Money?

1) Risk transfer and sharing with the private partner. (**Risk allocation** – quantitative and qualitative measurement)

2) Cost optimization along time horizon. (**Cost saving** – quantitative measurement)

3) Effective integration of public and private expertise to conduct thorough project assessments and optimize project scope. (**Union of expertise** – qualitative measurement)

4) Improved level of maintenance and services compared to traditional projects through the whole life-cycle approach. (**Monitoring along time horizon** – quantitative and qualitative measurement)

5) Acceleration of capital investments, additional funding to supplement traditional budget allocations. (**Additional financial resources** – quantitative measurement)

6) Implementation through faster completion of project phases. (**Time saving** – quantitative measurement)

Nevertheless, we would like to remain cautious about this instrument; the report on PPPs made by the European Court of Auditors[256] revealed that the potentials of the partnerships, from which VfM is created, have materialized less than expected and not many European states have sufficient experience in this assessment. Therefore, further proficiencies will be needed to make this tool widespread and able to fully exploit its potential.

[255] EPEC. (March 2015). *Value for Money Assessment - Review of approaches and key concepts.* Luxembourg: European PPP Expertise Centre: www.eib.org/epec.

[256] European Court of Auditors. (2018). *Public Private Partnerships in the EU: Widespread shortcomings and limited benefits.* Luxembourg: Publications Office of the European Union: https://op.europa.eu/webpub/eca/special-reports/ppp-9-2018/en/

3.4 Partnerships on hydrogen

3.4.1 Overview of the main collaborations

Bringing together policymakers and private companies may be the way to facilitate a cooperation and a coordination, accelerating the private sector's commitment to hydrogen, for the energy transition needed[257]; there are several cases of it, such as the contract between IRENA, as international organization, and the Hydrogen Council, which is an affiliation of investment companies, the one between IRENA and the World Economic Forum Hydrogen Toolbox, and the one concerning the World Business Council for Sustainable Development and The Sustainable Markets Initiative (SMI) of private companies. Other partnerships regarding hydrogen all around the world are already present; from the American H2USA[258], which promotes the commercial introduction and widespread adoption of hydrogen-fuelled fuel cell vehicles, the European Clean Hydrogen Partnership Joint Undertaking (CHPJU), established in November 2021 and supported by the Repower EU plan of 2022[259], that funds research and innovation for hydrogen applications[260], to the International Partnerships for Hydrogen and Fuel Cells (IPHE)[261] which counts 21 countries plus the European Commission for the commercialization of hydrogen technologies and fuel cells. Around 85% of the projects related to hydrogen power-to-gas are located in Europe, follows USA and Japan, with Germany that is already connecting hydrogen to the grid of distribution.[262] Investments on storage materials are supported by programs like the Hydrogen Materials-Advanced Research Consortium (HyMARC) and the Hydrogen Storage Characterization Optimization Research Effort (HySCORE) to intervene on the ways of storage hydrogen and lowering the cost of machineries.[263] As regards research in Italy, in addition to the co-financed project HyCARE cited in chapter 2, mention may be made of the project Hydrogen Joint Research Platform[264], started in November 2021 by a collaboration between the Milan Polytechnic Foundation universities and the Milan Polytechnic, together with the private companies Edison, Eni and Snam to develop hydrogen-related

[257] DNV. (2022). *Energy Transition Outlook 2022 - A global and regional forecast to 2050.* Oslo: DNV.

[258] See: https://www.h2usa.org/ [October 16, 2022]

[259] See: https://www.clean-hydrogen.europa.eu/index_en [October 25, 2022]

[260] See: https://wayback.archive-it.org/12090/20220602151204/https://www.clean-hydrogen.europa.eu/about-us/mission-objectives_en [October 16, 2022]

[261] See: https://www.iphe.net/partners [October 16, 2022]

[262] Yue, M., Lambert, H., Pahon, E., Roche, R., Jemei, S., & Hissel, D. (2021). Hydrogen energy systems: A critical review of technologies, applications, trends and challenges. *Renewable and Sustainable Energy Reviews 146*, 111180.

[263] Fuel Cells Technologies Office. (March 2017). *Hydrogen Storage DOE/EE-1552.* United States: U.S. Department of Energy - Energy Efficiency & Renewable Energy.

[264] See: https://www.fondazionepolitecnico.it/en/uncategorized-en/hydrogen-jrp-is-in-the-starting-blocks-ready-for-research-into-tomorrows-energy-vector-hydrogen/ [September 28, 2022]

technologies with the aim of creating a hydrogen supply chain in Italy as well. Regarding the fuel cells market is necessary a larger involvement of the public sector in partnerships that involve companies and academia to develop the supply chain of hydrogen, to better spread vehicles that firms have already produced.[265] Around three hundred companies are active in this market, having verified the economic feasibility of hydrogen fuel systems.[266] Hydrogen is also being considered for buses; an example was the European CHIC project completed in 2016, which reached 54 fuel cells buses in circulation, continued by the H2BUS EUROPE project[267], with the first phase commitment of reaching totalling 600 buses, supported by €40 million from the EU's Connecting Europe Facility, and which plans to add 20 hydrogen refuelling stations to the European hydrogen network. Furthermore, the EU Institutional Public-Private Partnership (IPPP) involves industries grouping about 130 companies 50% of which are small-medium enterprises, the research organizations gathering about 70 institutions, with a total budget of at least €1.3 billion and an EU contribution of 665 M€. Currently, under this partnership there are 244 projects for a total budget of 893 M€ divided for a 47% of the budget (418 M€) among energy projects to produce and distribute green hydrogen, to store and to integrate with renewable energies, and for fuel cells technology, while the other 42% of the budget (376 M€) is intended for transport projects regarding road vehicles, non-road vehicles and machinery, refuelling infrastructure, maritime and aviation sectors. Part of the remaining budget is for the cross-cutting projects to realize standards, safety measures, education, consumer awareness and to support the market update and fostering the commercialization of hydrogen in Europe.[268]

To conclude, the transition towards a low-carbon energy system is currently assessed by several partnerships with a significant coordination.[269] The potential of the governmental role here is to finance and support the development of projects through defined policies and responsive legal frameworks, regulations, and standards to ensure cooperation between the parties is as stable as possible with ex-ante evaluations and a relationship of trust throughout the working period.

[265] Brandon, N. P., & Kurban, Z. (2017). Clean energy and the hydrogen economy. *Phil. Trans. R. Soc. A 375: 20160400.*

[266] Yue, M., Lambert, H., Pahon, E., Roche, R., Jemei, S., & Hissel, D. (2021). Hydrogen energy systems: A critical review of technologies, applications, trends and challenges. *Renewable and Sustainable Energy Reviews 146*, 111180.

[267] See: https://www.fuelcellbuses.eu/projects/h2bus-europe [October 16, 2022]

[268] Atanasiu, M. (2019). *Public-Private Partnership on hydrogen - A European success story - #H2020Energy info days.* FCH Joint Undertaking. This document is available at: https://ec.europa.eu/inea/sites/default/files/june26-presentation_9.pdf.

[269] Brandon, N. P., & Kurban, Z. (2017). Clean energy and the hydrogen economy. *Phil. Trans. R. Soc. A 375: 20160400.*

3.4.2 The case of the Clean Hydrogen Partnership Joint Undertaking

Taking as a model the Clean Hydrogen Partnership Joint Undertaking (CHPJU) of the EU as an extensive public-private partnership, which is the successor of the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) founded in 2008, we can observe several characteristics of different projects. This PPP has the European Commission as public entity, the Hydrogen Europe as representative of industries, and the Hydrogen Europe Research as representative of the scientific community, and it has the objective to support Research and Innovation (R&I) aimed to hydrogen technologies. It is an incubator of smaller PPP; the EU will finance projects from 2021 until 2027, but several projects related to hydrogen were previously undertaken. We take as dataset the projects done and under development by the actors involved in the partnership found in the archive of the official website[270]: a sample of fifty projects in total on hydrogen until October 2022. The information we have taken are related to the start and end date of the project, thus calculating the duration, the state in which the project coordinator is located, the budget with the EU contribution, and the type of participants, whether companies, research organizations, or educational institutions. It cannot be ruled out that some end dates will be delayed because we have found that on the official website the dates for some projects are different and earlier than those listed on the specific project webpages accessible from the European CORDIS website where the funded projects can be seen.

The analysis looks at a range of information from the sample of 50 partnerships[271] to assess the private involvement and public participation in funding. Specifically, the following will be analysed:

1) Distribution of projects among EU countries
2) Started and terminated projects
3) Duration of projects
4) Project budgets
5) Project Coordinators by type
6) Project Participants by type

[270] Dataset created from: https://www.clean-hydrogen.europa.eu/projects-repository_en [October 25, 2022]

[271] More details on the projects can be found in Table 1 and Table 2 in the appendix.

3.4.2.1 Distribution of projects among EU states

In the sample taken as a reference, we can see the geographical distribution of coordinators who were or are involved in research projects for the implementation of hydrogen. 50 are the total number of projects launched from January 2010 to January 2021, while those currently active as of October 2022 are 20; we can see in the Figure 49 that in the years before 2017, the start-up of projects was fluctuating, while there has been a steady increase in the number of projects launched since then and this may bode well for the future of hydrogen.

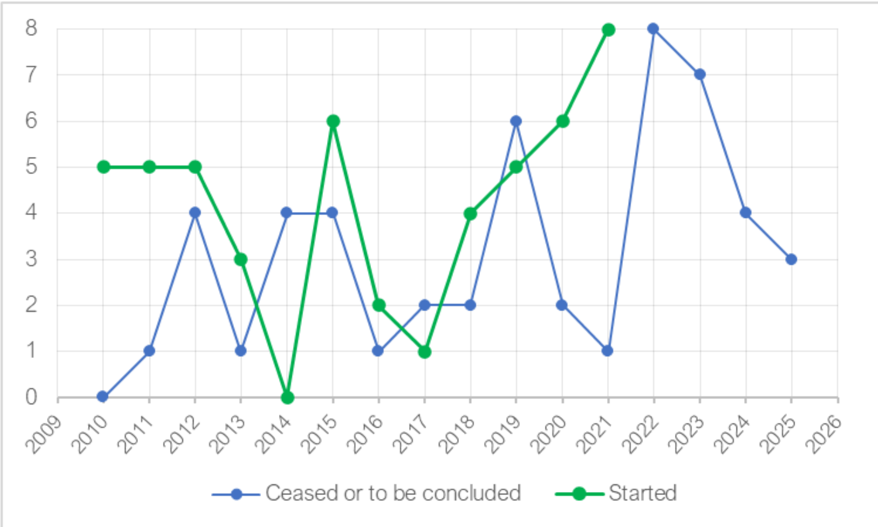

Figure 49 - Ceased and started of CHPJU projects by year. (CHPJU)

As shown in the following Figure 50, there are coordinators from fifteen different EU members where 10 projects are coordinated by Italian entities, followed by the French with 9 projects and the German with 7. Of the projects currently running, we find 6 active projects in Italy, 3 in France and Norway, 2 in Germany and Spain and 1 in Switzerland, Finland, the Netherlands and Sweden. Interesting in addition to the number of projects is the budget that follows them; indeed, as we can get in Figure 51, the most expensive project is called HEAVENN in the Netherlands, the only one in this country, with a budget of 96 191 884 €, whose European contribution, although substantial because it amounts to 20 M€, accounts for only 20.8% of the total. Germany follows, which has a total budget for all projects of 46 462 602 €, with a contribution of around 25 M€, and then France with 45 002 074 €, which, however, manages to obtain more public funds of around 32.5 M€. Compared to these two countries, Italy gets a larger European contribution with respect to the total budget, as out of a total of 35 929 663 € it covers the 75% with 26.8 M€ of public financing.

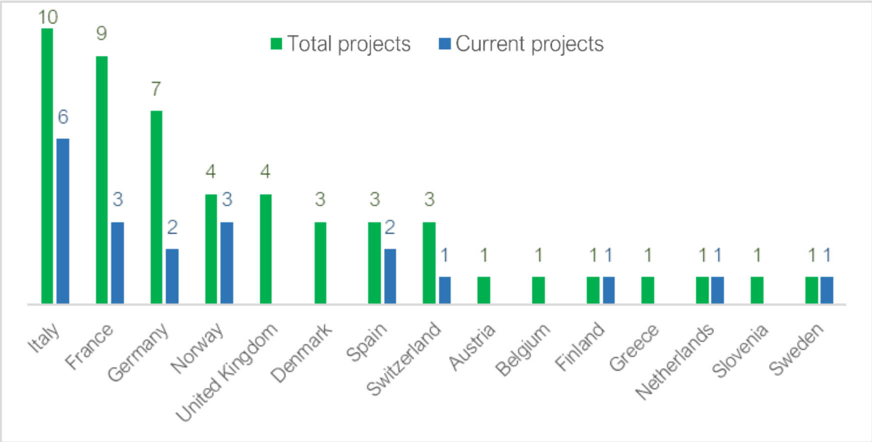

Figure 50 - Total number of CHPJU projects by nation. (Own elaboration from CHPJU)

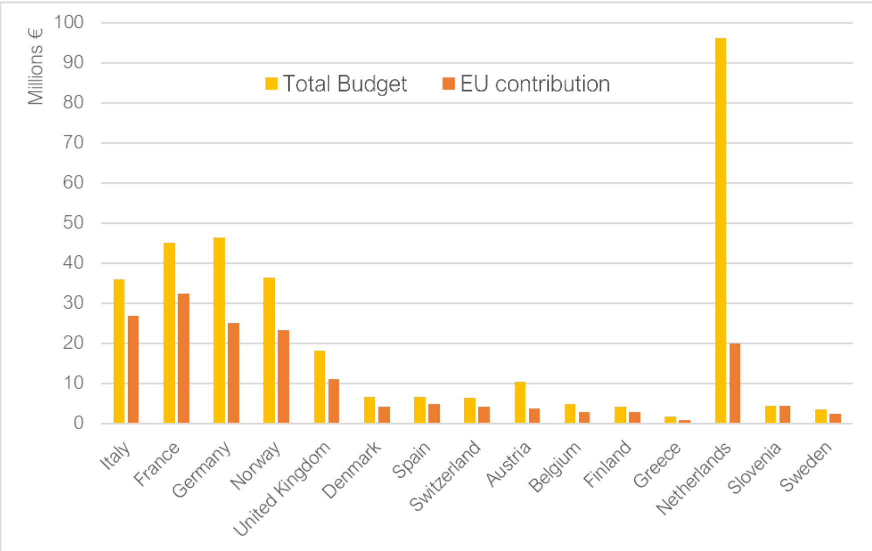

Figure 51 - Budget and public contribution of CHPJU projects by nation. (Own calculations from CHPJU)

At first sight, the Dutch project could be considered as an outlier due to its considerable difference from the other projects' budget; however, it is taken into account in the subsequent analyses since the dataset is relatively small and it is interesting to note how much a project may involve participants, affecting the budget and the public contributions received.

3.4.2.2 Budget and length

Analysing the budget specifically, from the results presented in Figure 52 we note that the range between the minimum and maximum budget for hydrogen projects is very wide, with the average amounting to 6.5 M€ and the European contribution on average covering about 73% of the total expenditure, where for quite small projects with a budget below the percentage is higher and equal to 79%, while for larger projects above the average expenditure the contribution in percentage terms is lower at 54%. The length of the projects averages 3 years and seven months and it can be seen that the ones that require a larger budget are those that on average last longer, up to 4 years and 5 months on average, and on the contrary the less expensive projects last a bit less (three months with the respect the average length). With these results, we can deduce that from a financial point of view, the public part, carried out in this case by the European Union, covers on average more than 2/3 of the total project cost, and it is likely that this high share is linked to the risk behind the investment in an innovative technology such as hydrogen. Private individuals, therefore, demand more public contributions to tackle these projects given the uncertainty of the development of a hydrogen market, but there are projects in which private individuals are more enterprising and the weight of the public funding is lower.

	Average	Median	Max	Min
Total budget	6 540 828 €	3 411 436 €	96 191 884 €	524 793 €
EU contribution	3 397 890 €	2 531 917 €	20 000 000 €	366 318 €
EU contribution %	73%	100%	100%	21%
For expensive projects	54%			
For cheaper projects	79%			
Length	3 years and 7 months	3 years and 6 months	5 years and 11 months	11 months
For expensive projects	4 years and 5 months			
For cheaper projects	3 years and 4 months			

Figure 52 - Budget, EU contribution, and length statistics for CHPJU projects. (Own calculations from CHPJU)

When we compute the median budget equal to 3 411 436 €, we note the relevance of the most expensive project, which influence the average budget increasing it, since the value is of more than 3 M€ lower than the average budget and the EU contribution covers the total investment for at least half of the ventures. For the length, instead, the value is not that different with respect to the average. In total, within this partnership, the investment on hydrogen's projects amounts to 327 041 421 € while the EU contribution is equal to 169 894 505 €, which corresponds to the 52%. However, taking the total expenditure of the Dutch Project out of the calculation, the weight of the European contribution in the total increases to 65%, making the public contribution the largest amount of the entire budget.

3.4.2.3 Coordinators and participants

Let us now turn to look at the partakers in these partnerships: as can be seen in Figure 53, the average number of entities involved in the projects is 8.22, which rounded off is 8, with projects that may have as few as 3 entities up to projects involving 35 entities between the public and private sector, while the median value of the participant is equal to 7, very close therefore to the average. For longer projects, with above average duration, the number of participants is greater than for smaller projects and equal to 10, leading to the inference that the greater the number of participants, the greater the duration of the partnership. We also analyse the proportion of EU contribution to more or less numerous projects; however, on this point we can see that the average does not deviate by even one percentage point from the overall average, which indicates that the weight of the public financial contribution is not related to the number of participants but probably more to the characteristics of the project itself.

	Average	Max	Min
Participants	8	35	3
For longer projects	10		
For shorter projects	7		
Length	3 years and 7 months	5 years and 11 months	11 months
For numerous projects	3 years and 11 months		
For small projects	3 years and 4 months		
EU contribution %	73%	100%	21%
For numerous projects	72.3%		
For small projects	73.7%		

Figure 53 - Participants, length, and public contribution statistics for CHPJU projects. (Own calculations from CHPJU)

From the CORDIS website of each project, it was possible to derive the type of activity that characterises each entity, and not directly the distinction between public and private entities, but the typology gives us an idea of the projects' involvement of private companies, research organisations, higher or secondary education establishments, public bodies and other entities that do not fall into the previous categories. Before proceeding to the analysis, it is important to distinguish between the coordinator of a project, i.e. the organisation which initiated and manages its success, and the participants who have entered into the collaboration. As the Figure 54 shows, out of the 50 projects in our sample, the type of entity that performs the coordinator function most is the research organisation; with 23 coordinated projects, it makes up 46% of the total. It is followed with 34% of initiatives made by private companies, 16% by educational institutions, and with 4% by other entities, while no public body is involved in the role of coordinator. The result is not surprising since these are projects aimed precisely at research in the development of hydrogen-related technologies, so actions starting from research organizations or universities were expected, but it is still relevant to note also the resourcefulness of private companies in implementing innovative projects regarding the emergent hydrogen.

On the other hand, the participants' situation is different; the participants[272] of all projects in the archive of the Clean Hydrogen Partnership Joint Undertaking are in total 411, and we can observe in Figure 55 a clear and greater involvement on the part of private companies, which cover 60% of the total. In this case, public bodies are also included, but they only account for 1% of the total.

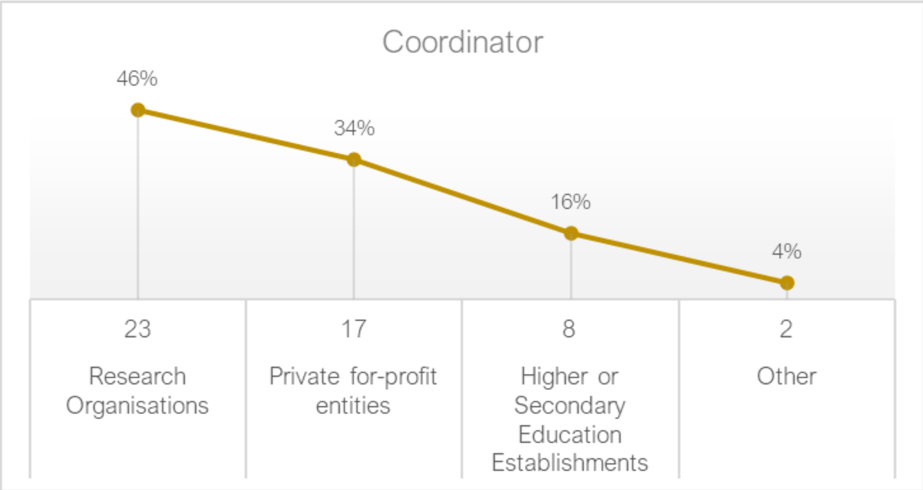

Figure 54 - Different activity type of CHPJU project's coordinator. (Own elaboration from CHPJU)

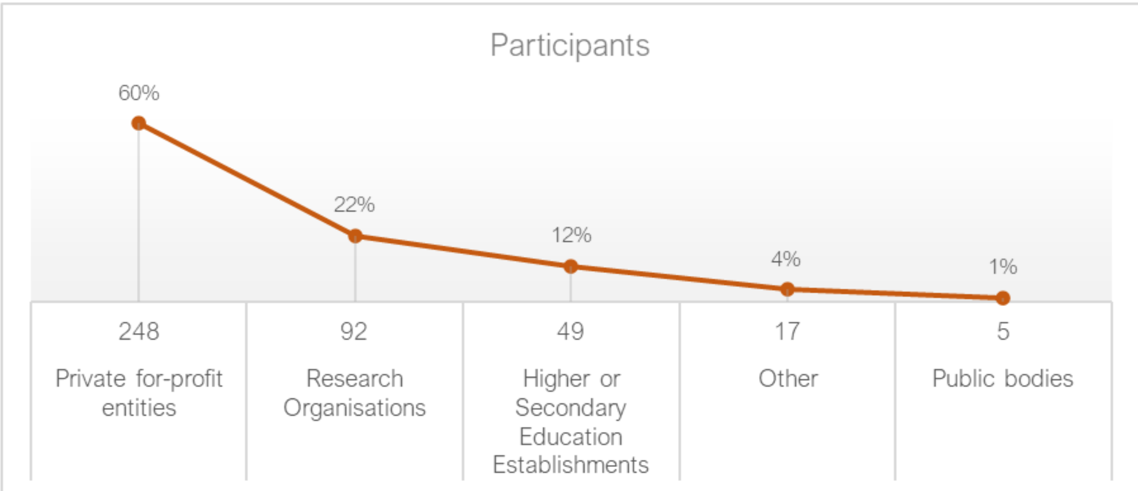

Figure 55 - Number of participants per type in CHPJU projects. (Own elaboration from CHPJU)

[272] In the participants are included third parties, i.e. "Legal entity other than a subcontractor which is affiliated or legally linked to a participant. The entity carries out work under the conditions laid down in the Grant Agreement, supplies goods or provides services for the action, but did not sign the Grant Agreement. A third party abides by the rules applicable to its related participant under the Grant Agreement with regard to eligibility of costs and control of expenditure." (CORDIS)

Curiously in Figure 56, we notice that although research organisations coordinate 46% of the projects the proportion of participants involved is equal to 39%, with an average of 7 participants per projects. Ventures coordinated by companies involve 31% of the participants, with an average of 8 members, followed by projects run by education establishments which account for 18% of the participants, more than the share of projects equal to 16%, with an average of 9 participants, while the remaining projects coordinated by other types of organisations involve 12% of the participants, but with an average of as many as 25 participants. To give an example of the "other" type, in the case of HEAVENN project the coordinator is a network that connects companies, institutions and NGOs called New Energy Coalition. Eventually, other entities can reach a much wider audience of participants with respect to the other coordinators' type, the education establishments are also capable to involve lots of subjects in their projects while research organizations and private companies maintain a less extensive collaboration.

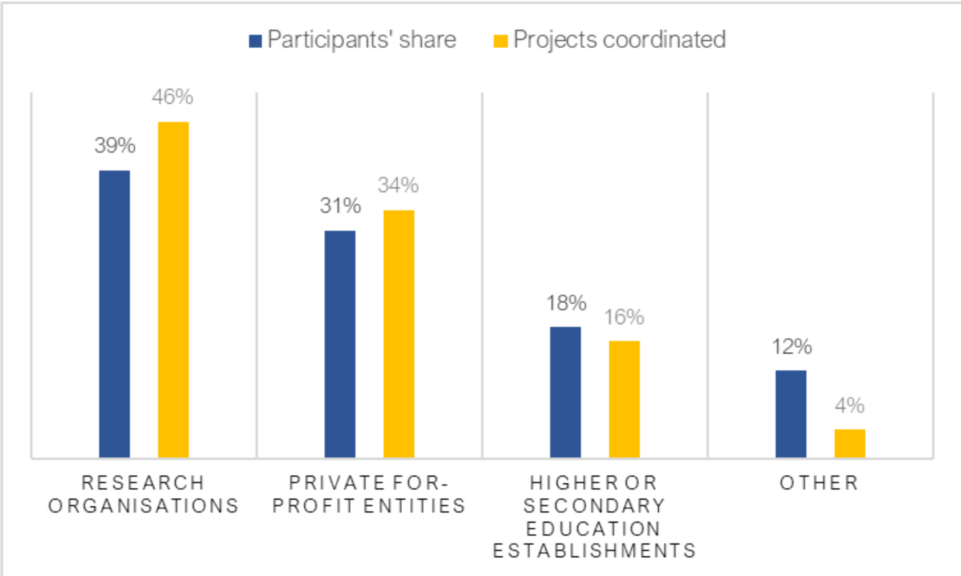

Figure 56 - Proportion of participants involved, and percentage of CHPJU projects coordinated by type.

Moreover, as can be seen in Figure 57, if we look specifically to the typology of partners divided by colours for each type of coordinator, we appreciate that the participation of private companies is the highest for all types of coordinators. We can see that it is higher in projects managed by research organisations and other entities, while it is lower but still above 50% in the case of coordinators such as education establishments and private companies. It is interesting to note that the involvement of research organisations is higher in projects coordinated by education establishments, 36%, and lower for others, 8%, while it is about the same for projects coordinated by private companies and research organisations themselves, which is about 20% of the total. For projects coordinated by others, the vast majority include private participants; however, this category includes the large Dutch project involving 35 different entities, which therefore has a major impact on the outcome of this category.

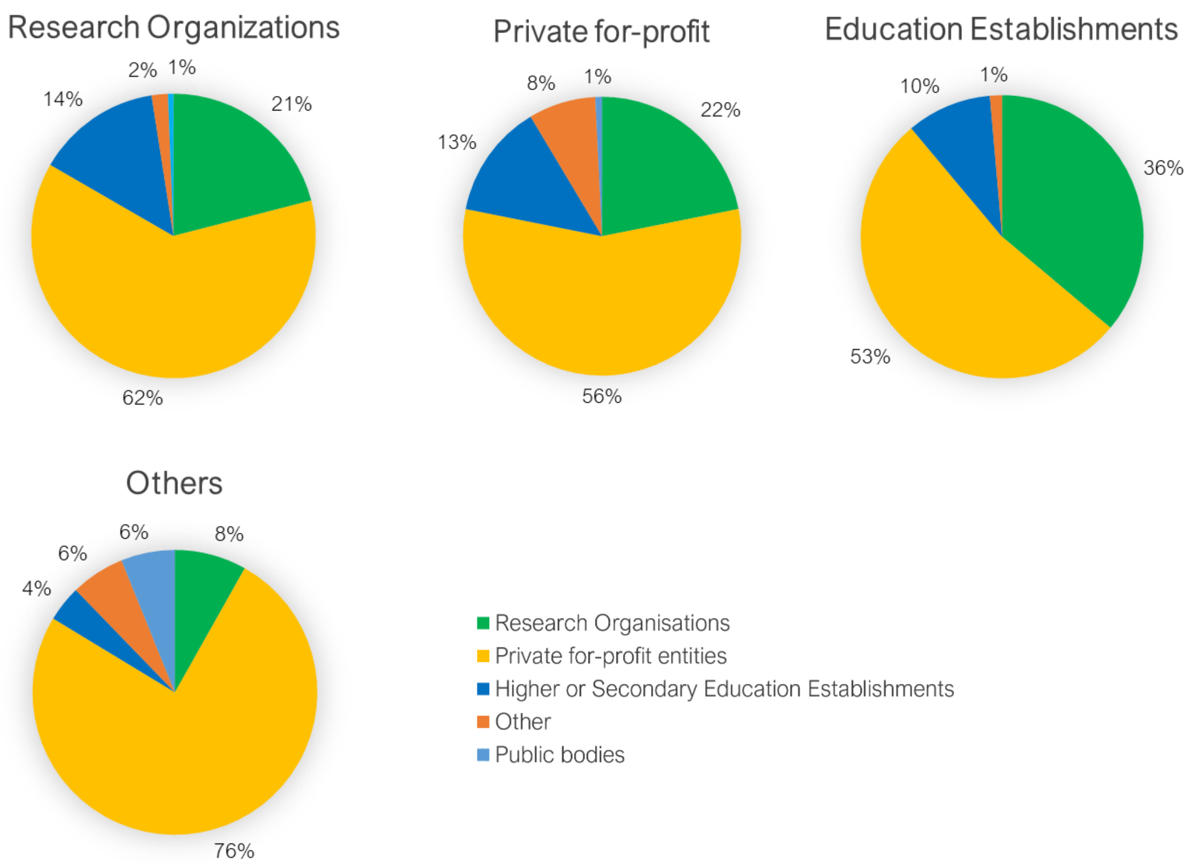

Figure 57 - Colours for the typology of the partners for each type of coordinator in CHPJU projects.

Public bodies are the less involved, only the coordination made by other entities is higher than one percent and equal to 6%. The participation of the education establishments is between 10 to 14% apart from the projects coordinated by others which is equal to 4%. What can be concluded from this data is that the largest financial contribution is made on the public side while the involvement is greater on the private side, confirming the argument that partnerships are a good instrument to engage the private sector. However, the initiative remains mainly on the public side, confirming a general uncertainty of the private sector towards hydrogen, since the amount of EU contribution suggests a risk-taking position by the institution in order to convince companies to participate, but with cases in which the private initiative can far exceed the public one, e.g. the Dutch project. This form of joint participation is therefore relevant to the development and deployment of a new type of energy such as hydrogen. Further analysis can be done over time to assess the developments of these projects and the returns that can be achieved through this type of collaboration.

Chapter 4 – The prospects for hydrogen

4.1 Forecasts and trends

Hydrogen is almost forthcoming in the main areas of its application; according to the 2019 roadmap of the then European Fuel Cells and Hydrogen 2 Joint Undertaking[273], hydrogen will be present, at least in part, in all sectors of its application from 2025. In Figure 58 are illustrated the predictions made for the market entry of hydrogen: only for urban transport buses is large-scale daily use expected, while for the other transports the waiting will be longer before seeing hydrogen as a real fuel alternative. The coloured bars in figure indicate the start of the commercialization of hydrogen in each sector, white triangles specify the date when daily hydrogen use is expected in the event that current policies proceed but no further initiatives are started (Business-as-usual scenario), while the dark triangles show a possible ambitious scenario based on the outlook made by the Hydrogen Council regarding joint investments between industries and policymakers, accelerating the introduction of hydrogen where currently possible. For instance, in the case of medium and large cars is seen that the use of hydrogen-powered vehicles will become customary only after 2045 with the business-as-usual scenario; however, the chance of having an acceptable mass market for hydrogen-based transportation could be achieved as early as 2025. Small cars instead, have a longer time horizon given that the direct electrification of the vehicle is evidently convenient, while it is surprising to see so late the arrival of hydrogen to move planes and ships since they are considered hard-to-abate sectors in which the effort should be amplified. The same applies to those industries, such as those related to steel production, which could potentially already use hydrogen in their industrial processes as feedstock, whereas much more time is expected for industry heat, the thermal energy directly used to create manufactured goods, where the amount of energy required at present is met through fossil fuels, and in any case the time to build a solid infrastructure must be taken into account. Indeed, while here the transition should be more in demand since it is the sector that pollutes the most with more than 3,000 TWh of energy consumption per year, it is expected that in the total energy consumption hydrogen could cover only 240 TWh by 2050 in industry sector, which is the 8%. Eventually, having hydrogen for power generation with fuel cells depends on the technologies which can potentially become widespread around 2030, while for the heating process in buildings there are already cases of energy mixes partly using hydrogen and projects regarding the full usage of hydrogen which are under development that could anticipate everyday use.[274]

[273] Fuel Cells and Hydrogen 2 Joint Undertaking (2019). *Hydrogen roadmap Europe - A sustainable pathway for the European energy transition.* EU publication. DOI 10.2843/341510.

Fuel Cells and Hydrogen 2 Joint Undertaking ceased operations on 29 November 2021. It is succeeded by the Clean Hydrogen Partnership Joint Undertaking, established on 30 November 2021.

[274] See: https://www.sgn.co.uk/H100Fife and https://hydeploy.co.uk/project-phases/ [November 1, 2022]

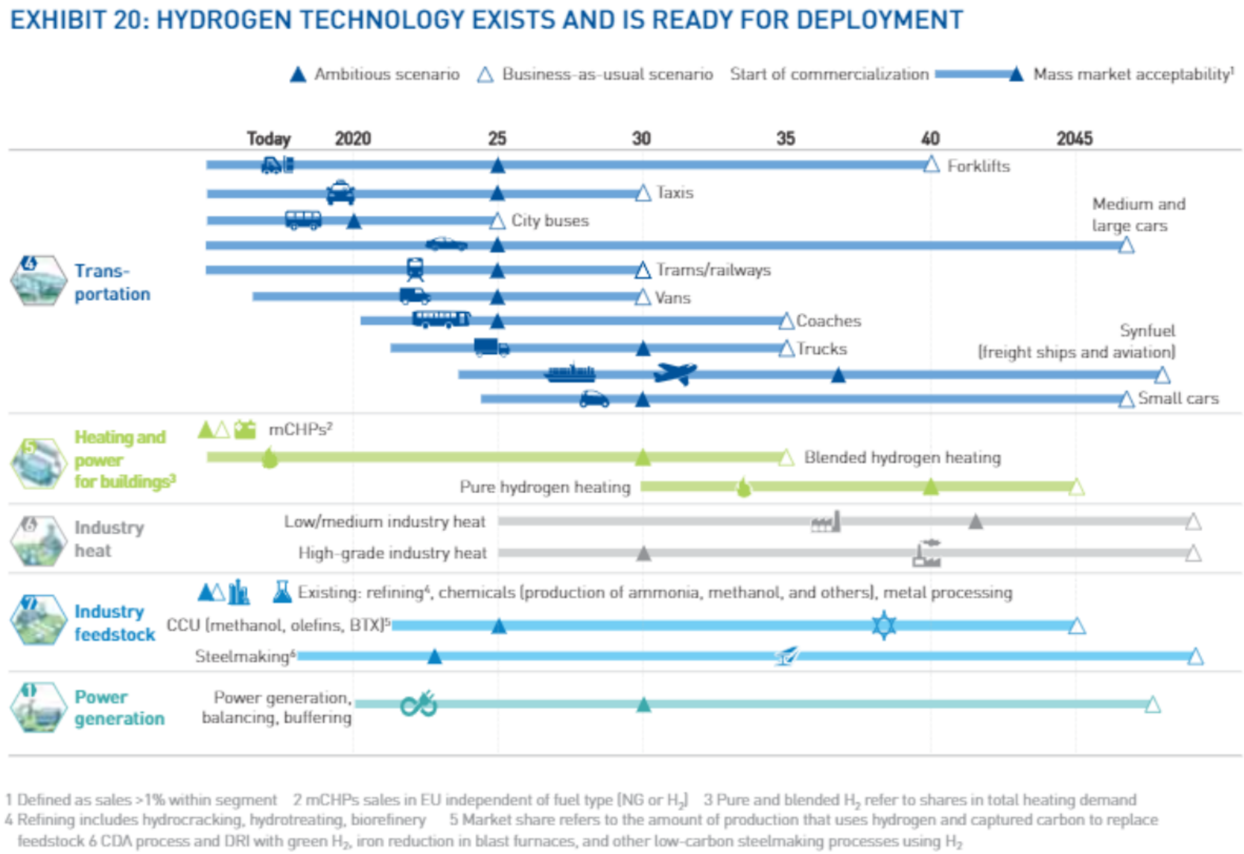

Figure 58 - Different scenarios for hydrogen's deployment in several sectors. (Former CHPJU)

From the global energy perspective of McKinsey[275] we can perceive how the forecast in fact leans more toward a stable scenario rather than an ambitious one: as depicted in Figure 59, 50% of energy consumption is projected to be covered by renewables and hydrogen, with the latter counting only 1/4 the share of renewables but still expected to exceed the share of methane gas. It is also interesting to notice how the forecast changes after only a few years; if we take as a reference the same report published in 2019[276], we see that the information contained within it do not take hydrogen into account in future energy consumption merely saying that as long as prices remain above $3.5/kg there will be no room, but that it can be important in a mix of blue and green hydrogen to meet climate goals and to decarbonize the hard-to-abate sectors. This suggests that we are living through uncertain years in which if at present there is no concrete evidence of the widespread use of hydrogen, we will probably see the beginning of its expansion; a few years can really be decisive, it only takes a few conditions to change the outcome of a report starting with the cost of production, the price of other fuels on the market, and ending with the large-scale implementation of hydrogen.

[275] McKinsey & Company. (2022). *Global Energy Perspective 2022 - Executive Summary.* McKinsey Global Institute. https://www.mckinsey.com/industries/oil-and-gas/our-insights/global-energy-perspective-2022.

[276] McKinsey & Company. (2019). *Global Energy Perspective 2019.* McKinsey Global Institute. https://www.mckinsey.com/industries/oil-and-gas/our-insights/global-energy-perspective-2019.

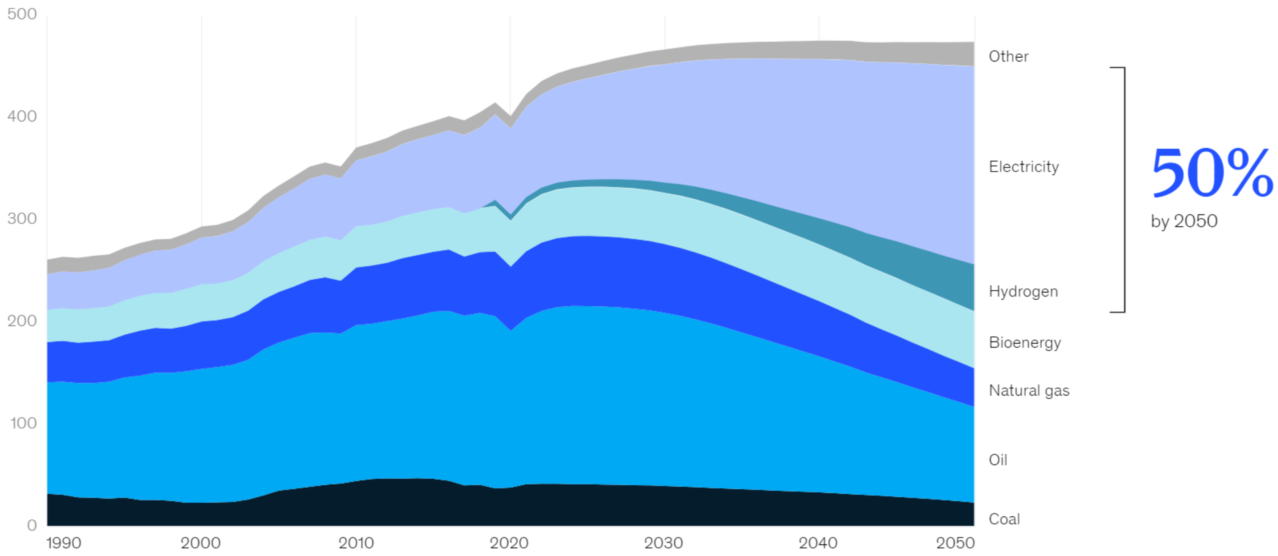

Figure 59 - Final energy consumption per fuel in million terajoule (TJ). (McKinsey)

Either way, hydrogen is projected to grow the most, with a compound annual growth rate in the 2019-2050 period of 6.5%, while for renewables it will be 2.8%, and it is thus projected to be the largest contributor of additional energy in the period between 2035 and 2050 due to its use and the ability to store energy as an alternative to electricity. Finally, it can be seen that the final energy consumption will find a stabilization at a level of 14% higher than today around 2040[277]; it could be decisive condition since with constant consumption, rather than having an increasing situation as from 1990 to 2019, there is a greater capacity to meet demand through a transition from fossil sources to electricity and hydrogen. Moreover, this trend is supported by the statement that the energy consumption per person would be lower and equal to 97 Gigajoules per year in 2050, while nowadays is equal to 121[278], despite economic growth and a growing population at least during the time horizon of hydrogen's diffusion; in Europe the GDP per capita was 38 800$ in 2017 and is expected to be 57 500 equivalent dollars in 2050[279], while predictions for population's trend are made by Our World in Data[280] which show that currently the earth population is growing at less than 1% and is not likely to exceed this increase, in a low fertility scenario we could reach zero growth in 2053 and begin a slow decline, with a medium fertility scenario we would reach it in 2086 and then decline, and with a high fertility scenario we would be left with a steady increase of about 0.6%.

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[277] McKinsey & Company. (2022). *Global Energy Perspective 2022 - Executive Summary.* McKinsey Global Institute. https://www.mckinsey.com/industries/oil-and-gas/our-insights/global-energy-perspective-2022.

[278] DNV. (2022). *Energy Transition Outlook 2022 - A global and regional forecast to 2050.* Oslo: DNV.

[279] Ibid.

[280] See: https://ourworldindata.org/explorers/population-and-demography?facet=none&hideControls=true&Metric=Population+growth+rate&Sex=Both+sexes&Age+group=Total&Projection+Scenario=Medium&country=~OWID_WRL [October 27, 2022]

4.2 Hydrogen's momentum

Today, hydrogen is produced and guaranteed with the participation of governments, that is why we have emphasised the role of public-private partnerships so that private companies and citizens can enjoy the benefits of hydrogen as soon as possible. The impetus from the private and public sides is gaining momentum, with the number of activities and initiatives growing both in Europe and the rest of the world.[281] In addition to the projects mentioned previously, there are many other initiatives to follow around the world, such as the world's currently largest hydrogen production plant in Japan by size, the Fukushima Hydrogen Energy Research Field (FH2R)[282], covering 180 000 m^2 of floor space and capable of producing up to 1 200 cubic metres of hydrogen every hour, 200 tons per year[283], which is an amount that according to the Japanese government is capable of powering 150 homes for a month or alternatively recharging around 560 fuel cell vehicles. The largest plant by production currently operating is located in Germany and is the Hyways for Future, with 1095 tons per year of hydrogen produced. These are still small values that will surely be increased with further installations; however, they show the willingness of local and national governments to open up the prospects towards this resource. The European Union is gearing up for hydrogen production with the creation of other so-called "Hydrogen Valleys" publicly and privately funded, which according to the Clean Hydrogen JU report[284] are set to increase the total production over time with the goal of reaching 10 million tons of green hydrogen produced. The perspective is to have hydrogen accounting for 13-14% of the energy mix by 2050[285] across Europe, thus an important help to achieve carbon neutrality. Governments and industries are going through a phase of great collaboration and investment, through technology development and lowering costs, to make it possible within a few years to introduce hydrogen on a large scale for the mobility, industry, and energy sectors.

In addition, investing on the reduction of CO_2 does not bring a negative economic growth; indeed, according to the article from Our Word in data[286] made in 2021 on carbon price the major

[281] International Energy Agency. (2022). *Global Hydrogen Review 2022.* Retrieved from IEA: https://iea.blob.core.windows.net/assets/c5bc75b1-9e4d-460d-9056-6e8e626a11c4/GlobalHydrogenReview2022.pdf.

[282] See: New Energy and Industrial Technology Development Organization (NEDO). https://www.nedo.go.jp/english/news/AA5en_100422.html [November 1, 2022]

[283] Weichenhain, U., Kaufmann, M., Hölscher, M., & Scheiner, M. (August 2022). *Going Global - An update on Hydrogen Valleys and their role in the new hydrogen economy.* Luxembourg: Publications Office of the European Union.

[284] Ibid.

[285] European Commission, Directorate-General for Energy. (08/07/2020). *Communication from the commission to the european parliament, the council, the european economic and social committee and the committee of the regions - A hydrogen strategy for a climate-neutral Europe.* Brussels: Document 52020DC0301. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52020DC0301.

[286] Roser, M. (2021, June 1). *The argument for a carbon price*. Retrieved from Our World in Data: https://ourworldindata.org/carbon-price

economies which reduced the emissions also achieved an economic growth from the period between 2005 and 2019. France, for example, increased GDP by 18% despite a 22% reduction in CO2 emissions, Germany with a 24% increase in GDP managed to reduce emissions by 21%, the UK the same reduced emissions by 28% followed by a 22% increase in GDP. In Europe, Ireland is the most virtuous example with a 42% decrease in emissions and an 81% increase in GDP. These results support the fact that investing in cleaner technologies such as hydrogen that reduce emission levels does not necessarily mean degrowth; the focus of this period should break away from the idea of growth and focus on the idea of conversion to an energy-sustainable civilization.

Attention must also be paid to the way in which these projects are financed; the use of common debt can be an excellent tool for the development of the economy, but it should not be considered as the main instrument to be used. Investing common resources is crucial for the energy transition and part of public financing is done through the debt system: the European commission, in order to finance the NextGenerationEU plan from which the funds for projects related to the energy transition come, use a diversified funding strategy that includes borrowing on the financial markets to cover about 30% of the total budget under the plan.[287] This was also made possible by the fact that the interest rates underwritten are lower than what individual European states would have obtained, as a larger and more solid institution such as the Union becomes an advantage in such cases. In general, indeed, an excessive increase in debt can slow down economic growth, therefore strict control of its level is vital[288], as it is also important to consider that public debt has a negative impact on public investment[289]; consequently, institutions that go beyond national debts already substantial, such as the European Union, can be crucial in the possibility of financing risky projects such as hydrogen-related ones, but always keeping the control on the instrument of debt. We would like to conclude with a quote from Carlos Alvarez Pereira, Vice President of the Club of Rome, which sums up the concept of debt as a form of financing, but which can be read as a debt we owe to the climate and which we must repay.

> *"What the system has done, as a mechanism to keep growing at all costs, is to burn the future. And the future is the least renewable resource. […] And by building an increasingly debt-oriented system - where we continue to consume, but create more and more debt - what we are doing is burning or stealing the time of posterity. Because their time will be spent repaying the debt."*

Carlos Alvarez Pereira – Wired US interview, 2022 July 6.

[287] See: https://ec.europa.eu/info/strategy/recovery-plan-europe_en & https://ec.europa.eu/info/strategy/eu-budget/eu-borrower-investor-relations_en

[288] Onofrei, M., Ionel, B., Firtescu, B., Roman, A., & Rusu, V.-D. (2022). Public Debt and Economic Growth in EU Countries. *Economies*, 10. 254. 10.3390/economies10100254.

[289] Kostarakos, I. (2021). Public debt and aggregate investment in the EU. *Applied Economics Letters*, 29. 1-7. 10.1080/13504851.2021.1931655.

Conclusions

Hydrogen-derived energy is no longer a mirage but a new frontier. We are essentially talking about green hydrogen, produced through sustainable methods excluding all other options for its production. In recent years it has been limited for reasons related to the cost of electrolysis and practicality of use due to lack of infrastructure for distribution, especially in the transport sector; however, projects and research are increasing in these areas, aiming to pave the way for the widespread use of hydrogen. Among the major benefits is the reduction of CO_2 emissions and the possibility of having energy untied from the extractive dependence of third countries, while still creating a manageable dependence to obtain the raw materials needed to build the foundations of an energy system ranging from renewables to hydrogen. We are aware that hydrogen will not be the future primary energy source; indeed, an integrated energy system exploiting the potential of renewables and generating hydrogen when they are unable to distribute or store energy, is ideal.

In this paper, it was found that currently the total cost of deriving its energy is comparable with those of commercial natural gas, especially in Italy, showing that the switching price, which takes into account the value of emissions, indicates a situation of parity between the use of methane and hydrogen, and that this will be the case also for fossil fuels in the future. We have seen that the value of shadow price for pollutant could be significant in the decision-making process; we have also observed that the value of emissions is strongly linked to climate goals, so if global temperatures are to be kept below a certain threshold, emissions prices will necessarily have to rise. Indeed, to date its value is underestimated because it refers to individual policies such as the carbon tax or the price on the European CO_2 market, which should hopefully represent the value in its totality. What the public side could do further to incentivize this switch is by adjusting directly these prices or by using other tools that allow for comparable prices; one proposal being made is to use the switching price as indicator for a bonus to be offered to those who switch from a certain fossil fuel to hydrogen, or a tax for those who decide to continue using them, or a mixed system.

Compared to other fuels, green hydrogen can already be cost-effective as direct energy, whereas in the transport sector we have seen that a longer time horizon must be considered. A broader hydrogen economy is also required because, despite its competitiveness, it will never be widespread in the absence of an adequate infrastructure for its transport and storage in liquid or gaseous form that makes it available to companies and citizens. In this regard, hydrogen is still being regulated at the international level, given the few standards currently in place, but its use can be pushed forward with the help of Public-Private Partnerships, highlighting the role that the public and private sectors play in developing technologies and infrastructure. The potential of these alliances can generate value that justifies their use, particularly through the ability to allocate risks that can be taken in all phases of a project efficiently among the parties. Risk allocation is an important advantage brought by the PPP to minimise the costs and maximise the value of the project, and therefore a key part of assessing the ability of hydrogen to enter the energy market. The private sector retains the most important risks, especially in relation to their potential impact; consequently, the public sector must bear part of these risks in order to avoid not only opportunistic behaviour caused by asymmetric information but also to grant more funds than would be necessary to cope with the risks. Other potentials derived from the PPP compared to a conventional public procurement are the union of expertise, the capability to monitor partners along the time horizon, time and cost saving and management of financial resources. Currently there are initiatives to undertake these shared projects that concern the development of the technologies needed for hydrogen and related to its direct production, in which the public side plays a leading role in promoting them especially at the European level and in which we have verified that they are really able to involve the private sector, making it a key player in their implementation.

This work has realized that hydrogen in the current context is feasible and must be realized now to prevent it from remaining a hope and becoming a reality in a context of economic development and environmental protection. Today, renewables and hydrogen are a concrete action to be taken, especially by governments representing the most developed economies. The role of PPP is in force and should be increased overcoming its main obstacles by making processes and participation as transparent as possible, improving the ability to benefit from its potential to secure technologies and build a hydrogen network, arriving at an economic and energy system also based on hydrogen. The economic feasibility has changed in a short time favouring the concrete possibility of investing in hydrogen, now greater political willingness can involve economic actors to initiate a radical change in the way we produce and consume energy.

Appendix

Dataset of projects started within the Clean Hydrogen Partnership Joint Undertaking.

(From January 2010 to October 2022 - sample of 50 observations)

Table 1 - General information on 50 projects on hydrogen research and innovation made by CHPJU.

Project	*Coordinator*	*Participants (coordinator excluded)*	*Starting date*	*Ending date*	*Length in months*	*Location*	*Budget €*	*EU contribution €*	*EU contribution %*
SO-FREE	Research Organisations	9	01-Jan-21	31-Aug-24	43	Italy	3045360	2739090	89.94%
SHERLOHCK	Research Organisations	6	01-Jan-21	31-Dec-23	35	France	2563320	2563320	100.00%
SH2E	Research Organisations	6	01-Jan-21	30-Jun-24	41	Spain	2142780	1997620	93.23%
eGHOST	Research Organisations	5	01-Jan-21	31-Dec-23	35	Spain	1133540	998991	88.13%
E2P2	Research Organisations	7	01-Jan-21	30-Sep-24	44	Sweden	3521480	2499720	70.98%
COSMHYC DEMO	Research Organisations	5	01-Jan-21	31-Dec-23	35	Germany	3773860	2999640	79.48%
CoacHyfied	Private for-profit entities (ex	15	01-Jan-21	31-Dec-25	59	Germany	7329180	4999440	68.21%
BEST4Hy	Private for-profit entities (ex	8	01-Jan-21	31-Dec-23	35	Italy	1586020	1586020	100.00%
RoRePower	Research Organisations	5	01-Jan-19	31-Dec-23	59	Finland	4220093	2999190	71.07%
RUBY	Higher or Secondary Educati	12	01-Jan-20	31-Dec-24	59	Italy	2999715	2999715	100.00%
ShipFC	Other	14	01-Jan-20	31-Dec-25	71	Norway	13179056	9975477	75.69%
SWITCH	**Research Organisations**	7	01-Jan-20	31-Dec-22	35	Italy	3746754	2992521	79.87%
THOR	Private for-profit entities (ex	11	01-Jan-19	30-Sep-22	44	France	2884330	2853958	98.95%
THyGA	Private for-profit entities (ex	8	01-Jan-20	31-Dec-22	35	France	2468826	2468826	100.00%
VIRTUAL-FCS	Research Organisations	9	01-Jan-20	31-Dec-22	35	Norway	1897806	1897806	100.00%
WASTE2GRIDS	Higher or Secondary Educati	3	01-Jan-19	31-Dec-20	23	Switzerland	528750	528750	100.00%
WASTE2WATTS	Higher or Secondary Educati	10	01-Jan-19	31-Mar-23	50	Switzerland	1681602	1681602	100.00%
REFHYNE	Research Organisations	6	01-Jan-18	31-Dec-22	59	Norway	19759516	9998043	50.60%
Haeolus	Private for-profit entities (ex	5	01-Jan-18	31-Mar-22	50	Slovenia	4387063	4387063	100.00%
REFLEX	Research Organisations	9	01-Jan-18	31-Dec-22	59	France	2999575	2999575	100.00%
REMOTE	Higher or Secondary Educati	14	01-Jan-18	30-Jun-23	65	Italy	6740031	4995950	74.12%
HEAVENN	Other	35	01-Jan-20	31-Dec-25	71	Netherlands	96191884	20000000	20.79%
HyCARE	Higher or Secondary Educati	9	01-Jan-19	31-Dec-22	47	Italy	1999230	1999230	100.00%
VOLUMETRIQ	Research Organisations	8	01-Sep-15	31-Aug-19	47	France	4988450	4961950	99.47%
HyBalance	Private for-profit entities (ex	7	01-Oct-15	30-Sep-20	59	France	15803441	7999371	50.62%
HPEM2GAS	Research Organisations	6	01-Apr-16	30-Sep-19	41	Italy	2654250	2499999	94.19%
AutoRE	Private for-profit entities (ex	9	01-Aug-15	30-Apr-19	44	United Kingdo	4464447	3496947	78.33%
ELYntegration	Research Organisations	5	01-Sep-15	31-May-19	44	Spain	3301391	1861309	56.38%
HySEA	Private for-profit entities (ex	6	01-Sep-15	30-Nov-18	38	Norway	1511780	1494780	98.88%
ECo	Higher or Secondary Educati	9	01-May-16	30-Apr-19	35	Denmark	3239138	2500513	77.20%
COSMHYC	Research Organisations	5	01-Jan-17	28-Feb-21	49	Germany	2496830	2496830	100.00%
SCORED 2.0	Higher or Secondary Educati	6	01-Jul-13	30-Jun-17	47	United Kingdo	3656760	2183020	59.70%
HYAC	Private for-profit entities (ex	4	01-Oct-13	30-Sep-14	11	Denmark	737920	497129	67.37%
H2REF	Research Organisations	7	01-Sep-15	31-Dec-19	51	France	7127941	5968554	83.73%
ONSITE	Research Organisations	7	01-Jul-13	30-Sep-17	50	Italy	5571479	3012038	54.06%
DESTA	Private for-profit entities (ex	4	01-Jan-12	30-Jun-15	41	Austria	10441619	3874272	37.10%
TOWERPOWER	Private for-profit entities (ex	4	01-Nov-11	31-Oct-14	35	United Kingdo	9403106	4936631	52.50%
Don Quichote	Private for-profit entities (ex	8	01-Oct-12	31-Mar-18	65	Belgium	4936805	2954846	59.85%
MATHRYCE	Research Organisations	7	01-Oct-12	30-Sep-15	35	France	2446373	1296249	52.99%
EURECA	Research Organisations	8	01-Jul-12	31-Aug-15	37	Germany	6299714	3557293	56.47%
EDEN	Research Organisations	6	01-Oct-12	30-Jun-16	44	Italy	2653574	1524900	57.47%
H2moves Scandinavia	Private for-profit entities (ex	9	01-Jan-10	31-Dec-12	35	Germany	18731663	7732503	41.28%
PrimoLyzer	Private for-profit entities (ex	5	01-Jan-10	30-Jun-12	29	Denmark	2619754	1154023	44.05%
HYDROSOL-3D	Research Organisations	4	01-Jan-10	31-Dec-12	35	Greece	1729085	984375	56.93%
HyGuide	Private for-profit entities (ex	4	01-Oct-10	30-Sep-11	11	Germany	524793	366318	69.80%
HyLIFT-DEMO	Private for-profit entities (ex	9	01-Jan-11	30-Jun-14	41	Germany	7306562	2877294	39.38%
HyQ	Research Organisations	14	01-Mar-11	28-Feb-14	35	France	3719818	1385219	37.24%
FC-EuroGrid	Higher or Secondary Educati	9	01-Oct-10	31-Dec-12	26	United Kingdo	805931	588982	73.08%
ADEL	Private for-profit entities (ex	12	01-Jan-11	31-Dec-13	35	Switzerland	4155776	2043518	49.17%
CoMETHy	Research Organisations	11	01-Dec-11	31-Dec-15	48	Italy	4933250	2484095	50.35%

Table 2 - Typology of the participants and relative coordinator for each project of CHPJU.

	Participants						
Project	Research Organisations	Private for-profit entities (excluding Higher or Secondary Education Establishments)	Higher or Secondary Education Establishments	Other	Public bodies (excluding Research Organisations and Secondary or Higher Education Establishments)	Total	*Coordinator*
SO-FREE	1	6	1	1	0	9	Research Organisations
SHERLOHCK	0	3	3	0	0	6	Research Organisations
SH2E	4	2	0	0	0	6	Research Organisations
eGHOST	3	1	1	0	0	5	Research Organisations
E2P2	0	7	0	0	0	7	Research Organisations
COSMHYC DEMO	1	3	0	0	1	5	Research Organisations
CoacHyfied	0	13	2	0	0	15	Private for-profit entities (exc
BEST4Hy	2	6	0	0	0	8	Private for-profit entities (exc
RoRePower	0	5	0	0	0	5	Research Organisations
RUBY	5	4	3	0	0	12	Higher or Secondary Educati
ShipFC	2	10	1	1	0	14	Other
SWITCH	3	4	0	0	0	7	Research Organisations
THOR	4	4	3	0	0	11	Private for-profit entities (exc
THyGA	3	3	0	2	0	8	Private for-profit entities (exc
VIRTUAL-FCS	0	5	4	0	0	9	Research Organisations
WASTE2GRIDS	1	1	1	0	0	3	Higher or Secondary Educati
WASTE2WATTS	3	6	1	0	0	10	Higher or Secondary Educati
REFHYNE	1	5	0	0	0	6	Research Organisations
Haeolus	1	3	1	0	0	5	Private for-profit entities (exc
REFLEX	1	6	2	0	0	9	Research Organisations
REMOTE	3	11	0	0	0	14	Higher or Secondary Educati
HEAVENN	2	27	1	2	3	35	Other
HyCARE	4	5	0	0	0	9	Higher or Secondary Educati
VOLUMETRIQ	0	7	1	0	0	8	Research Organisations
HyBalance	0	6	0	1	0	7	Private for-profit entities (exc
HPEM2GAS	0	5	1	0	0	6	Research Organisations
AutoRE	2	5	2	0	0	9	Private for-profit entities (exc
ELYntegration	2	2	1	0	0	5	Research Organisations
HySEA	0	2	4	0	0	6	Private for-profit entities (exc
ECo	4	4	1	0	0	9	Higher or Secondary Educati
COSMHYC	1	4	0	0	0	5	Research Organisations
SCORED 2.0	2	3	1	0	0	6	Higher or Secondary Educati
HYAC	1	2	0	0	1	4	Private for-profit entities (exc
H2REF	0	6	1	0	0	7	Research Organisations
ONSITE	0	5	1	1	0	7	Research Organisations
DESTA	1	3	0	0	0	4	Private for-profit entities (exc
TOWERPOWER	0	3	0	1	0	4	Private for-profit entities (exc
Don Quichote	1	5	0	2	0	8	Private for-profit entities (exc
MATHRYCE	3	4	0	0	0	7	Research Organisations
EURECA	4	3	1	0	0	8	Research Organisations
EDEN	1	3	1	1	0	6	Research Organisations
H2moves Scandinavia	3	4	0	2	0	9	Private for-profit entities (exc
PrimoLyzer	2	2	1	0	0	5	Private for-profit entities (exc
HYDROSOL-3D	2	2	0	0	0	4	Research Organisations
HyGuide	1	0	2	1	0	4	Private for-profit entities (exc
HyLIFT-DEMO	2	5	1	1	0	9	Private for-profit entities (exc
HyQ	4	10	0	0	0	14	Research Organisations
FC-EuroGrid	4	4	0	1	0	9	Higher or Secondary Educati
ADEL	5	6	1	0	0	12	Private for-profit entities (exc
CoMETHy	3	3	5	0	0	11	Research Organisations

Risk Matrix - Photovoltaic Solar Plant - Global Infrastructure Hub

Table 3 - Indicative risk allocation among public and private sectors in a PPP by GIH.

		Public	Shared	Private
Land and Site Risk	Provision of required land - general	X	O	
	Timing of provision of required land	X		
	Provision of temporary additional land	X		O
	Heritage / indigenous land rights	X		O
	Resettlement	X		O
	Suitability of land	X	X	O
	Key planning consents		X	
	Subsequent planning approvals	O		X
	Access to the site and associated infrastructure	X		
	Site security	X		X
	Utilities and installations	O		X
	Site condition	O	O	O
	Existing asset condition	O		X
Social Risk	Community and businesses	X	X	O
	Resettlement	X		O
	Heritage / indigenous people	X		O
	Industrial action (labour disputes and strike action)	X	X	X
Environmental Risk	Obtaining environmental consents	O		X
	Compliance with environmental consents and laws			X
	Environmental conditions caused by the project			X
	External environmental events	X	X	
	Climate change event	O	X	
Design Risk	Suitability of design	O		X
	Approval of designs	O		X
	Changes to design	X		X
Construction Risk	Cost increases	O	O	X
	Works completion delays	O	O	X
	Project management and interface with other works/facilities	O		X
	Quality assurance and other construction regulatory standards		X	
	Health and safety compliance			X
	Liability for death, personal injury, property damage and third party liability			X
	Defects and defective materials			X
	Intellectual property	O		X
	Industrial action	X	X	X
	Vandalism		O	X
Variations Risk	Variations Risk (Service changes)	X	O	X
Operating Risk	Increased operating costs and affected performance	O	O	X
	Performance/ price risk			X
	Operational resources or input risk		X	X
	Intellectual property	O		X
	Health and safety compliance	O		X
	Liability for death, personal injury, property damage and third party liability	O		X
	Maintenance standards	O		X
	Interface			
	Industrial action	X	X	X
	Vandalism		O	X

Demand Risk	General principles	X		
Financial Markets Risk	Inflation	O		X
	Exchange rate fluctuation	O	O	X
	Interest rate fluctuation	O	O	X
	Unavailability of insurance	O	X	O
	Refinancing		X	X
Strategic/ Partnering Risk	Private Partner failure/insolvency			X
	Sub-Contractor failure/insolvency			X
	Change in Private Partner ownership			X
	Permitted Contracting Authority step-in	X		X
	Change in Contracting Authority ownership/status	X		
	Disputes		X	X
Disruptive Technology Risk	Disruptive Technology Risk (Obsolescences)	X	X	X
Force Majeure Risk	Force majeure events	X	X	
	Force majeure consequences		X	
MAGA Risk	Material Adverse Government Action Risk (MAGA)	X		
Change In Law Risk	Compliance with applicable law	X		O
	Change in law (and taxation)	X	O	
Early Termination Risk	Contractual termination provisions		X	
	Contracting Authority default termination	X		
	MAGA / Change in law termination	X		
	Voluntary Termination by Contracting Authority	X		
	Force Majeure and Uninsurability termination		X	
	Private Partner default termination			X
	Strength of Contracting Authority payment covenant	X		O
Condition At Handback Risk	Condition At Handback Risk			X
X	Allocation of Risk			
O	Circumstance Dependent Risk			

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