https://doi.org/10.52326/jes.utm.2022.29(1).05
CZU 662.769.2:620.9

THE TRANSITION TO A HYDROGEN ECONOMY

Titu-Marius I. Băjenescu*, ORCID ID: 0000-0002-9371-6766

Swiss Technology Association, Electronics Group Switzerland
*Corresponding author: Titu-Marius I. Băjenescu, *tmbajenesco@gmail.com*

Received: 12.19.2021
Accepted: 01.28.2022

Abstract. The article examines the problem of the hydrogen market - from production to how to use it, as well as the prospects for the development of these energy sources. To combat climate change, more and more countries are investing in low-carbon energy, which is produced from renewable sources and is therefore neutral throughout the chain. Thus, the global hydrogen market is growing. Hydrogen can help decarbonise industrial sectors and combat climate change, either as an environmentally friendly fuel in the transport sector or as a means of reducing emissions in steel production and many other industries. Hydrogen can also play a vital role in energy transport. But even though hydrogen does not pollute itself, because its combustion releases only water vapour, it emits CO_2 when fossil fuels are used for its production ("Grey" hydrogen). "Green" hydrogen is still in its infancy: less than 1% of global hydrogen production, which is itself only 2% of global energy consumption. "Green" hydrogen is very expensive to produce, considerably more than "Grey" hydrogen.

Keywords: *Hydrogen energy, "Green hydrogen",* "Grey" *hydrogen, present challenge, Hydrogen economy, CO_2-free hydrogen, Use of hydrogen.*

Rezumat. Articolul analizează problema pieței de hidrogen - de la producere si pana la modul de utilizare, precum si perspectivele dezvoltării acestei surse de energie. Pentru a combate schimbările climatice, tot mai multe țări investesc în energie cu emisii scăzute de carbon, care este produsă din surse regenerabile și, prin urmare, este neutră pe tot parcursul lanțului. Astfel, piața globală a hidrogenului este în creștere. Hidrogenul poate ajuta la decarbonizarea sectoarelor industriale și la combaterea schimbărilor climatice, fie drept combustibil prietenos cu mediul în sectorul transporturilor, fie ca mijloc de reducere a emisiilor în producția de oțel și în multe alte industrii. Hidrogenul poate juca, de asemenea, un rol vital în transportul de energie. Dar, deși hidrogenul nu poluează în sine, arderea sa eliberând doar vapori de apă, acesta emite CO_2 atunci când se folosesc combustibili fosili pentru producerea sa (hidrogenul „gri"). Hidrogenul „verde" este încă la început: mai puțin de 1% din producția globală de hidrogen, care reprezintă ea însăși doar 2% din consumul global de energie. Hidrogenul „verde" este foarte scump de produs, considerabil mai mult decât hidrogenul "gri".

Cuvinte cheie: *Energia hidrogenului, Hidrogenul "verde", hidrogenul"gri", Provocare actuală, Economia hidrogenului, hidrogenul fără CO_2, utilizarea hidrogenului.*

Introduction

Etymologically, the word hydrogen is a combination of two Greek words, meaning 'to produce water'.

Elemental hydrogen is the main component of the Universe, accounting for 75% of its mass. In the plasma state, it is found as the majority element in the composition of stars. Elemental hydrogen is very rare on Earth. In the 16th century, the Swiss physician Paracelsus investigated the properties of the 'air' that is released when vitriol reacts with iron. A century later, the Irish scientist Robert Boyle isolated a smoking liquor from this 'air'.

To implement the energy and climate plans and achieve the targets, the EU is allocating substantial funds to all Member States between 2021 and 2027 through the following programmes: Horizon Europe, InvestEU, Connecting Europe Facility, Recovery and Resilience Facility, Technical Support Instrument, LIFE programme, European Agricultural Fund for Rural Development and Innovation Fund.

Without minimising the importance of the others, I believe that Horizon Europe launched in January 2021, worth over €100 billion, is of strategic importance because it was created exclusively to stimulate European research and innovation [1]. The programme is aimed at companies of all sizes, aims to encourage collaboration between the public and private sectors and in the coming months, more detailed information is expected about it and its strategic planning process, work programmes, funding calls and other relevant activities.

Although the EU is allocating the largest R&D budget in its history through this programme, competition for funding can be fierce and I think it would be good to pay a bit more attention to it! An agreed direction at EU level for achieving CO_2 neutrality - meaning achieving a balance between emissions and reductions in the atmosphere - would be towards the widespread use of hydrogen, and it is more than likely that a significant proportion of Horizon Europe funding will be spent on research and development of technologies for its production, storage, transport and conversion to electricity [2, 3].

The use of hydrogen as an efficient form of renewable energy storage relies on its ability to be converted back into electricity [4 - 6]. The most likely focus will be on very low-carbon hydrogen - green hydrogen - that is, hydrogen produced exclusively from cheap green energy sources such as solar panels, wind and hydro, which can be easily converted to hydrogen in nearby electrolyser stations [7, 8]. Unlike electricity, hydrogen can be stored and then transported long distances without loss through existing methane gas pipelines [9].

The properties of hydrogen

The advantages of hydrogen are numerous [10 - 12]:

- it is a very abundant atom on earth (in the form of water),
- it is the most energetic molecule (120 MJ/kg), i.e. 2.2 times natural gas,
- it is neither polluting nor toxic,
- its combustion in the air generates only water,
- It is the lightest gas, which is a positive factor with regard to safety (high speed of diffusion in the air).

The disadvantages of this gas include [13 - 15]

● its lightness implies an energy density by volume that is less favourable for transport and storage in gaseous form than for natural gas (a factor of 4 at 200 bar, for example)

● its flammability and detonation limits with air are wider than for natural gas (by a factor of about 5), but in fact only the lower limit counts: 4% by volume in air instead of 5.3% for the lower flammability limit and 13% instead of 6.3% for the lower detonation limit

● the minimum energy required to ignite it is 10 times less than that required for conventional hydrocarbons (20 µJ for hydrogen, compared to 260 for propane),

● its flame is almost invisible, and its combustion (not electrochemical) in the presence of air generates NOx.

● Its image in the public is not good (it is considered a dangerous gas) and its acceptability is therefore not yet acquired.

The “green” hydrogen

The battle for "green" hydrogen is in full swing. To combat climate change, more and more countries are investing in this low-carbon energy, which is produced from renewable energy sources and is therefore neutral throughout the chain. Although hydrogen does not pollute in itself, since its combustion only releases water vapour, it emits CO_2 when fossil fuels are used for its production. This is known as "grey" hydrogen, which emits as much CO_2 each year as the United Kingdom and Indonesia combined (830 million tonnes according to the IEA, the international energy agency) [16, 17]. Green hydrogen is still in its infancy. Its importance is extremely low today: less than 1% of global hydrogen production, which itself represents only 2% of global energy consumption. Certain problems have so far hindered the democratisation of hydrogen, notably its difficult storage and dangerous transport [18, 19]. And green hydrogen has an additional subtlety: it is very expensive to produce, even more so than grey hydrogen. Its production by electrolysis of water costs about four times as much as grey hydrogen by steam reformation of methane.

While Emmanuel Macron has just announced an additional envelope of 2 billion Euros (in addition to the 7 billion unveiled in September 2020), to boost the development of green hydrogen in France and integrate it into its national energy strategy, one country is making it the core of its energy policy, to the point of wanting to export it: Iceland [20].

A symposium on green hydrogen brought together French and Icelandic institutions and companies at the Senate, which examined the opportunities and challenges of this energy source. Iceland's President Guðni Jóhannesson took the opportunity to declare that he wanted to make green hydrogen "the key pillar of his national energy strategy". This rhetoric was immediately echoed by Iceland's private sector players, such as IDUNNH2, which declared its desire to "make Iceland the leader in green hydrogen", notably by focusing on transport and the export of e-fuels [21, 22].

Hydrogen storage

Hydrogen can only play its role as an energy carrier if it can be stored efficiently, at low cost and under acceptable safety conditions. At room temperature and atmospheric pressure, hydrogen is a highly volatile gas due to the small size of its molecule. The challenge is to create compact, low-cost tanks. When there is no need to reduce the storage volume (for example, for stationary applications), it can be stored in gaseous form at a relatively low pressure (75 bar). This means of storage is inexpensive and perfectly controlled. Storage in liquid form at low pressure is currently mainly reserved for certain very high technology applications such as space propulsion. It allows large quantities of hydrogen to be stored in a small volume. Current tanks condition the hydrogen to -253°C at 10 bars [23]. But it is impossible to avoid leaks: even very well insulated tanks absorb heat which slowly vaporises the liquid. In order to achieve satisfactory compactness while avoiding the disadvantages associated with the very low temperatures of storage in the liquid state, efforts are being made to develop storage in the gaseous state under high pressure (700 bar) [24]. The aim is to reconcile impermeability, resistance to high pressure and resistance to shocks by working on an architecture and materials adapted to the reservoir. Lastly, a more recent line of research concerns the use of materials called hydrides which have the capacity to absorb and desorb hydrogen in a reversible manner, under temperature conditions ('solid' storage). Storage in hydrides is the most efficient way to achieve high energy density.

However, this is at the expense of weight, since the weight of the material in which the hydrogen is embedded must be added to the balance. Depending on the intended use of the hydrogen, the criteria of cost, performance, compactness or weight of these different technologies are arbitrated [25, 26].

Use of hydrogen

Worldwide hydrogen consumption is estimated at more than 500 billion cubic metres per year for various purposes and in various fields, the variety and need for which is increasing as fossil fuel resources dwindle and as climate change increases due to rising CO_2 emissions into the atmosphere [27]. In order to ensure access to hydrogen sources for different consumers, an appropriate infrastructure needs to be developed [28].

Figure 1 shows the percentages of hydrogen use in various industrial sectors. Figure 2 gives a schematic representation of steam reforming of methane. Figure 3 shows the hydrogen fuel cell. Figure 4 shows a hydrogen atom and Figure 5 shows the operation of a fuel cell.

In the air, on land or at sea: who will be driving on hydrogen tomorrow?

Cars, vans, trucks, trains, buses, boats and even aeroplanes could all use hydrogen. Hydrogen is seen as an alternative to batteries at the start of the 2020s, replacing everything that runs, flies or sails on fossil fuels.

The public authorities are not the last to believe in it. France and Germany are backing their H_2 (hydrogen) industries with billions. Japan and South Korea are making it a national priority. If we refer to the many announcements (nearly two hundred initiatives in France!), everyone should be driving on hydrogen in ten years' time... Except that in reality, nothing is less certain [26, 28].

But what exactly are we talking about? Hydrogen is the simplest of materials, very present in nature but almost never in its pure state. Producing - or rather isolating - hydrogen (H_2 molecule) - for example from water (H_2O molecule) - requires energy. The operation known as hydrolising allows this energy to be stored and then released in the form of electricity using a fuel cell. The hydrogen-powered vehicle then emits nothing more than a little water vapour [29].

These vehicles are far from being science fiction. To get an idea of what they are like, we headed for the foot of the Eiffel Tower, where at the end of May a hydrogen "village" was set up at the initiative of Toyota and the H_2 Energy Observer ship project. Several prototypes and solutions based on the Japanese manufacturer's fuel cell were on display. It was a good opportunity to review the modes of hydrogen mobility and their development potential [30].

Passenger cars

Some manufacturers (Toyota, but also Honda, Hyundai and Mercedes) market hydrogen-powered cars. These vehicles combine the advantages of a battery-powered electric car (zero emissions when in use) without the disadvantages (hydrogen refills in three minutes). However, the solution remains confidential for private individuals and will probably remain so for a long time [31].

The first problem is that the manufacture of H_2 gas is still very expensive when it is green hydrogen produced by hydrolisis from a wind turbine or solar panels. Currently, the only affordable way to produce hydrogen is to "crack" methane (known as steam reforming), which not only burns a lot of carbon energy but also releases the CO_2 contained in the methane. The climate balance is catastrophic [32].

Second problem: the large-scale deployment of hydrogen stations is very expensive (around 1 million Euros per station) and complex. H_2 is super-explosive, difficult to store and transport in large quantities. Without a vast supply network, it is not conceivable that motorists will adopt this technology. Oil-based fuels are running out, polluting and contributing to global warming. Now it's time for hydrogen, the most common element in the universe [33].

Annette and Ron simply rented a car, a Honda. So far, nothing extraordinary. Except that they have become the first people to use a vehicle that runs on hydrogen and spits out ... only water! It's nothing to do with a billionaire's eco-fad: they only pay 600 dollars (about 400 Euros) a month. Nor is it a gadget for shopping around the corner [34]. The Honda FCX Clarity can travel 430 km before it has to go back to the hydrogen pump. And the little Japanese car, which reaches 16.0 km/h, does not emit a single gram of CO_2!

Since 16 June 2008, the Clarity has been the first hydrogen-powered car to go into series production. Japanese manufacturers are ahead of the game. Most of them already have their prototypes. They will be presented at the Paris Motor Show, which starts on 4 October (in 2008). In France, Peugeot has its Partner H_2Origin and Renault, its Scenic ZEVH2. And this is just the beginning. At European level, a six-year, €470 million research programme will be launched in mid-October, and companies in the sector will be asked to invest at least as much [35 - 36]. This means that almost a billion Euros will be spent to achieve the European objective of starting to market hydrogen cars between 2015 and 2020. That's right! You'll be driving one before long.

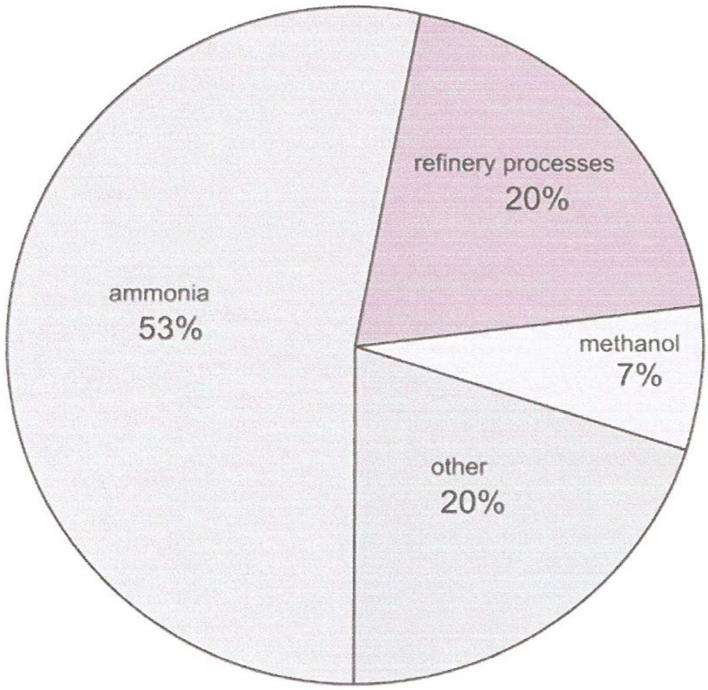

Figure 1. Use of hydrogen.

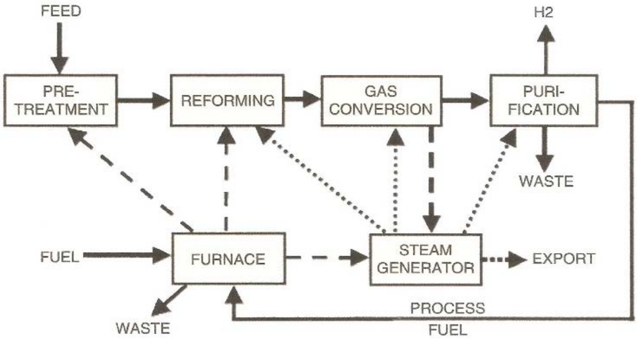

Figure 2. Schematic representation of steam methane reforming.

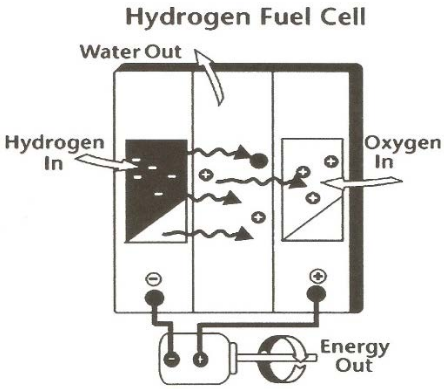

Figure 3. Hydrogen fuel cell (after [1]).

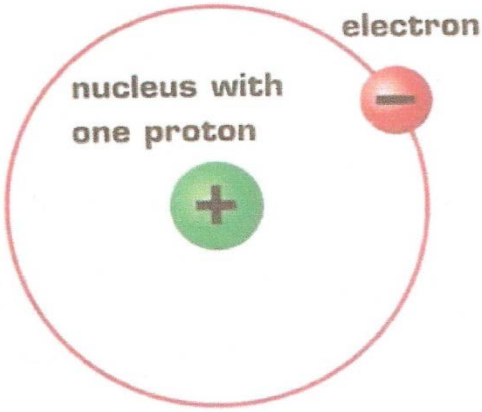

Figure 4. A hydrogen atom.

And not run out of fuel, since it's everywhere (see box His Majesty the Hydrogen). It's infuriating! The most common element in the universe does not exist in its pure state on Earth, but only in combination with more complex molecules.

The hydrogen we put in our tanks will have to be found by tearing hydrogen atoms from the molecules that contain it.

Entrepreneurial perspective

To seize the opportunities in this field, companies need to take strategic risks. They should strive to build ecosystems, continuously develop further insights and proactively interact with policy makers. On the demand side, much of the attention will be focused on the big brands of the world. They are looking at renewable alternatives for their non-electrifiable energy needs so that they can fulfil their sustainability ambitions [32, 33]. This could lead to a hydrogen-based equivalent to the current Power Purchase Agreements (PPAs) that have emerged in the electricity market.

On the supply side, consortia of leading global energy companies will focus on expanding the hydrogen market. Due to their size - and thus their ability to manage such large-scale projects at all - they are just as predestined for this as they are due to their very own interest in using the hydrogen business to secure their relevance in a decarbonised world of the future. They will therefore increase the pressure on governments to enable an appropriately sized hydrogen market [37].

We have an order of merit that fundamentally closes on the price of CO_2. As long as fossil fuels close the merit order, one of the fundamentals we have to consider is the CO_2 price. According to information from *European Commission* documents, the tonne of CO_2 could reach between 55 and 90 Euros in 2030, and the evolution of the CO_2 price from 2021 (doubling the price compared to 2020, to around 50 EUR/t CO_2) makes the worst case scenario impossible to ignore. In any fossil fuel energy production, at a price of 90 EUR/tonne/CO_2, the energy price would transfer somewhere in the range of at least 45 EUR/MWh even with the most modern technology (and around 80 EUR/tonne for coal).

Hydrogen has been tested for alternative use in vehicles equipped with internal combustion engines [38]. Its main advantage is that it is environmentally friendly, as water vapour is produced when it is burnt. The disadvantages are the high explosion hazard, the difficulty of storing it in vehicles and the lack of a hydrogen refuelling station infrastructure. It can be used for direct electricity generation via fuel cells.

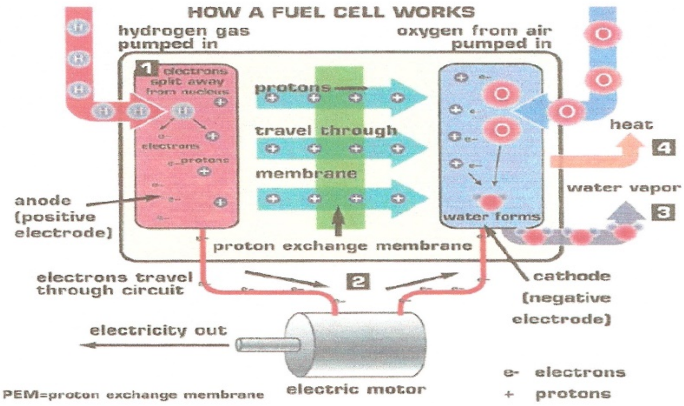

Figure 5. Operation of a fuel cell (after [1]): 1. Electron splits; 2. Electrons travel through the circuit to make electricity, then the protons travel to the cathode. At this stage, hydrogen reforms and unites with oxygen; 3. Water vaporizes and 4. Heat is produced.

Hydrogen – a good fuel

Hydrogen accounts for about 2% of the EU's energy mix, 95% of which is produced by burning fossil fuels, which releases 70 - 100 million tonnes of CO_2 every year [39]. According to research, renewable energies could provide a substantial part of the European energy mix by 2050, with hydrogen accounting for up to 20% of this mix, or between 20 - 50% of energy needs in transport and 5 - 20% in industry [40, 41]. It is mainly used as a raw material in industrial processes, but also as a fuel for space rockets. Hydrogen can be considered a good fuel because of its properties: Its use as an energy source does not produce greenhouse gases (water is the only by-product) It can be used to produce other gases, such as liquid fuels Existing infrastructure for transporting and storing gas can be reused for hydrogen It has a higher energy density than batteries, so can be used for long-distance, or large tonnage transport.

Conclusion

The current context of globalization of market innovation is helping to understand the hydrogen learning processes inside and outside companies, how they acquire new knowledge, how they organize their resources and capabilities to sustain the business strategy.

References

1. European Union, *A Hydrogen Strategy for a Climate-Neutral Europe*, juillet 2020, https://eur-lex.europa.eu/legal-content/FR/TXT/PDF/?uri=CELEX:52020DC0301&from=EN
2. Zohuri B. *Hydrogen Energy - Challenges and Solutions for a Cleaner Future,* Springer, 2019.

3. Global Shift Institute, *Bulletins d'août 2019, d'août 2020 et de décembre 2020*, https://www.globalshift.ca/bulletins/
4. *Hard-to-electrify sectors*: Secteurs difficiles à électrifier; *Hard-to-abate sectors*: secteurs dans lesquels la réduction des émissions est difficile
5. Word Energy Council, *New Hydrogen Économy – Hope or Hype,* https://www.worldenergy.org/assets/downloads/WEInnovation-Insights-Brief-New-Hydrogen-Economy-Hype-or-Hope.pdf
6. IRENA. *Green Hydrogen, A Guide to Policy Making*, https://www.irena.org/publications/2020/Nov/Green-hydrogen
7. IRENA. *Hydrogen Cost Reduction, Scaling up Electrolysers to meet the 1,5° Climate Goal*, https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf
8. Hydrogen Council, Path to Hydrogen Competiveness, A Cost Perspective, Janvier 2020,
9. https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf
10. Gilles L. Bourque et col, IREC, *L'hydrogène, un vecteur énergétique pour la transition*, janvier 2020, https: //irec.quebec/ressources/publications/Hydrogene-Vecteur-energetique-pour-la-transition-IREC2020.pdf
11. IRENA, *As global economies strive for carbon neutrality, cost-competitive renewable hydrogen is possible within the decade,* Quaterly janvier 2021, https://www.irena.org/-/media/Files/IRENA/Agency/ Quarterly/ IRENA_ Quarterly_2021_Q1.pdf
12. BDI 2018: Klimapfade für Deutschland. Boston Consulting Group und Prognos im Auftrag des BDI.
13. Beckers T., Gizzi F., Schäfer-Stradowsky S., Wilms S. u.a. (2018): Rechtliche Rahmenbedingungen für ein integriertes Energiekonzept 2050 und die Einbindung von EE-Kraftstoffen. Forschungsbericht von BBH (Becker Büttner Held), LBST (Ludwig Bölkow Systemtechnik), ISE (Fraunhofer Institut für Solare Energiesysteme) und IKEM (Institut für Klimaschutz, Energie und Mobilität) im Auftrag des Bundesministeriums für Verkehr und digitale Infrastruktur.
14. BMWi (Bundesministerium für Wirtschaft und Energie) (2019): Dialogprozess Gas 2030 – Erste Bilanz – Oktober 2019. Berlin
15. Dena 2018: Leitstudie integrierte Energiewende. Gutachterbericht von ewi Energy Research & Scenarios GmbH im Auftrag der Dena. Berlin
16. IEA 2019: The Future of Hydrogen - Report prepared by the IEA for the G20, Japan, June 2019, Paris
17. IW Köln und frontier economics, (2018): Synthetische Energieträger – Perspektiven für die deutsche Wirtschaft und den internationalen Handel. Eine Untersuchung der Marktpotenziale, Investitions- und Beschäftigungseffekte. Studie im Auftrag von IWO, MEW und UNITI.
18. LBST (Ludwig Bölkow Systemtechnik) (2019): Wasserstoffstudie Nordrhein-Westfalen. Eine Expertise für das Ministerium für Wirtschaft, Innovation, Digitalisierung und Energie des Landes Nordrhein-Westfalen
19. Nymoen H., Sendler S. C., Steffen R., und Pfeiffe R. (2019): Kurzstudie "Quote erneuerbare und dekarbonisierte Gase". Kurzstudie im Auftrag der Vereinigung der Fernleitungsnetzbetreiber Gas e.V. (FNB Gas) Nymoen Strategieberatung GmbH, Berlin.
20. POWER TO X ALLIANZ (2019): Ein Markteinführungsprogramm für Power to X-Technologien.
21. Smolinka T., Wiebe N., Sterchele P., Palzer A. u. a. (2018): Studie IndWEDe. Industrialisierung der Wasserelektrolyse in Deutschland. Chancen und Herausforderungen für nachhaltigen Wasserstoff für Verkehr, Strom und Wärme
22. UBA 2019: Ressourcenschonendes und treibhausgasneutrales Deutschland. Szenario GreenEe. UBA, Dessau-Roßlau
23. WWF 2019: Klimaschutz in der Industrie. Forderungen an die Bundesregierung für einen klimaneutralen Industriestandort Deutschland. WWF Deutschland, Berlin
24. The Oxford Institute for Energy Studies, "EU Hydrogen Strategy - A case for urgent action towards implementation" July 2020
25. Accompagner la transition vers l'hydrogène vert, https://group.bureauveritas.com/fr/magazine/accompagner-la-transition-vers-lhydrogene-vert, 12 mai 2021.
26. Bento N. "La transition vers une économie de l'hydrogène : infrastructures et changement technique" Thèse de doctorat, Université Pierre Mendès-France - Grenoble II,, 2010
27. OIES: Europe's energy transition trajectory: Is conventional wisdom at risk of becoming inconvenient truth? - June 2021

28. Dans les airs, sur terre ou sur mer : qui roulera à l'hydrogène demain ? *Le Monde,* 24/06/2021
29. Thomas Sandy C. E. *Solar Hydrogen,* ISBN-978-1-54-39742
30. Goltsov A. Victor and Veziroglu T. Nejat. *"A step to the road to hydrogen civilization", International Journal of Hydrogen Energy*, Vol. 27, Issues 7–8, July–August 2002, pp. 719-723
31. Ball M., Wietschel M. (2009), "The future of hydrogen - opportunities and challenges", International Journal of Hydrogen Energy 34: 615 – 627
32. Rifkin J. (2007), "Leading the way to the hydrogen economy and a Third Industrial Revolution: a New Energy Agenda for the European Union in the 21st Century", Présenté au Parlement UE en hiver 2007
33. Rifkin J. (2002). *L'Economie Hydrogène. Après la Fin du Pétrole, la Nouvelle Révolution Economique*, Ed. La découverte, Paris
34. Dunn S. (2002). "Hydrogen futures: towards a sustainable energy system", *International Journal of Hydrogen Energy* 27 (3): 235-264
35. Marchetti C. (1985). "Nuclear plants and nuclear niches", *Nuclear Science and Engineering* 90, 521– 526.
36. Sperling D., Gordon D. (2008). Advanced passenger transport technologies. Annual Review of Environment and Ressources 33, 63–84
37. Van Benthem A.A., Kramer G.J., Ramer R. (2006). An options approach to investment in a hydrogen infrastructure. Energy Policy 34, 2949–2963
38. International Energy Agency (IEA), (2009). Transport, Energy and CO_2: Moving Toward Sustainability. IEA/OECD, Paris
39. World Business Council for Sustainable Development (WBCSD), (2004). Mobility 2030: Meeting the Challenges to Sustainability, /http://www.wbcsd.chS
40. Conseil d'Analyse Stratégique (CAS), (2008). Perspectives concernant le véhicule "grand public" d'ici 2030. Coordination Jean Syrota, 18 septembre, /http:// www.strategie.gouv.frS
41. Bento N. "Is carbon lock-in blocking investments in the hydrogen economy? A survey of actors' strategies" Energy Policy 38(2010), 7189-7199.