Hydrogen and decarbonation

Preface

Roland Lescure, Minister Delegate in charge of Industry

Introduction
What strategy for the low-carbon hydrogen industry?

Claude Trink and Mathieu Monville,
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National Strategy

Decarbonated hydrogen: an interministerial strategy and renewed governance

Hoang Bui, General Secretariat for Investment, under the authority of the Prime Minister

France has built a Hydrogen strategy to guarantee its independence. Through this strategy, which it has endowed with substantial financial resources (€8.9 billion), it aims to produce its own hydrogen by electrolysis and accelerate the deployment of its decarbonization, while at the same time pursuing a global industrial ambition. It is thus racing in the leading pack.

After the health crisis, the State's departments got down to work and adopted a new form of governance, in which they systematically work in interministerial cooperation – a work that is the basis of the France Relance and France 2030 investment plans – and in permanent interaction with private players, notably through the National Hydrogen Council. The gas crisis has further strengthened our collective conviction that we must urgently break our dependence on fossil fuels, thanks to hydrogen and our decarbonized energies.

But the road is still long and paved with pitfalls. Is hydrogen always the best solution? Did we launch ourselves too early into electrolysis? Is it a no-regrets investment? Will we have enough electricity and "Made in France" equipment to install 6.5 GW of electrolysis capacity by 2030? Will we succeed, thanks to this massive deployment, in lowering the cost of decarbonated hydrogen produced? To do this, can we count on innovation, increasing the power and performance of electrolysers and building gigafactories of equipment thanks to the exceptional financial support provided under the European IPCEI program, with the aim of supporting the dynamism of our industrialists?

When our neighbors, Spain or Germany, urge us to invest in hydrogen transport infrastructures by pipeline, are we right to say no because of the stranded costs, even if major industrialists ask us to do so? What if the real question is when? That is, when should we revisit the question of what infrastructure might be needed to develop our own hydrogen pools? Will Germany, which has to import green hydrogen on a massive scale, destabilize local, and especially French, European production? What will be the price of this liquefied hydrogen (or ammonia) imported via Northern European terminals and the cost of its distribution? How can we find our economic reference points when the price of electricity, which until now represented 70% of the cost of the decarbonized hydrogen produced, has been multiplied by almost 9 (July 2022 compared to the end of 2020) and that of natural gas has been multiplied by 6?

What if the most important thing was the crew? Our ability to listen to each other, to understand the environment around us and the economic and technical developments to constantly readjust our course together? But also our ability to know how to change course when the path we have chosen leads us to a dead end.

An ambitious strategy for the development of hydrogen in France: issues and challenges

Philippe Boucly, President of France Hydrogène

The French hydrogen strategy is based on three pillars: 1) decarbonizing industry and relying on the large quantities of hydrogen needed to develop a competitive French electrolysis industry; 2) decarbonizing professional mobility (heavy or intensive); and 3) maintaining a high level of excellence for French research and innovation and developing skills and training.

To achieve the objectives set, the French hydrogen industry must change scale and pool uses in order to reduce costs. It is also necessary to promote technological neutrality and, alongside electrolysis, to develop other production methods (steam reforming of natural gas and CCS, thermolysis of biomass, plasmalysis of methane, etc.). In addition, Europe's support policies must be extended to low-carbon hydrogen, in particular to achieve the ambitious targets set by the REPower EU plan.

The deployment of hydrogen technologies must be a lever for reindustrialization. Finally, access to low-cost electricity and to an organized hydrogen market in the medium term thanks to an adapted transport and storage infrastructure is a key issue for producers and consumers.

Regulatory issues of risk management related to new hydrogen technologies

Bruno Debray, Benno Weinberger and Franz Lahaie, INERIS, Verneuil-en-Halatte

Hydrogen as an energy carrier is identified as a technological brick for the transition to low carbon energy. The number of installations using hydrogen and of vehicles

using this gas as a fuel is expected to increase. Their diversity should also increase. Regulations will have to accompany these developments. In this article, we present the general regulatory framework applicable to hydrogen technologies and some of the issues and challenges of adapting these regulations to promote the development of the installations and components necessary for the production of this gas and its new applications in terms of mobility.

Hydrogen, a regulator's point of view

Ivan Faucheux, Member of the college of the French Energy Regulatory Commission

The energy crisis is forcing all players in the energy system to rethink their historical operating methods. The brutality of this crisis, which originates in an even more appalling geopolitical brutality, is accelerating these reflections and forcing them to act even faster than anticipated. Hydrogen, before being an energy carrier, especially for transport, is a basic molecule for industry. Because of its dependence on gas and its carbon character, the production of hydrogen by decarbonized means is becoming a climatic emergency, but also a geostrategic one for Europe and France.

In this article, we intend to give, as a member of the CRE, the point of view of this commission, but with some more personal comments. As a preliminary caveat, the figures provided are often pre-crisis (especially for gas and electricity prices) and must therefore be considered above all as orders of magnitude. As we do not have a crystal ball that is good enough to predict prices three years from now, which will depend on the conditions of gas supply from Russia and the availability of nuclear power for France, we invite the reader to use them as a first-order proxy to project oneself into a future where the crisis of the war in Ukraine will be managed, but where the climate emergency will remain...

A major asset in the French strategy: the important project of common European interest (PIIEC/IPCEI) on hydrogen

Olivier Marfaing, General Directorate of Enterprises (DGE), Ministry of the Economy, Finance and Industrial and Digital Sovereignty

The development of the hydrogen sector covers a double challenge, both ecological and economic. The European and French strategies announced in 2020 set an ambitious course on both fronts, while recognizing the scale of the industrial transformation and investments required to develop this sector. State support is essential to sustain R&D, industrialization and the deployment of associated technologies. Strong political action at the French and European levels has enabled the launch of an important project of common European interest (PIIEC) on hydrogen at the end of 2020. In this article, we present the important tool that is this PIIEC and the modalities of its implementation for the benefit of hydrogen over the years 2021-2022. We will provide an initial feedback and give some initial perspectives.

Supporting the deployment of the French hydrogen industry at the initiative of local ecosystems

David Marchal and Luc Bodineau, Ademe

Ademe (French Agency for Ecological Transition) has been supporting hydrogen technology for more than fifteen years on the R&D side and, since 2018, with regard to the deployment of territorial ecosystems. For the Agency, its support must pursue a triple objective: to be able to massively decarbonize certain sectors that have no other alternative (heavy mobility, industry), to accompany the maturation of a French industrial sector and to ensure the development of hydrogen with benefits for the electrical system. In this article, we recall the fact that the industry has reached technological maturity and specify the future R&D challenges. In addition, we describe the markets to be supported as a priority in terms of price competitiveness and industrial issues. We also focus on territorial ecosystems, which constitute one of the short-term markets for initiating the development of the sector in the territories and offer the first outlets for manufacturers before the implementation of more massive support mechanisms. Finally, we shed light on the foresight exercise that is Transition(s) 2050, which helps to reinforce the orientations of public policies and identify promising sectors that are not currently supported.

Territorial projects and development of services and skills for the sector

The Lorraine coal basin, a territory that has long been interested in hydrogen

Gilbert Pitance, Chairman of the Council of the IUT de Moselle Est – First Director of ALPHEA

Heavy industry and energy-consuming regions working on the long term have always practiced prospective studies. Lorraine prepared the end of its steel and coal activities.

The birth of nuclear electricity production in Cattenom prompted reflection on the massive production of hydrogen via a technology watch unit and various tests and studies from 1995.

The proximity of neighboring Germany has made it possible to initiate fruitful contacts with organizations having the same goal.

The data collected and the impulse given have made it possible, despite the structure's shutdown, to be active during the implementation of national hydrogen strategies in France and Germany and to offer a replacement activity in a cross-border area during the shutdown of one of the last coal-fired power plants in France.

Hydrogen Strategy: a new stage in the reindustrialization of a border region

Claude Trink, President of the Pôle de plasturgie de l'Est (PPE), **and Gilbert Pitance**, General Delegate of PPE

An industrial development program for East Moselle has been defined within the framework of a reindus-

trialization that has become essential following a series of industrial closures. This program is based on 30 years of local knowledge in the use of hydrogen and is mainly oriented in two directions: on the one hand, the progressive installation of massive hydrogen production equipment in order to satisfy the needs of heavy mobility and especially the decarbonization of neighboring industries and the Saarland steel industry by adapting the existing transport and storage infrastructures; and, on the other hand, the creation of a training and certification center in order to develop the necessary professional skills. This program is thus part of the implementation of a cross-border Hydrogen Valley extended to Saarland, Luxembourg and Belgium.

ISTHY: a test and certification center for the hydrogen industry

Michel Romand, Haitham S. Ramadan and Paul Morot, ISTHY (Institute of Hydrogen Storage)

ISTHY (the Hydrogen Storage Institute), the first French test and certification industrial laboratory, is dedicated to actors of hydrogen whether they are integrators, manufacturers, users, or impartial organization in their field. The activity of this latter consists of the conformity and certification tests that will be applied to tanks or storage systems before being placed on the market. For the test and certification process, ISTHY follows either/both regulatory or/and normative standards depending on the application market (mobility, stationary, transport, etc.). From a scientific point of view, this paper deals with discussing the main storage technologies, components, systems, together with their characteristics and positionings regarding the different application markets. The different test and certification standards are presented. ISTHY contributes to the knowledge dissemination to human resources in the hydrogen sector through its training academy and participates in the scientific research.

A training project anchored in a territory to increase the skills of hydrogen technicians: the "Terre de SyHyEn" project

Thierry Zimny, Professor of analytical chemistry at the University of Lorraine, **and Mathieu Monville**, Hydrogen project manager at the Pôle de Plasturgie de l'Est (PPE)

The current ecological and energy crisis is accelerating the development in France of a massive low-carbon hydrogen production sector, a development supported by a public incentive policy. In this announced international competition, a crucial issue is to anticipate training needs and to set up evolving courses that adapt to the needs of the industry's players. Local initiatives are emerging, but there are still not enough of them to meet the challenges ahead. The "Terre de SyHyEn" project, accredited by the Materalia competitiveness cluster, is an example of how a region can bring together technological training players based on a network of university technology institutes (IUTs) to serve an economic and ecological ambition.

A course of excellence to train expert engineers in the field of hydrogen energy

Pr Nadia Yousfi Steiner, University Professor

Winner of the IDEFI program led by the French government in 2012, the CMI curriculum of the FIGURE network has led a profound and sustainable transformation of universities, both in terms of teaching practices and in terms of training quality. The CMI H3E is one of these CMIs, created in 2014 at the University of Franche-Comté around hydrogen Energy to train scientific and technical executives in hydrogen with enhanced capacities in innovation and societal openness.

Benefiting from an exceptional Training-Education-Research-Industry ecosystem: 2 leading laboratories on hydrogen, a strong industry, a "Territoire hydrogène" labeled region since 2016 and a university that counts Environment and Hydrogen among its priorities, the CMI H3E aims to offer excellent training for a new generation. It relies on 2 historical master's degrees in electrical and thermal engineering and on a teaching staff of recognized experts.

New uses

Decarbonizing the steel industry: the challenges of "green steel"

Jean-Pierre Birat, Founder and Chairman of IF Steelman

The Steel industry generates 7% of the world's anthropogenic emissions and is faced with the challenge of reducing its emissions by 55% in 2035 and of reaching Net-Zero by 2050. As society will continue using steel for a long while, breakthrough solutions ought to be implemented to meet these very ambitious goals. R&D has been busy in the last 30 years to identify and experiment solutions up to high TRLs. If they still fall short of full maturity, the problem is that the business model to finance them remains elusive. Among the solutions, direct reduction based on green hydrogen is promising to replace smelting-reduction carried out by carbon in a blast furnace. The article reviews the various breakthrough solutions available and focuses on hydrogen: in France, there are advanced projects at ArcelorMittal and in the SARLORLUX "Grande Region", where hydrogen would be generated in France, for injection into blast furnaces in Saarland, across the border.

Synthetic fuels produced from electrolytic hydrogen and CO_2 emissions from the cement sector: a vector for decarbonizing maritime transport

Pierre De Raphélis-Soissan, Hynamics' Development Director, **and Arthur Parenty**, Hynamics' Public Affairs Officer

Responsible for 2.5% of global greenhouse gas emissions, international shipping is one of the most difficult sectors to decarbonize. Among the possible decarbonization vectors that would allow us to maintain

an acceptable service for the economy, synthetic fuels produced from electrolytic hydrogen and CO_2 have clear advantages: in the form of synthetic methanol, they can be used to power existing combustion engine systems; moreover, they do not require recourse to biomass. While numerous projects for the mass production of synthetic fuels are being developed across Europe, a number of industrial, energy and regulatory challenges still need to be overcome to unlock the full potential of this sector.

Decarbonized mobility: the first bus retrofit project, the Normandy experience with Nomad

Thomas Tixier, Territorial Marketing Manager Transdev Normandie, **Amandine Allard**, Customer Manager Transdev Normandie, **and Antoine Millet**, Operations Manager Transdev Le Havre

Initiated by Transdev Normandie with the Normandy Region and carried out over two years in cooperation with a dozen institutional, industrial and academic partners, Nomad Car Hydrogen is the first project in the world involving the retrofit of a diesel thermal coach into a hydrogen electric coach.

By contributing to the reduction of greenhouse gas emissions and atmospheric pollutants, the Nomad Car Hydrogen is a sustainable and zero-emission mobility solution, contributing to the mitigation of climate change and the protection of the quality of the air in the Normandy region, while paving the way for a new sector allowing the retrofitting and life-cycle extension of heavy vehicles.

Through its collaborative and innovative character, the project contributes to the emergence of the H_2 ecosystem in Normandy. Indeed, it foreshadows the needs and resources necessary for its development such as the training of employees, knowledge of the environmental impacts associated with the life cycle of the new vehicle, the sociological analysis of the stakeholders, the reprogramming of the refueling station, adaptation of local authorities' specifications, risk and incident procedures (in connection with the SDIS), regulatory and legal documentation, technical retrofit expertise as such.

Hydrogen and truck freight transport

Jean-Pierre Hauet, Chairman of the Scientific Committee of Équilibre des énergies, **and Servan Lacire**, Director of R&D and Innovation at Bouygues Énergies & Services and Vice President of the Centrale Supelec Sustainable Energy Group

Electrolytic hydrogen is likely to contribute, alongside the direct use of electricity, to the decarbonization of the economy. The professional transport market, whether by road, rail or sea, is often cited as an important potential market for hydrogen. A study conducted by Équilibre des énergies evaluated the potential market for road freight transport and analyzed the infrastructures to be put in place by 2030 and 2050 for this market to develop. It shows that the hydrogen market for trucks can open up if hydrogen corridors are set up at the trans-European level. But the competition with electric road systems has to be taken into consideration.

The hydrogen train

Stéphane Kaba and Laurent Dufour, Alstom

As a major contributor to the mobility sector, rail transport has a strong growth potential both for passengers and freight, given its fundamental role in the ecological transition. In a context where more than half of the European rail network is not electrified, the massive use of diesel trains is no longer compatible with the objectives of carbon neutrality by 2050. Public authorities seek to decarbonize mobilities by promoting modal transfer towards train and by replacing diesel train fleets by zero-emission solutions. Introducing hydrogen fuel cells in railways is a promising alternative in this race for decarbonation. As trains are showing massive, predictive, localizable and long-lasting usages, rail mission profiles are indeed an immediate and privileged use case. Hydrogen technology also offers high levels of performance in terms of range, speed, capacity and comfort. Finally, the large-scale deployment of hydrogen throughout Europe will strengthen the competitiveness of these solutions.

Alstom was a pioneer in the use of hydrogen in rail. Alstom designed, developed and manufactured the first 100% hydrogen regional train, the Coradia iLint, which is in commercial service since 2018 in Germany. The challenge associated with the integration of various elements (fuel cell, tanks, batteries, etc.) was overcome while meeting operational safety constraints. An acceleration of developments is now necessary in order to extend hydrogen technology to other types of passenger trains (e.g. regional bi-mode) and to freight locomotives while promoting synergies with other types of applications such as maritime or stationary.

New infrastructures and new offers

Building a European electrolysis industry: the transition to the industrialization stage

Roland Héquet, Vice President Strategy, Partnerships and Mobility, John Cockerill Hydrogen

Hydrogen is poised to establish itself as the major energy carrier of the 21st century, replacing and initially complementing current fossil fuel-based sectors. Hydrogen produced from renewable energy sources will account for 20% of Europe's electricity consumption in 2050 and will revolutionize industry, mobility and more generally energy management.

The production of this decarbonated hydrogen is a great opportunity for Europe in many ways. Of course, in terms of the fight against pollution and global warming but also in terms of economic and even technological leadership.

Electrolysers are a key element in the decarbonated hydrogen production chain. Building a European sector around this product is a major challenge requiring

significant research and development efforts, judicious technological choices, a normative framework and support to the sector.

Decarbonization of industry: the Hydrogen joker

Jean-Marc Leonhardt, H2V

Green hydrogen is on a roll!

Not a day goes by without announcements of hydrogen production projects. Today, 17 countries officially have a Hydrogen strategy, and 20 other countries have announced that they are actively working on this subject.

But this is not the first time that hydrogen is in the spotlight. Already in 1970, in France, some people imagined converting surplus nuclear electricity into hydrogen. Then in the 2000s, following the soaring prices of petroleum products and natural gas. Both times, the pressure quickly fell back for economic reasons.

Today, the situation has changed. Of course, the economic equation is not (yet) solved, but the urgency of reducing our CO_2 emissions has become somewhat more important than the economic aspects. Hydrogen appears to be an unavoidable solution to the global warming problem. Hydrogen, both the molecule and its energy content, is destined to replace traditional energy sources in almost all sectors, including industry, transportation and heating.

After the somewhat utopian scenarios of 2015 (for example, using only surplus renewable energy and storing it in the form of hydrogen in the natural gas network – the so-called "Power To Gas" scenario – which considerably limits the hours of production and increases the cost of hydrogen ; or imagine that hydrogen would first be disseminated in the form of micro-installations spread over the territory), the time is now for massive production installations, located in zones of massive or potentially massive consumption (zones called "basins" by France Hydrogen). It is obvious that massive production is necessary to reduce costs (CAPEX and OPEX), and that this only makes sense if consumption is on the same scale as production.

As a result, all efforts are now directed towards industry, which will drive volumes, allowing costs to fall and thus opening the doors to other applications such as mobility and energy uses. But how will hydrogen serve industry?

This is what we propose to review in this article.

MosaHYc or the conversion of a methane transport network to pure hydrogen transport

Laurent Muzart and François Martin, GRTgaz Hydrogen Division

The decarbonization of industry and mobility is at the heart of the challenges facing territories like Warndt Naborien, which requires a change of scale commensurate with the ambitions to foster and make more competitive the alternatives to fossil fuels.

The "Grande Region Hydrogen" is a hydrogen valley between France and Germany made up of projects covering the entire value chain. The MosaHYc project, the hydrogen transportation component of the ecosystem, is an industrial-scale demonstrator for the conversion of a natural gas transmission pipeline into hydrogen, which requires work on 4 key points:

- The evolution of steel integrity;
- The conformity of network equipment (valve, regulator…);
- The adaptation of equipment dedicated to quality and metering;
- The definition and implementation of industrial safety measures.

GRTgaz wants to position itself as a leading player in this field thanks to its "Research & Innovation Center for Energy", and its expertise in the management of gas infrastructures.

Production of "turquoise" hydrogen by methane pyrolysis

Laurent Fulcheri, Research Director, PSL University, Mines ParisTech, PERSEE, Processes, Renewable Energy and Energy Systems Center, Sophia Antipolis

The production of "Turquoise" hydrogen is now attracting growing interest. This pathway is based on the pyrolysis of natural gas at high temperatures for the co-production of hydrogen and solid carbon. The main advantage of this method is its very low carbon footprint and its lower energy intensity than water electrolysis. In this article are discussed the different methods of methane pyrolysis with a particular focus on plasma pyrolysis which is the only and very first technology deployed at industrial scale allowing the co-production of hydrogen and high added value carbon black.

The HyPSTER project: emergence of a new form of massive hydrogen storage essential to achieving carbon neutrality

Yann-Éric Moret, Engineering student at the École Polytechnique, intern at Storengy

In order to reach carbon neutrality by 2050, Europe is banking on renewable hydrogen. And the emerging use of this new energy will have to be accompanied by massive storage solutions – all the more so in the current context of insecurity of supply of Russian gas. For more than 50 years, salt cavern storage has been used to store natural gas: it is now one of the most promising methods for storing flexibly massive amounts of hydrogen, thus bringing a solution to the intermittency of renewable electricity sources. However, its large-scale implementation requires the prior validation of certain technical parameters. In this context, the company Storengy has launched the first pilot project for pure hydrogen storage in a salt cavern for economic and industrial reproducibility, the HyPSTER project. In this article, we highlight the new technical issues raised by hydrogen storage in salt caverns, and an analysis of its strategic interest.

Decoupled Water Splitting for Green Hydrogen Production: Reshaping Water Electrolysis

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Green hydrogen production at scale is essential to fight global warming and climate change. The present water electrolysis technologies present significant barriers to meet this challenge, due to high system and operational costs that emerge from the need to divide each cell into gas-tight cathodic and anodic compartments to avoid mixing hydrogen with oxygen, and from intrinsic energy losses in the complex oxygen evolution reaction. Recent efforts to overcome these barriers include transformative approaches to decouple the hydrogen and oxygen evolution reactions using soluble redox couples or solid redox electrodes that mediate the ion exchange between the primary electrodes such that hydrogen and oxygen are generated at different times and/or different cells. This leads the way to membraneless electrolyzer architectures that can enhance safety, reduce system costs, and provide operational advantages such as high-pressure hydrogen production. In particular, E-TAC water slitting offers these advantages as well as ultrahigh efficiency and compact design of rolled electrode assemblies, opening new frontiers for advanced water electrolysis.

Green hydrogen in Morocco: state of play and prospects

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In order to meet the objectives of international agreements (including the Paris Agreement), a profound transformation of the global energy system is required. In this regard, governments, companies, energy organizations and research institutes are exploring the potential of green hydrogen to achieve the Net Zero targets for carbon dioxide (CO_2) emissions from the energy sector. Morocco is determined to bring its energy security to a strategic and sovereign level by using all the possibilities that its positioning and potential offer. Indeed, the Kingdom's new development model calls for accelerating its supply of competitive low-carbon energy to society, as well as to the service and industrial sectors.

The discovery of natural hydrogen by Hydroma, a "Game Changer" for the energy transition

Asma Diallo, Cheick Sidi Tahara Cissé and Jacques Lemay, Hydroma Inc., **and Denis Joseph Brière**, Chapman Petroleum Engineering

Dihydrogen, commonly known as "hydrogen", is at the forefront of solutions identified to achieve carbon neutrality. To date, a whole palette of colors, as rich as a rainbow, is used to categorize it according to its carbon footprint and its environmental value (green, blue, etc.). One color that is not talked about enough is white hydrogen, also called "gold hydrogen", or natural hydrogen, or even native hydrogen.

Natural hydrogen is a new source of renewable primary energy, which can accelerate the achievement of global climate goals.

This discovery was made in Mali by Hydroma Inc., the Canadian company of Malian entrepreneur Aliou Diallo, who has demonstrated resilience and innovation in a complex security and sub-regional context.

In this article, we retrace the journey from the discovery of natural hydrogen to its use in the Bourakebougou pilot plant. We also present the challenges and prospects of this discovery for the African continent and the energy transition.

Miscellany

Public support for disruptive innovation

Christophe Strobel, Xavier Lachaume and Adrien Sutter, General Directorate of Enterprises of the Ministry of Economy, Finance and Industrial and Digital Sovereignty

Disruptive innovation is innovation that disrupts a market and its players. It is by nature unpredictable, complex, long-term and risky. It can result from the introduction of disruptive technologies: radically different technologies that make existing technologies obsolete. To encourage disruptive innovation, support for the emergence and maturation of new technologies is therefore essential.

A particularly successful approach has been developed by the US Defense Advanced Research Projects Agency (DARPA). In this article, we briefly outline the different public support approaches for innovation, then the specificity of disruptive innovation and the DARPA model, as well as its replications abroad.

Issue Editor : ***Claude Trink and Mathieu Monville***