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Innovative technologies for energy transition: advances in 2023

Authors:

- *The Energy Transition Management Team - Private Debt Expertise, Sienna Investment Managers*
- *Bernard Blez, Senior Consultant - former R&D Director at Engie*

COP 28 held in Dubai last December 2023 demonstrated once again that the transition to a low-carbon economy is not progressing fast enough. To achieve the objectives of the Paris Agreement, we still need to make an enormous effort: we need to **triple the** global deployment speed of **renewable energies** and **double energy efficiency** efforts, all before 2030. And to gradually move away from fossil fuels, we need to be able to **store** intermittent renewable energies on a massive scale and have sufficient **decarbonated energies** available **in liquid or gaseous form**. Fortunately, many technical solutions already exist to address all these issues, but their performance and associated costs still need to be significantly improved before they can be deployed on the massive scale needed to achieve NetZero. There is a great deal of R&D work to be done in all these areas, and their progress will determine our ability to collectively achieve the objectives of the Paris Agreement.

Here is an overview of the main advances made in 2023 in key new technologies within Energy Transition.

1. Photovoltaics: the 30% efficiency target within reach

Since the beginning of the decade, researchers have set themselves the goal of significantly increasing PV cell efficiency without increasing costs, from 20% (current average efficiency of low-cost cells, excluding space technologies) to 30%. The stakes are high, as this would enable a 50% increase in energy output for the same surface area. Today, this objective seems within reach, with several significant breakthroughs achieved by 2023.

This year, INES achieved 25% efficiency with **heterojunction cells** (also known as "HJT" for "Silicon heterojunction"). This technology offers key advantages: high conversion efficiency, favorable temperature coefficient, a simple process compatible with competitive production costs, and the possibility of making double-sided panels to improve final productivity.

Even better: the Ecole Polytechnique Fédérale de Lausanne (EPFL), in collaboration with the Centre Suisse d'Innovation (CSEM), has overcome the 30% efficiency hurdle with its **perovskite-silicon tandem** cells. This result has been independently certified by the National Renewable Energy Laboratory (NREL) in the USA.

2. Wind turbines: larger and more sustainable

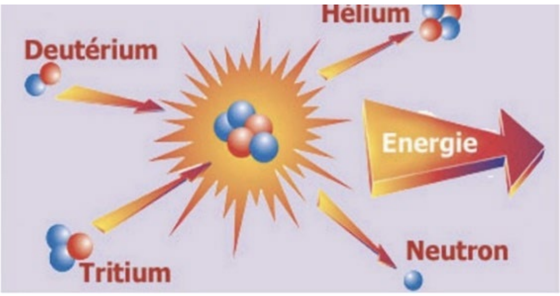
Despite the economic difficulties facing the sector, R&D efforts in the wind power sector remain strong, particularly in the fields of **floating** wind turbines, **vertical-axis** wind turbines and **high-altitude onshore**

wind turbines. These technologies offer decisive advantages: greater electricity production capacity, greater adaptability to environmental conditions and a smaller footprint on the ground.

At the same time, the **race for size** continues. Equinor has announced the commissioning of an 88 MW floating wind farm in Scotland. Scheduled to open in 2023, this will be the world's largest floating wind farm. And manufacturer Vestas, which has been working on a new **15 MW offshore wind turbine with a** production capacity **50% higher** than that of the previous generation, has just signed its first installation in a floating offshore wind farm in South Korea in 2023.

Last but not least, there have been major advances in the **recyclability of blades**, the most complex component in wind turbines to recycle. Launched in September 2020, the ZEBRA (Zero wastE Blade ReseArch) project, involving a consortium led by the Jules Verne Institute for Technological Research (IRT), set out to demonstrate the technical, economic and environmental relevance of **thermoplastic wind turbine blades** produced to scale 1, in an eco-design approach that facilitates recycling. After just over a year of development, material testing and process trials, the world's largest 62-meter recyclable thermoplastic blade, based on Arkema's Elium® liquid resin, was designed and built at LM Wind Power's Pondeferrada site in Spain. Composite materials made with this resin offer the same performance as thermosetting resins, with a unique advantage: recyclability. This is achieved using an advanced chemical recycling method that completely depolymerizes the resin, separating the fiber from the resin and recovering a new virgin resin and high-performance glass fibers ready for reuse.

3. Nuclear energy: renewed interest in Small Modular Reactors... and historic advances in fusion technology



In the field of nuclear energy, **fusion** is the holy grail: unlike fission, which aims to break a heavy nucleus into lighter ones, fusion assembles light nuclei (two forms of hydrogen: deuterium and tritium) to form a heavier nucleus (helium). What fission and fusion have in common is the release of enormous energy, almost a million times greater than the energy released during combustion in an engine. The advantage of fusion is that it does not have the two major drawbacks of fission: the difficulty of controlling the reaction (which poses all the safety problems we know about), and the production of long-lived radioactive waste. But fusion is still at the stage of fundamental research, with a distant industrialization horizon (several decades). Indeed, it requires extremely high energies to initiate the nuclear reaction, which until now have been higher than the energy released by the reaction itself.

In December 2022, scientists at the National Ignition Facility (NIF) announced a ***historic breakthrough*** in fusion. For the first time, they succeeded in releasing more energy from fusion reactions than was needed to cause them (***break-even***).

In 2023, a new experimental milestone was reached. Japan and Europe (ITER project) have inaugurated the world's largest experimental nuclear fusion reactor at the National Institute for Quantum Science and Technology (QST), north of Tokyo. In a five-storey high machine, a kind of sphere around a giant torus, Japanese and European researchers have succeeded in generating, for the first time and for ten seconds, the **plasma** - a cloud of ionized gas - needed to ignite nuclear fusion. The temperature of the plasma is over **15 million degrees Celsius**. Although several countries have already succeeded in creating plasma, none has yet managed to produce it in such large quantities, with a **record volume of 160 cubic meters**. The generation of this plasma is intended to refine the technologies used in ITER, the experimental fusion reactor, twice the size, currently under construction in Cadarache, France, as part of an international cooperation project involving the European Union and Japan, China, South Korea and the USA.

Industrial applications are still a long way off, but these advances in fusion are **historic**.

On a less disruptive note, the energy consequences of the war in Ukraine have rekindled interest in **small modular nuclear reactors (SMRs)**. The French government has announced its intention to launch the construction of a prototype SMR before the end of the 2030s. By June 2023, the government had allocated 10 and 15 million euros respectively to start-ups Naarea and Newcleo. In December 2023, at the *World Nuclear Exhibition* in Paris, the government announced that six new start-ups would benefit from public funding to accelerate their development. They will receive 77.2 million euros in subsidies, plus 18.9 million euros from the Commissariat à l'Energie Atomique (CEA) to test their technologies.

Start-up Jimmy has been awarded the lion's share of the subsidies (€32 million). Its high-temperature reactor for **producing decarbonized industrial heat** is the most technically mature. The other candidate start-ups offer a variety of technologies for **generating electricity**: pressurized water mini-reactors; molten-salt and fast-neutron micro-reactors using previously irradiated fuel; or lead-cooled fast-neutron reactors. The application of all these technologies on the scale of an SMR still requires a great deal of R&D effort.

4. Electricity storage: real incremental progress on conventional batteries, but R&D sluggish on solid-state batteries

Li-Ion battery technology **continues to progress**, not only in terms of cost, but also in terms of storage capacity per unit volume and weight. These last two characteristics are key to electric vehicle applications.

Li-Ion batteries are making rapid progress. In the space of ten years, their specific energy has risen from 100 to 250 Wh/kg, and their specific gravity from 100 Wh/liter to 450 Wh/liter. Significant R&D efforts by all players in the field are expected to take them beyond 300 Wh/kg and 600 Wh/litre.

Another technology is gaining in maturity: **Sodium-Ion batteries.** They have the advantage of not requiring lithium (a critical raw material) but have the disadvantage of a lower energy density than Li-Ion technology. They are particularly interesting for small, inexpensive electric vehicles. The year 2023 will see the promises of 2022 come to fruition, with the **first commercial production of** promising **Sodium-Ion batteries.** New product announcements are multiplying from both newcomers and established players. For example, US-based battery system developer and manufacturer Acculon Energy began mass production of its sodium-ion battery modules and packs in 2023 and unveiled plans to expand production to 2 GWh by mid-2024.

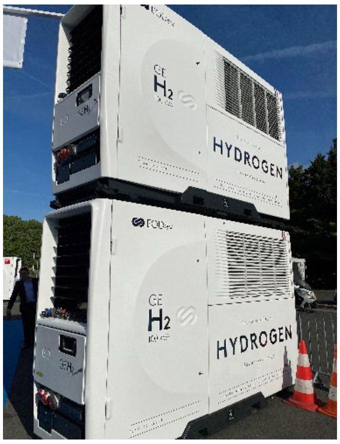
Carmaker Stellantis, for its part, believes in **Li-Sulfur** batteries. It has just invested in a Silicon Valley-based start-up specializing in this technology. It has developed a solution that aims to deliver twice the energy density of lithium-ion, thanks to a nickel-manganese-cobalt-free cathode, using a cheap, abundant and less polluting element: sulfur.

But the breakthrough technology everyone is waiting for is the **solid-state battery.** Start-ups and major automakers, as well as Chinese battery giants, are all working on this technology, because they all want to be the first to find the battery that will give electric cars fast recharging and a range of 1,000 kilometers. So far, however, there have been no major breakthroughs, and **no significant results are expected before 2030**.

5. Hydrogen to decarbonize heavy industry and mobility: R&D efforts still needed on all technologies… and the still uncertain prospect of a major technological breakthrough: natural hydrogen.

Low-carbon hydrogen is a potentially very attractive solution for decarbonizing heavy industry, especially processes that cannot be electrified, and heavy mobility, which is difficult to electrify with batteries because they are too heavy and too bulky to provide the energy and range needed by heavy vehicles. To develop this new sector on an industrial scale, we need effective, economical solutions for all links in the low-carbon hydrogen value chain: production, transport, storage and use in the two main target markets. Today, the maturity of the corresponding technologies varies widely.

5.1. Produce low-carbon hydrogen by electrolysis… or extract it from underground?


EODev brand generator integrating a PEM Toyota battery (photo B. Blez at the 2023 Hyvolution show)

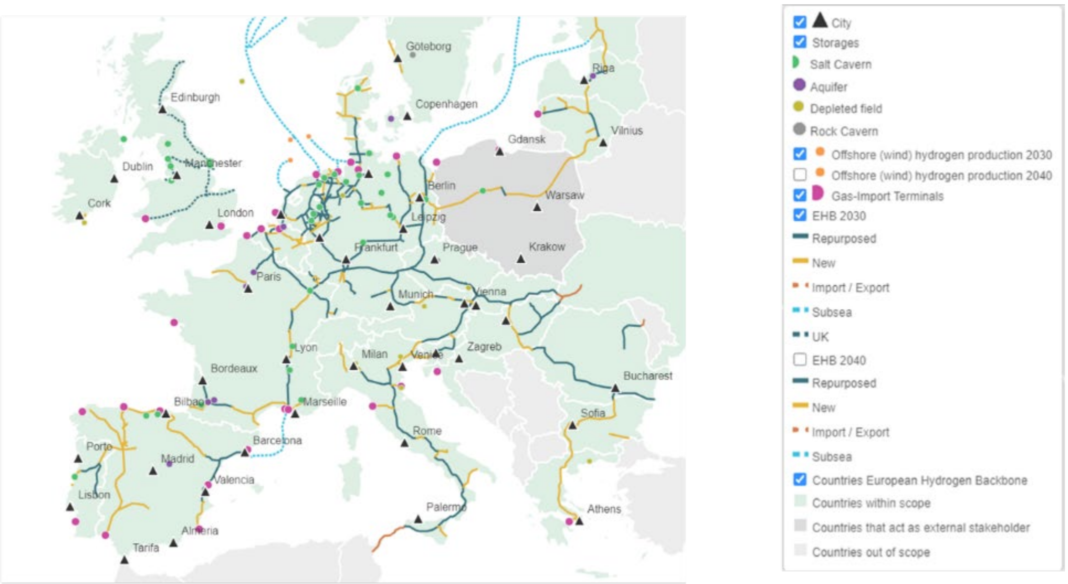
To produce hydrogen without emitting CO2, the most developed technology today is water **electrolysis**, carried out via an **electrolyzer** powered by low-carbon electricity. The most mature electrolyzer technology is alkaline electrolyzers. But these have two drawbacks: they are not flexible enough to respond to rapid load variations (inevitable when powered by wind or PV), and they are heavy and bulky. They are now increasingly being replaced by a more recent, mature technology: **PEM (Proton Exchange Membrane**) **electrolyzers.** These more compact, highly flexible electrolyzers, which operate at pressures of up to 80 bar (allowing some of the compression work to be done before use), have made considerable progress in recent years. Although significant R&D is still required to improve this technology (higher efficiency, lower costs), it has reached sufficient maturity for large-scale industrial production of PEM electrolyzers to be set up. As in the case of battery manufacturing plants, we speak of **Gigafactories**. In mid-2021, US energy solutions company Cummins Inc. announced that it would build a €50 million PEM cell gigafactory in Spain. Its initial capacity will be 500 MW per year, with plans to expand to over 1 GW per year. And in early 2023, the American giant Chemours announced that it would invest over 180 million euros in the Oise region to build a plant for the production of membranes for PEM electrolyzers.

At the same time, however, a **fundamental breakthrough in** hydrogen production may be in the offing: the exploitation of hydrogen present underground (sometimes called ***natural hydrogen*** or ***white hydrogen*** or ***gold hydrogen***), which would be formed continuously through the action of various natural mechanisms (*see box below*). If the existence of such natural resources is confirmed, and if they prove to be exploitable at a reasonable cost, we would then be in the presence of a real ***game changer*** for the Energy Transition, on a local or even global scale, depending on the quantities that prove to be industrially exploitable. Without being a miracle solution, this *natural hydrogen* could be a new, **clean energy** that **is constantly being renewed**, accessible via **mature extraction technologies** well mastered by oil and gas companies. But **many questions remain to be answered** before we can **determine the real potential of this new sector**, and **fundamental R&D and practical exploration work** only got off the ground in a significant way barely 5 years ago. A number of very promising advances have been made recently, but we're still only at the **very beginning of this new adventure**!

5.2. The major infrastructures needed to develop hydrogen markets

Let's move on to the next links in the value chain: **hydrogen transport and storage**. While we've known how to transport and store hydrogen for decades on a small scale, things get more complicated when we talk about trans-European hydrogen networks and large-scale storage on the scale of networks, when such infrastructures will be necessary if we want to produce decarbonized hydrogen in the quantities expected for the Energy Transition. The last two years have seen the **launch of numerous R&D projects and**

demonstrators on these subjects: start-up of the first sections of the ***European hydrogen transport backbone*** project (map below), launch of projects to convert natural gas transport networks to hydrogen (€117 million MosaHYc project by France's GRTGaz and Germany's CREOS to convert 70 km of existing gas network in Moselle and Saarland, announced in December 2023), launch by STORENGY of the Hypster project to test an underground storage technology already used for large-scale strategic natural gas storage: salt cavern storage.



https://ehb.eu/page/european-hydrogen-backbone-maps

Map of the future European Hydrogen Backbone (EHB) Horizon 2030

Natural hydrogen

Until recently, it was thought that hydrogen gas did not exist in significant quantities in its natural state on Earth, as it was too light and too reactive to remain trapped underground for several hundred thousand years. But this certainty was put into question by the unexpected discovery of a hydrogen deposit in Mali in 1987, by a company looking for water. Although no one was interested at the time, the entrepreneur embarked on a visionary gamble: to exploit this hydrogen. And he succeeded: since 2012, the village of Bourakébougou has been powered by electricity produced from this hydrogen.

Since then, scientists have been wondering how such a deposit could have formed, and of course, whether such deposits exist elsewhere. And the first answers are opening up some particularly interesting prospects, even if several major uncertainties remain.

The key to explaining the presence of hydrogen underground is that it is produced naturally and continuously. The mechanisms are beginning to be elucidated and are varied: oxidation of iron-containing rocks by water, spontaneous electrolysis in the presence of natural radioactivity, or bacterial production.

Recently, natural hydrogen emissions have been discovered all over the planet. They have been found in hydrothermal springs (geothermal energy), in mountain ranges such as the Alps and Pyrenees, and in iron-rich continental rocks such as in Australia, Namibia and Brazil, and around uranium mines.

Could this unsuspected, decarbonized natural energy contribute to the decarbonization that everyone is calling for? To answer this question, we still lack key knowledge about the quantities accumulated underground and their accessibility. To provide some answers, we first need to better understand the mechanisms of formation, in particular the parameters that influence the rate of hydrogen formation, but also how it can accumulate in significant quantities in favorable geological configurations, and how to detect them.

5.3. Hydrogen technologies progress in parallel

Innovation is also progressing in the field of **hydrogen applications** and is absolutely essential if we are to make the use of hydrogen to decarbonize industry and heavy land transport operational and economical. Over and above the production and delivery costs of hydrogen itself, which depend on the technologies mentioned above, the economic competitiveness of these new sectors also depends on the performance and cost of hydrogen-powered equipment and processes.

For **land transport, the** prospects for **reducing the manufacturing costs of** hydrogen fuel cell **vehicles** are still considerable, thanks to major innovations: development of **new fuel cell technologies** using fewer rare and expensive materials, development of **pressurized hydrogen tanks in composite materials** that are less expensive and easier to integrate into vehicles. And let's not forget the possible return of **hydrogen-powered vehicles with internal combustion engines**, another way of reducing the extra cost of new hydrogen-powered vehicles, and the possibility of **retrofitting diesel trucks. For** example, at the HYVOLUTION trade show in Paris, Safra, a leading player in the renovation of passenger transport equipment, and *Hyliko*, a hydrogen mobility platform for road haulage, announced their partnership for the hydrogen retrofit of heavy

Hylico hydrogen truck, presented at the 2023 Hyvolution show (photo B. Blez) goods vehicles in series production. BMW has just announced the launch of a hydrogen-powered saloon car in 2025.

For **non-land-based transport,** decarbonated hydrogen is **not for the immediate future**. For **heavy shipping,** the **extra cost of hydrogen is prohibitive**, and major shipowners will initially prefer LNG, which is less carbon-intensive than the heavy fuel oil currently used. And for **air transport (wide-body, long-haul),** we shouldn't expect liquid hydrogen aircraft before 2040-2045, even if Airbus has already launched an R&D program on the subject. The problem is that hydrogen, even liquefied, has a much lower energy density than kerosene (for an energy content equivalent to 1 m^3 of kerosene, you need 4 m^3 of liquid hydrogen), so the whole structure of the aircraft must be reconceptualized. The **gradual incorporation of low-carbon synthetic kerosene** (SAF, produced from decarbonated hydrogen) seems more within reach, as it does not require any major modification of aircraft. In the meantime, we are seeing innovations in the niche market of **business jets, such** as the Swiss company Sirius Aviation.

As for **hydrogen applications to decarbonize industry**, the use of low-carbon hydrogen as a raw material (for fertilizers, iron and steel, certain textiles, etc.) in place of grey hydrogen (manufactured from fossil fuels, producing large quantities of CO2) poses no technical problem, since it is the same H2 molecule. The only obstacle at present is the availability and cost of the necessary quantities of low-carbon hydrogen. On the other hand, **new** hydrogen **applications** to decarbonize heavy industry still require industrial-scale pilots. This is the case for the Direct Reduction of Iron (**DRI**) technology, which transforms iron ore (iron oxide) into metallic iron using hydrogen instead of coke, without emitting CO2. Arcelor Mittal is one of the steelmakers strongly committed to this decarbonization path, with already more than 10 DRI units worldwide, including the only operational unit in Europe. In France, the steelmaker plans to build a DRI unit in Dunkirk, with an annual capacity of 2.5 million tonnes, to transform iron ore with hydrogen, without recourse to coal. These new industrial facilities will be operational from 2027 and will gradually replace two of ArcelorMittal's three existing blast furnaces in Dunkirk by 2030.

6. CCUS: a spectacular revival of major projects in Europe

The market for the **capture and underground storage of C02 (CCS)** has also evolved considerably in recent years. After a period when costs were prohibitive and social acceptance of large-scale underground storage represented an insurmountable obstacle, the market's development prospects are now brightening up in the face of the increasingly clear recognition by the International Energy Agency (IEA) and the European Union that the objectives of the Paris Agreement will not be met without this solution. Because even if almost total decarbonization is possible in the long term in a large number of sectors, there will always be cases where CO2 emissions cannot be cancelled out (cement industry, fertilizers, etc.). In these sectors, the only solutions will be to capture and sequester CO2 over the long term, or to offset emissions through other types of carbon sink.

This has led to a resurgence of work on the subject, with a growing number of pilot projects for large industrial facilities, in **geographical areas where underground storage is feasible** (under the sea, in old, depleted gas or oil fields, etc.). **In Europe,** no fewer than **71 CO2 infrastructure and shipping projects are** scheduled for 2023, including **18 projects of common interest (PIC)** submitted by December 2022.

While technological solutions for **capturing CO2 downstream of industrial processes are making little headway** (amine capture), despite various R&D efforts to reduce energy costs, the design of the **complete chain** from capture to landfill, including transport and storage of CO2, is the subject of a **new approach that can be** described as innovative in its **global** approach to the problem. The idea is to collect the CO2 captured at various industrial sites via large-scale transport networks, and to converge it at one or more specially equipped port terminals. The CO2 would then be transported by ship or undersea pipeline to an offshore deep disposal site.

This is exactly the approach adopted by the *Northern Lights* project along the Norwegian coast (TotalEnergies, Equinor and Shell). This large-scale CO2 transport and storage project was approved by the Norwegian government in 2020 and designated as a project of common interest (PIC1) by the European Union. In December 2022, *Northern Lights* took delivery of the first seven of twelve tanks for temporary onshore CO2 storage. Offshore drilling operations have also recently been completed, and construction of the future vessels has begun. Carbon capture and storage operations are scheduled to begin in 2024. *Northern Lights* is the first project to create a cross-border value chain designed to offer European manufacturers the possibility of permanently sequestering their CO2 emissions underground. Facilities in the first phase of the project will store up to 1.5 million tonnes of CO2 per year, before being expanded to 5 million tonnes by 2026.

7. Summary and conclusion

This overview shows just how many technological advances have been made in the last 12 or 24 months: inexpensive PV cells with 30% efficiency now seem within reach; wind turbines are continuing to reduce their footprint and will become 100% recyclable; Li-Ion, Li-Sulfur and Sodium-Ion battery technologies are improving, with rapidly increasing energy density; the state of the art in low-carbon hydrogen technologies means that the first building blocks of the major infrastructure needed for mass deployment can now be constructed; and the vision of the complete value chain for CO2 capture, transport and storage is becoming clearer, and is giving rise to the first pilots on a European scale. At the same time, renewed interest in small modular nuclear reactors and the very latest advances in the search for exploitable deposits of natural hydrogen point to very promising longer-term prospects.

This overview is far from exhaustive, as many other subjects are likely to provide other new levers for decarbonizing our economies in the short and medium term, such as AI applications for energy efficiency or methane leak detection, or new biomethane production technologies, or the use of new materials to decarbonize the cement industry.

It should be noted that we have chosen not to address two major issues that underlie all technological developments: that of the raw materials required, and the key issue of the social acceptability of emerging innovations. These topics merit specific developments.

In conclusion, what emerges from this overview is the extent to which solutions for the Energy Transition are evolving rapidly, driven by the unprecedented mobilization of public and private players and the increasingly clear messages on the urgency to act conveyed by the IPCC and the International Energy Agency (IEA). It is crucial that all the players involved - manufacturers, researchers, financiers, politicians, legislators, etc. - work together to develop innovative solutions that will enable us to achieve the objectives of the Paris Agreement, while accepting the risks inherent in innovation. Because the riskiest strategy for everyone would be not to innovate at all.

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