European Institute for Energy Research by EDF and KIT

March 2023

R&D WHITE PAPER

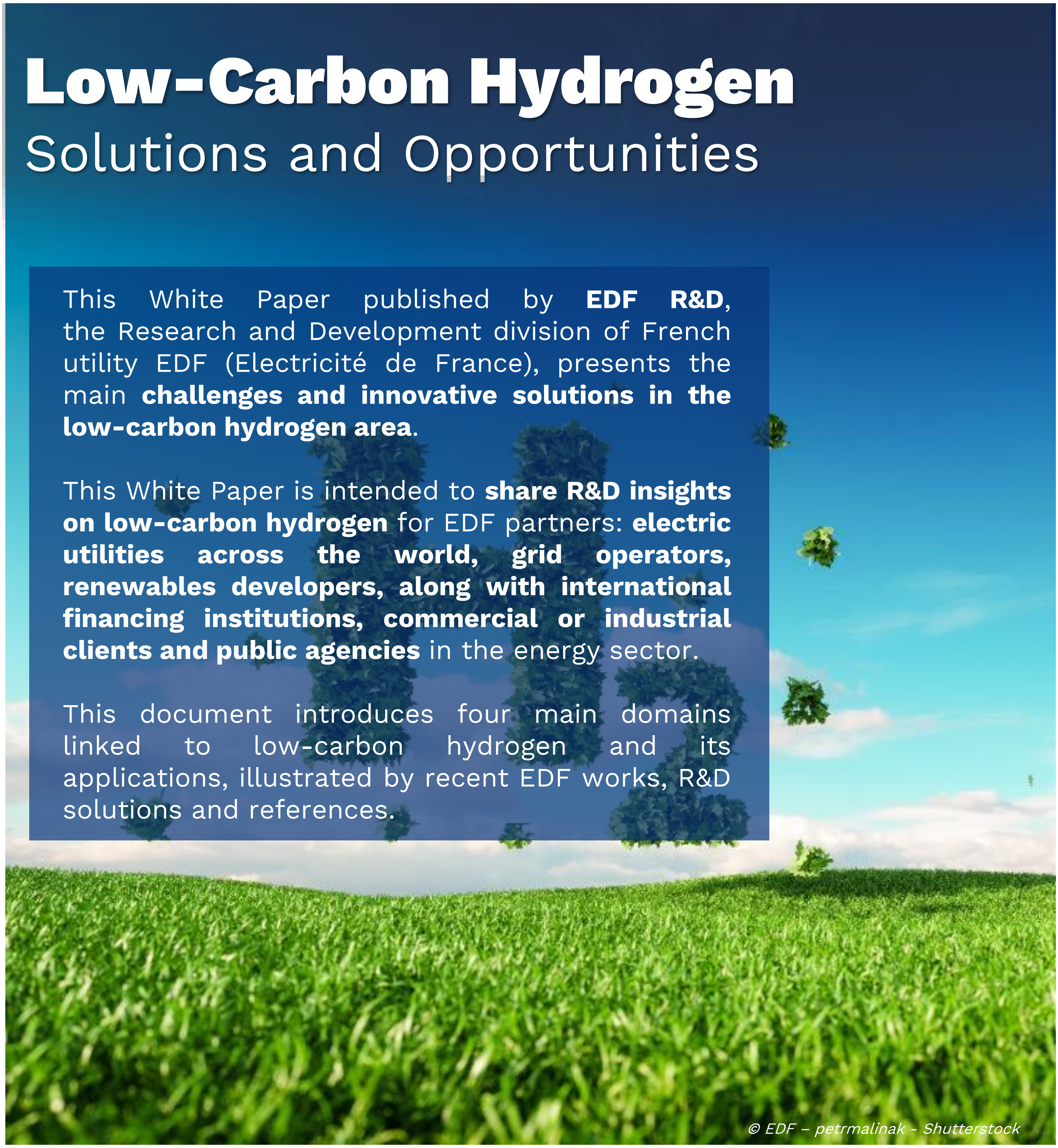
Low-Carbon Hydrogen

Solutions and Opportunities

This White Paper published by **EDF R&D**, the Research and Development division of French utility EDF (Electricité de France), presents the main **challenges and innovative solutions in the low-carbon hydrogen area**.

This White Paper is intended to **share R&D insights on low-carbon hydrogen** for EDF partners: **electric utilities across the world, grid operators, renewables developers, along with international financing institutions, commercial or industrial clients and public agencies** in the energy sector.

This document introduces four main domains linked to low-carbon hydrogen and its applications, illustrated by recent EDF works, R&D solutions and references.



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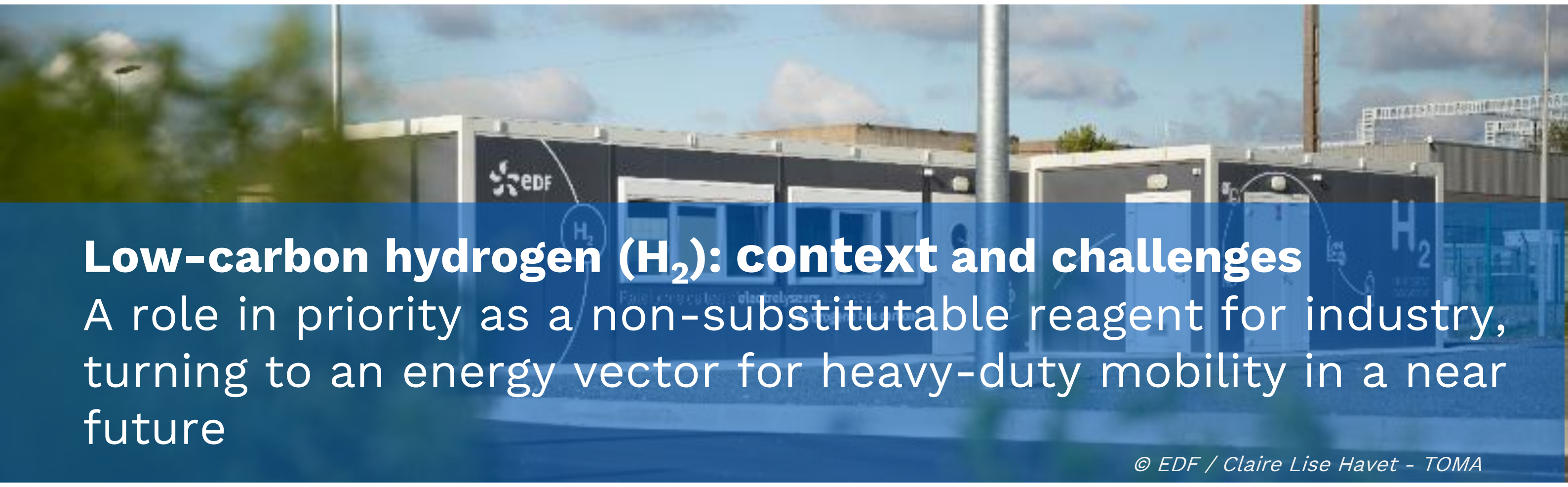

Low-carbon hydrogen (H_2): context and challenges

A role in priority as a non-substitutable reagent for industry, turning to an energy vector for heavy-duty mobility in a near future

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A key support to reduce the carbon footprint of energy markets

Today, 90 Mt_{H2} are yearly consumed worldwide as reagent of heavy industry processes (ammonia production, olefins transformation and treatment in particular). However, nowadays, the H_2 molecule is widely (~96 %) issued from carbon-intensive reforming processes using fossil reagents. As a result, producing 1 kg of *fossil H_2* induces more than 10 kg of CO_2, representing around 3% of global CO_2 emissions. It is why the International Energy Agency recently estimated the significant role of a low-carbon H_2 for reaching the neutral carbon pathway by 2050. About 550 Mt H_2/yr will thus be needed to decarbonise in priority the industry as energy reagent and heavy-duty mobility as new energy carrier, while avoiding ~6 $GtCO_2$ annually.

European and national strategic policies are being merged to highlight decarbonised H_2 as part of the economy recovery plan and the European Green Deal, strengthened in the context of energy and geopolitical crises. Thus, the recent European hydrogen roadmap at horizon 2030 promotes the deployment of *electrolytic H_2* power plants: 40 GW in Europe and 40 GW in nearby strategic regions (Maghreb, for instance). In total, about 20 Mt_{H2} would be produced thanks to consistent public and private aids (several hundred billion euros). Water electrolysis is commonly cited as the most promising technology to produce low-carbon *electrolytic H_2* while assuming the electricity comes from clean sources, otherwise freeing from fossil fuels.

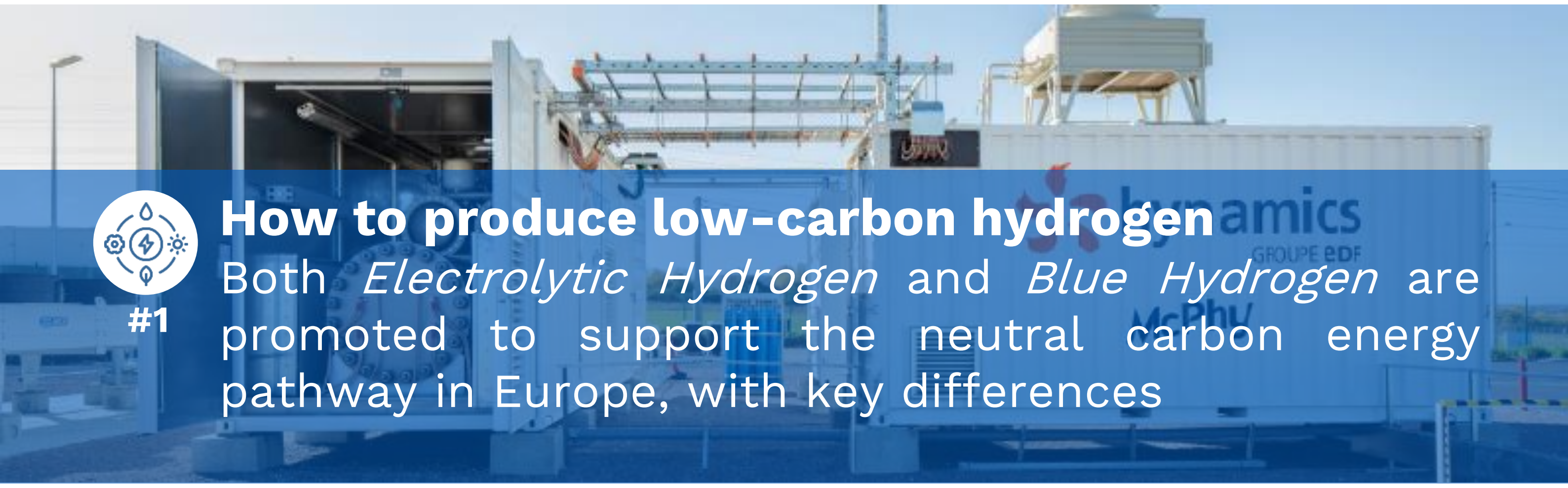
In this context, two visions are proposed. A first vision of large scale H_2 hub projects built at optimal locations for coupling low-cost renewables and water electrolysers (Middle East, South America…). This vision requires interconnected transmission and distribution circuits. Then, a local vision, based on the development of decarbonised energy hubs, with electrolytic H2 production as close as possible to places of consumption (nuclear or renewables).

In 2022, EDF announced the launch of a Hydrogen Plan to implement 3 GWs of *electrolytic H_2* (eq. 450 kt_{H2} per year) by 2030. For that, EDF relies on its strong R&D expertise in the hydrogen field to serve the Group's business entities. Indeed, since the pioneer R&D works undertaken in the early 1970s, low-carbon H_2 technologies and businesses have been at the heart of the excellence and know-how developed by the European Institute for Energy research (EIFER). This institute was jointly founded by EDF and the Karlsruhe Institüt für Technologie (KIT) in 2002 aiming at enhancing collaboration through joint projects applied to industrial issues. Besides, in 2020, EDF R&D commissioned an H2 platform at EDF R&D Lab "Les Renardières" dedicated to the qualification of performance and reliability of MW-scale electrolysers. Finally, EDF Group has acted several businesses and strategic positions in hydrogen markets by taking stakes in 2018 in a leading electrolyser manufacturer. EDF also created Hynamics in 2019, a 100% EDF subsidiary for electrolytic H_2 production and supply offers.

> The H2 theme is emerging in all international R&D centres especially in France, Germany (EIFER), UK (e.g., Teeside industrial cluster), Italy (e.g., test benches for small scale electrolyzers) and Singapore (e.g., a new kW-scale H2 loop in the MASERA Smart Energy Testbed).

Will water supply impact the H_2 development?

Theoretically, every kg of H_2 should consume 9 kg of demineralized water, implying strict quality requirements to avoid shorter lifetime of electrolysers. Further external factors could affect the holistic water footprint (e.g., water accessibility, evaporation…). Overall, electrolysis does not create any additional water demand compared to the one for H2 production from natural gas or coal. Water usage projections by 2050 shouldn't be a major concern for the global H_2 business compared to other economic sectors. In some regions, sea water desalination appears as the main option for water supply using reverse osmosis process (electro-deionization).



How to produce low-carbon hydrogen

#1

Both *Electrolytic Hydrogen* and *Blue Hydrogen* are promoted to support the neutral carbon energy pathway in Europe, with key differences

Towards a competitive electrolytic H2 process

Two main technologies of decarbonised H_2 production are leading in the market: the *electrolytic H_2* using water splitting process combined to a low-carbon electricity source and the “blue H_2” based on a fossil fuel reforming process implying additional CO_2 capture and sequestration (CCS) steps (solution to be confirmed though). EDF is convinced that electrolytic H2 is the only technology able to produce low-carbon H2 at industrial scale.

In Europe, the "Low-Carbon hydrogen" label must respect severe carbon-footprint taxonomy rules (<3 kg CO_2/kg_{H2}) and tracking processes to guarantee the origin of decarbonised energy sources. Thus, producing electrolytic H_2 requires either direct connection to decarbonised electricity sources (wind, solar, hydro, nuclear) or to the public grid assuming a very low CO_2 electricity mix (which widely differs across countries).

Different electrolysis systems can be used according to the economic and operational profiles: Alkaline technology (AEL) is the most mature in terms of high-power capacity, Polymer-based membrane technology (PEM) is the most flexible and compact technology. Soon, Solid-Oxide cell technology (SOC) operating at higher temperature (>800°C) will be the most efficient by using *on-site* recovery heat. For now, producing electrolytic H_2 is 2 to 4 times more expensive than producing fossil H_2 or “blue H_2”.

To reduce the production cost, the first challenge is to validate sufficient reliability and maturity in a high-volume rate of production: today, the power capacity of the deployed units in the world is in the range of few tens of MWs, whereas industrialisation and optimisation steps are underway to achieve a gigawatt-scale pathway. In such scope, EDF R&D is involved in technical expertise and performance benchmarking of more advanced hydrogen technologies leveraging its R&D facilities and labs. As examples, in the frame of the European **AD ASTRA** project, EDF designed qualitative Accelerated Stress Tests (AST) protocols to calibrate the key degradation drivers of SOC systems and to evaluate diagnosis / prognosis algorithm. It resulted a tailored control system for improving reliability and preventive maintenance steps. Besides, EDF is engaged in one of the three pilot projects (with H2Mare and TransHyDE) selected and co-funded by the German Federal Ministry of Education and Research (BMBF) for validating a GW capacity milestone of electrolytic H_2 infrastructures: **H2GIGA European project** (see page 5).

EDF focuses its business activities on *electrolytic hydrogen* projects in close collaboration with its clients and does not intend to develop “*blue H2*” projects.

FCTestLab at EIFER Institute

FCTestLab activities cover the operations of the entire value chain of low temperature hydrogen systems, from its production (PEM, AEL, compression/storage) to its usage into fuel cells. For that, four independent testing cabinets provide online electro-chemical measurement facilities to operate integrated cell components and prototype modules at kW-scale.

H2 platform at EDF R&D Lab ‘Les Renardières’

To support the development of on-field H_2 production and uses, this platform allows testing and qualifying electrolyzers at the megawatt scale (up to 10MW). Various sources of electricity (renewables, grid mix) can be used. H2 compression and storage is under development. Ultimately, R&D in e-fuels will be carried out.

How to secure low-carbon hydrogen infrastructure

#2

Final hydrogen price depends on conditioning, transportation and distribution forms

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Towards a safe and highly efficient hydrogen infrastructure

[...] The second challenge is to ensure low-cost electrolytic H_2 production sites. For that, a combination of few parameters is fundamental to reach a competitive hydrogen price below 3,5€/kg_{H2} (and even 2 €/kg_{H2} in optimal conditions): affordable and sustainable electricity source, highly efficient technologies and high utilisation rate of hydrogen infrastructures, use of sustainable and high performing core components...

In particular, hydrogen conditioning at high pressure (>700 bars) represents a large share of the total CAPEX of an electrolytic H_2 infrastructure (specific case of the mobility). In this context, EDF R&D contributes to the development of industrial pilots and field tests, leveraging its experience in the installation of monitoring systems and analysis of resulting data. Through several European R&D projects **(COSMHYC, COSMHYC XL, COSMHYC DEMO),** EDF supports R&D activities related to innovative hydrogen compression solutions. They contribute to reducing energy consumption and lowering total CAPEX of hydrogen refueling stations.

Moreover, the output hydrogen price depends on the distance between the producer and the consumer: transportation and distribution segments costs can constitute key elements in the "from well to wheel" economic equation. Hydrogen can be regionally transported and distributed, both as a gas or in liquid forms, by pipelines or in special cases in containers by road and rail. Gaseous and liquid hydrogen carriage are subjected to strict regulations ensuring public safety and control.

EDF R&D has developed a set of evaluation and simulation tools to support its partners in de-risking projects during the pre-feasibility or feasibility phases. These tools integrate extensive physical models of H_2 technologies and other related auxiliaries (heat transfers, power electronics, components...) with the ability to represent grid constraints. The outcomes allow to determine tailored H_2 system sizing and associated control laws, lifespan and economic values (CAPEX, OPEX).

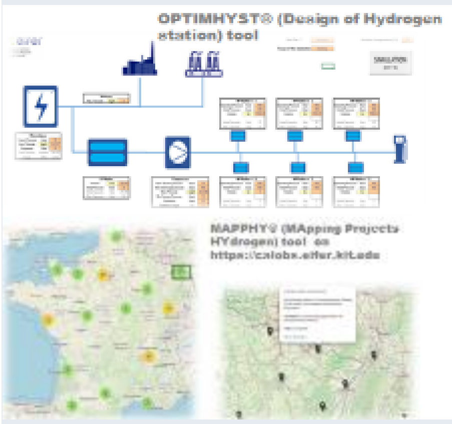
To accelerate the time-to-market of breakthrough hydrogen technologies, suitable markets and trends in the main sectors of industry and transport are analysed by EDF R&D.

> EDF R&D is involved in several on-field demonstrators and has developed related system modeling tools to evaluate hydrogen solutions. These activities help EDF to evaluate the impact of conditioning, transportation and distribution on H2 projects' economics.

COSMHYC project

COSMHYC is an innovative thermochemical H_2 compressor solution based on hydride metals. EDF R&D qualifies its performance from lab-scale at the FCTestLab, up to on-field implementation. This also enables the valorisation of H_2 related patents and know-how.

EDF R&D H2 toolset



EDF R&D has built a set of digital tools adapted to the different stages of H_2 projects development (consultancy, pre-feasibility, detailed sizing...). For instance, OPTIMHYST is a sizing tool that integrates technological bricks (production, distribution...) according to the H2 demand.

How to promote hydrogen as chemical reagent through "greener" and “no regret” CO_2 industries

#3

A rule in the decarbonisation of strategic industries

Hydrogen is currently used as a non-substitutable reagent in several heavy industry sectors (ammonia production, oil refining, steel production, chemical industry for methanol production). Together, those processes represent more than one billion tons of CO_2 equivalent per year in the world. Thereby, these sectors claim to decarbonise H_2 by either making additional sequestration steps of CO_2 in an adapted geological site (saline cavity) or by promoting water electrolysis process using low-carbon electricity.

Based on technical experiments and analysis, EDF considers that the most efficient and mature solution to decarbonise H2 is the on-site production of H_2 by water electrolysis for small and medium-size industries to free long-distance transportation costs via trailer trucks (bottles). In addition, for larger industries, carbon price and regulatory incentives for renewables could stimulate on-site carbon-free solutions.

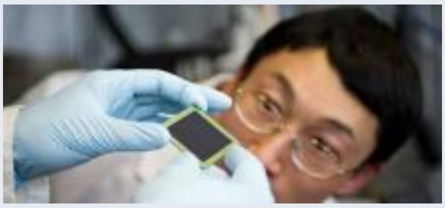
Through its wide range of partnerships (industrial, start-up, academic), EDF R&D is developing its competences and know-how in such scope: **H2GIGA** European project coordinated by the chemical industry Dechema, aims to develop the production of electrolytic H_2 in an industrial context in Germany. Among over 130 institutions coming from industry and research (technology manufacturers, automation, digitalisation and quality control stakeholders), EDF R&D (via EIFER) is mainly involved in the assessment of the SOC technology at high power level and industry profile conditions.

In addition, EDF R&D was involved in the **GrInHy** project. One of the main objectives consisted in the evaluation of the reversibility concept of SOC technologies (i.e. choice of SOC handling between fuel cell operation for producing electricity and electrolysis profile for producing hydrogen). Through its labs, EDF R&D has qualified electrical and electrochemical performance and durability of SOC products before on-site installation at an industrial metallurgist.

EDF participates in different projects to evaluate the development of this emerging technology which may play a role in the future to produce H2. Another studied market implies the reaction of CO_2 molecules, captured from industrial exhaust fumes or through Direct Air Capture, with low-carbon H_2 to produce syngas (H_2 + CO). It results an e-fuel chain value process for industrial uses (chemistry) and also for mobility.

EDF R&D can also support industries or local authorities in the pre-feasibility studies of need and ensure the project management of projects related to hydrogen installations.

EIFER/ICT LAB



The EIFER research activities on H_2 collaborate with the Institute for Chemical Technologies (ICT H2 Lab, Fraunhofer). It covers the electrochemical testing of core components and lifetime assessment of high temperature solid oxide based-technologies (SOC). The lab includes cells and small-sized stacks (kW-scale) monitored under various operational conditions and profiles (co-electrolysis, fuel cell).

H2GIGA European project

In this project EDF R&D, via EIFER, contributed to the development of innovative cells and stacks as well as on the understanding of degradation mechanisms in order to improve the reliability of the whole electrolysis system. This project aimed to develop the industrial mass production of electrolysis.

#4 How to promote hydrogen as an energy carrier through heavy-duty mobility in complement to battery electric vehicles

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Towards the decarbonisation of heavy-duty mobility

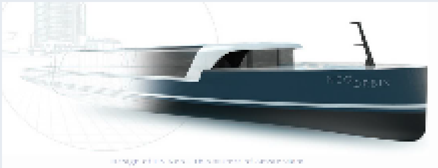
Concerning the use of hydrogen as an energy carrier, EDF considers no cost-effective business model regarding the injection of hydrogen into gas networks. However, the current geopolitical context could deeply influence public authorities to consider this option through policies support.

Regarding electric mobility, the fuel cell electric vehicle (**FCEV**) using a PEM technology looks well positioned to complement the battery electric vehicle (**BEV**). Indeed, even though the landscape of light duty H_2 vehicles is evolving around the world with 45 000 units on road (USA, Japan, Korea and EU), the tendency is to promote H_2 solutions for higher on-board energy demand. It should be the case for heavy duty vehicles (trucks, trains, buses, ships, aircrafts). Today, mobility projects are engaged at different stages for local development: in the nearest term, powering fleets of buses, garbage trucks, trains in non-electrified areas and in the longer-term ships and aircrafts. EDF, through its subsidiaries, supports the development of H_2 refueling stations for mobility. EDF R&D contributes to support its partners in de-risking projects by carrying out system modelling, technical specifications and tests needed before the final installation at the customers' premises. Thus, EDF R&D has already developed and monitored several pioneer hydrogen demonstrators like **FAHYENCE** (Sarreguemines, FR). In the UK (Midlands), EDF R&D is studying the prefeasibility concept of a 44-Ton FCEV truck with, notably, Cenex, Arcola Energy, Toyota and ITM Motive as partners (**H2GVMids** project). Finally, EDF Hynamics recently started hydrogen business by operating a 0.5 MW filling station for a bus fleet in Auxerre (FR) (**AuxHYGen** project).

In the long-term, significant opportunities will probably be linked to the use of e-fuels, synthetic fuels derived from hydrogen in combination with CO2 (e-ammonia, e-methanol or e-kerosene) for maritime and aviation mobility. Indeed, low-carbon H_2 is widely seen as a promising alternative to fossil fuels for inland and short sea shipping while e-fuels should be more dedicated to long distance. In such a way, EDF R&D is coordinating the European interregional **H2SHIPS** project, in collaboration with partners like Port of Amsterdam, Birmingham university, HAROPA and Hynamics, in studying H_2 solutions for decarbonising river boats.

> Regarding energy transport, we can compare battery and fuel cell technologies. In terms of energy efficiency, the energy conversion process of the battery is more efficient (90%) than the one of H2 (30%). In terms of energy density, H2 is much more efficient (>550 Wh/kg) than the conventional battery (≈150/200 Wh/kg).

H2SHIPS European project



To assess an H_2-based zero-emission energy solution for ships, a port vessel retrofit with H_2 propulsion and circular economy principles will be built in Amsterdam. It will demonstrate the added-value of H_2 for on-sea transportation and develop a blueprint for its adoption.

FAHYENCE, H_2 Refueling station

In Sarreguemines, an H_2 refuelling station including an on-site AEL electrolyser was implemented in 2017 by McPhy, and operated by the city. EDF R&D analysed the performance of the installation by creating a remote monitoring and control system. The refuelling station (120 kW) delivers 350 bars for about a dozen vehicles.

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EDF R&D has **three Labs in France and six abroad** (China, Germany EIFER, Italy, Singapore, UK, USA) and an office in Brussels.
This white paper was co-written with **EIFER** (European Institute for Energy research) which has been at the heart of the excellence and know-how on H_2 for almost two decades.

OUR 4 SCIENTIFIC PRIORITIES

1. **DECARBONISING OUR CLIENTS' USES WITH ELECTRICITY**
2. **STRENGTHENING THE PERFORMANCE OF GENERATION ASSETS**
3. **INVENTING TOMORROW'S ENERGY SYSTEMS**
4. **ACCELERATING DIGITAL TRANSFORMATION**

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