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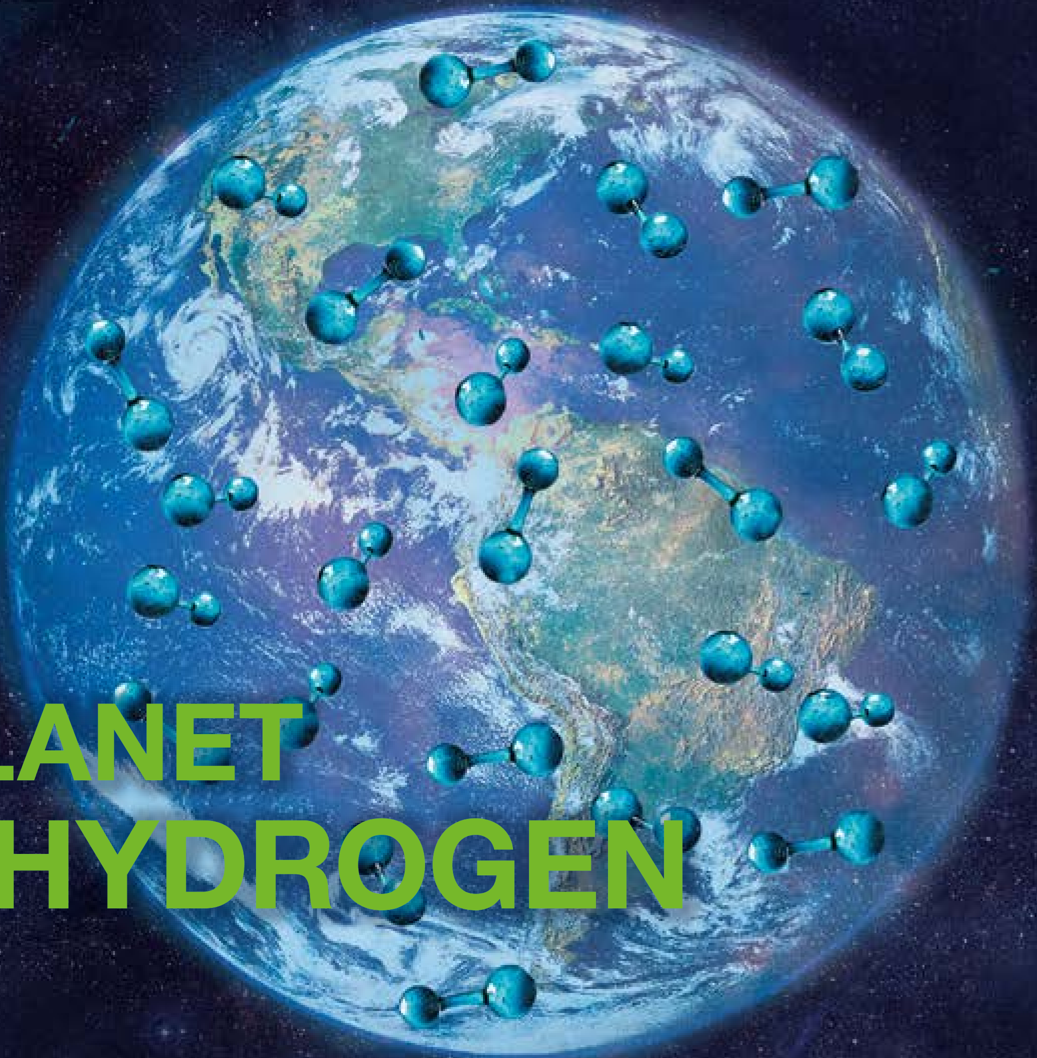

PLANET HYDROGEN

THE INTERVIEWS: Marco Alverà, Claudio Descalzi, Aurelio Regina, Francesco Starace

Hydrogen, energy of the future

by **Federico Testa**,
Professor of Economics and Business Management at the University of Verona - President of ENEA

With the Green Deal, Europe aspires to become the world's first climate-neutral continent by 2050. To achieve such a goal, it will be necessary to respond to major challenges and make careful choices to invest in an integrated, more efficient and interconnected energy system that can enhance the characteristics and advantages of each different energy carrier.
In this context, **hydrogen, which as an energy carrier is considered essential to the energy transition process and the reduction of climate-changing emissions, has become the focus of the political, energy and industrial debate.**
Last July, the European Commission launched the European hydrogen strategy with a dual objective: on the one hand, to support the use of hydrogen as a substitute for fossil fuels, and on the other to decarbonise its production by giving priority to green hydrogen (i.e. from renewables), but also considering other low-carbon production processes. Green hydrogen can contribute to cleaner and more sustainable industrial processes, extensive zero-emission mobility and reduced pollution from domestic heating, while also ensuring the flexibility and resilience of the energy system thanks to its capability to act as a link between the gas and electricity sectors.
According to the report "Hydrogen Roadmap Europe: a sustainable pathway for the European Energy Transition"[1], hydrogen will be able to bring significant socio-economic and environmental benefits to Europe since not only will it cover up to 24% of its final energy demand and create more than 5 million jobs by 2050, but it will also contribute to the reduction of 560 million tonnes of carbon dioxide.
In the proposal of the Italian National Recovery and Resilience Plan (NRRP), under the M2C2 Energy Transition and Sustainable Mobility mission €3 billion were allocated to promote hydrogen production, distribution and end use.
Italy can achieve a strategic position in all the economic sectors that contribute to the hydrogen value chain (production, logistics, transport and distribution, and end use in industry, mobility and residential sectors) since we can rely on a great manufacturing tradition, consolidated know-how, internationally renowned research centres and a geographical advantage that could make our country the future primary hydrogen hub in Europe and the Mediterranean area.
The national industrial chain involved in the development of hydrogen could be strengthened, which will entail some positive impacts in terms of production value and employment prospects, with between 300,000 and 500,000 more jobs expected in the next 30 years, depending on the level of technology implementation and the momentum of the transition process.[2]
Putting diverse technologies to their best use, according to the principle of technological neutrality, will prove crucial within a coordinated, integrated national initiative that promotes a horizontal approach through the **supply chain** and is able to convert the challenges ahead of us into positive actions.
The introduction of hydrogen as an energy carrier is a new development in energy system management, therefore an integrated and coordinated system approach that takes into account all different aspects is needed.

Some sectors are more technologically mature and ready, while others require further effort and investments in research and development. **Technologies, products, processes and solutions need to be developed to promote the establishment of a hydrogen-based ecosystem, while the supply of innovation, technology development and competence from the research sector is to be coupled with the demand for innovation and closed-loop management solutions from the operators of the production chain.**

However, **technology readiness alone is not sufficient. The concurrent implementation of legislation, regulations and incentives is needed to achieve the objectives set**. It is critical to reduce unnecessary bureaucracy, simplify and harmonise the formalities to be complied with for the construction of plants and infrastructure, and ensure definite and rapid schedules. It is also important to promote a closer and more stable relationship between research and the industrial system; to put a governance structure in place for strengthening the effectiveness and efficiency of the adopted strategies; to ensure the continuity and consistency of the policies introduced, with a view to a true paradigm shift for paving the way towards a sustainable future.

It would also be useful to develop and implement demonstrators on a significant scale (Hydrogen Valley). These could also act as technology incubators and service start-ups for the hydrogen industrial chain to create local ecosystems that could also be reproduced and expanded to other areas.

In this context, the world of research and innovation has a leading role to play to assist the recovery, within a competitiveness and sustainability perspective, aimed at measurable returns in terms of growth and development.

For over 30 years, ENEA has been carrying out research on and experimental development of the entire hydrogen supply chain, from production to end uses; we have competence, cutting-edge laboratories and infrastructure and can act as a link between research and industry. We have a comprehensive approach to hydrogen aimed at accelerating research and innovation and providing industrial chains with hi-tech infrastructure that can bridge the gap between laboratory and industrial scale.

We are active in national and international bodies for the promotion of the hydrogen economy; we have a number of partnerships with outstanding companies in the sector for technology development and transfer; we coordinate several European projects and fulfil prominent roles in an array of international initiatives.

Furthermore, ENEA assists the Italian Ministry of Economic Development, acting as a technical-scientific advisor within the hydrogen IPCEI (Important Project of Common European Interest), and works together with Confindustria, with which an out-and-out "pact for hydrogen" was signed to identify the potential for development of the Italian hydrogen industrial chains, cutting-edge technologies, innovative solutions and possible operational scenarios.

ENEA is not the only organisation in Italy that can provide support or offer valuable tools to achieve these objectives. Among companies, associations, and the scientific community and there are numerous entities whose contribution is also important, and whose experts authored some of the analyses and proposals that appear in this issue, which was designed to offer the broadest and most in-depth overview of the hydrogen scenarios, giving due space to research, innovation and national and international strategies.

I would therefore like to thank all those who contributed with their interesting articles and interviews, but also ENEA researchers, technologists and all the staff, because without their work, their ability to win calls for research funds and their daily commitment, we could not progress further in energy, towards new challenging achievements.

Federico Testa

1. Fuel Cells and Hydrogen Joint Undertaking FCH JU
2. Ambrosetti study "H2 Italy 2050"

Planet Hydrogen

In Italy and around the world, hydrogen is increasingly emerging as a key factor in the energy transition and a lever for economic development. By 2050, it is estimated that green hydrogen could meet a quarter of the global energy demand, with more than $60 trillion investments worldwide[1] and 5.4 million new jobs[2] in Europe alone, while a European House Ambrosetti-Snam study highlights that Italy could cover 23% of its energy needs with hydrogen, avoiding 97.5 million tonnes of CO2eq.

In this context, the European Commission launched an ambitious strategy last July, followed by national plans in Germany, France and Spain. Italy is also at work in the same direction, which is considered a priority for action by Stefano Cingolani, the Minister of Ecological Transition.

But what are the prospects and possible scenarios for the emergence of a hydrogen economy at a global level? How should our country act to create a hydrogen supply chain and gain spaces and competitiveness? Can we become a hub among Africa, the Mediterranean and Northern Europe? And what about research and innovation? In the following pages, together with the exponents of institutions, businesses and research, we have tried to address these issues, to analyse the environmental and economic aspects, the opportunities, but also the challenges, the barriers and the critical factors to overcome.

Our journey across the "Planet Hydrogen" begins with a key figure for the European R&I strategy and investment, Marya Gabriel, Commissioner for Innovation and Research, and continues with the contribution of Laurent Antoni, President of Hydrogen Europe Research, the European association of fuel cell and hydrogen research organisations. The horizon widens to include three "beacon countries" on three different continents: North America, with Sunita Satyapal, Director of the Hydrogen and Fuel Cell Technologies Office of the Department of Energy (DOE) of the United States; Australia, with Ken Baldwin, Director of the Energy Change Institute of Australian National University; and Asia, with Noboru Hashimoto of Panasonic Yamanashi University in Japan.

As for Italy, its dynamic panorama is apparent from the various contributions, highlighting many on-going activities and a strong desire to participate even at an international level. This, for example, is the case of the Important Projects of Common European Interest (IPCEI) illustrated by Mario Fiorentino, General Director for Industrial Policy, Innovation and SMEs at the Ministry of Economic Development by Maurizio Delfanti, CEO of Italy's Electric System Research, or of Mission Innovation, which Marcello Capra writes about. R&D activities and other on-going initiatives are focussed on by Antonino Aricò, Director of the Institute of Advanced Technologies for Energy of the CNR and by Luigi Crema the Vice President of H2IT, while Andrea Bombardi, RINA Executive Vice President, and Antonio Lucci, Senior Business Development Manager, underline the growing role of their company. The opportunities of the italian hydrogen supply chain are focused by Valerio De Molli, Managing Partner and CEO of The European House – Ambrosetti.

Regarding large organizations (and others), their priorities for action and willingness to be at the forefront emerge from the interviews with four of the major players in the sector: Aurelio Regina, Chairman of Confindustria Energy Technical Group, and the CEOs: Francesco Starace, of Enel, Claudio Descalzi of Eni, and Marco Alverà of Snam.

The last leg of our journey is dedicated to ENEA's R&D, its technologies, projects, infrastructure and investments in support of industrial production chains and satellite activities. Among these stands out a €14 million Hydrogen Valley to be realized at the ENEA Research Centre of Casaccia, north of Rome, to create an open "integrated ecosystem" for businesses, an incubator of technologies and services that brings together Research, Industry and Institutions under a green pact to build a hydrogen economy. Enjoy the reading.

Cristina Corazza

1. Bloomberg New Energy Finance
2. H2IT, the Italian Hydrogen Association

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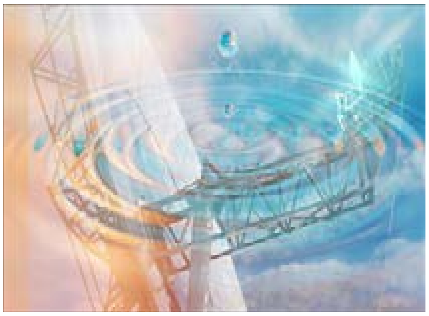
Summary



THE INTERVIEWS

FOCUS ENEA

Contributions

Research & Innovation: a Key Driver of Clean Energy Transition

Research&Innovation are key drivers to reach a 'hydrogen economy' for a clean energy transition in line with the Green Deal objectives. The EU hydrogen strategy proposes to make hydrogen production greener and sets a target to produce up to 10 million tonnes of clean hydrogen by 2030, while expanding its use in sectors where it can replace fossil fuels. In this context, Horizon Europe, the new programme which is being launched now, provides an increased budget to support R&I activities, jointly with industry. At least, the development of a 'hydrogen economy' depends on striking a balance between increasing supply and demand: as new hydrogen applications emerge, the supply chain naturally becomes more complex but, at the same time, there are many improvements in the efficiency, reliability, cost, and safety of processing, storing, and transporting hydrogen in Europe.

Ricerca e innovazione sono elementi chiave per arrivare ad una 'economia dell'idrogeno' e ad una transizione energetica in linea con gli obiettivi del Green Deal. Tuttavia, ad oggi, la produzione di idrogeno è ancora insufficiente e basata in gran parte sui combustibili fossili. La Strategia Europea per l'Idrogeno mira ad una produzione sempre più 'pulita' per arrivare a 10 milioni di tonnellate di idrogeno verde al 2030 e sostituire il più possibile i combustibili fossili. In questo contesto, occorre trovare un punto di equilibrio fra incremento della domanda e dell'offerta: soddisfare nuove richieste diventa sempre più complesso ma, allo stesso tempo, in Europa si stanno facendo molti passi in avanti sul fronte dell'efficienza, dei costi, della sicurezza dei sistemi di stoccaggio e trasporto. E il nuovo programma quadro per la ricerca Horizon Europe prevede ingenti investimenti in particolare per le partnership ricerca e imprese.

DOI 10.12910/EAI2021-001

di **Mariya Gabriel,** ***Commissioner for Innovation, Research, Culture, Education and Youth (*)***

The European Green Deal outlines our ambition to make the continent climate-neutral by 2050. The energy system accounts for about 75% of the EU's greenhouse gas emissions and the use of Hydrogen as a fuel, carrier, and energy storage medium is certainly promising. The European Commission launched an ambitious **EU Hydrogen Strategy[1]** in July 2020. It sets out a vision of how the EU can use it as viable solution to decarbonise different sectors of our economies.

Hydrogen is versatile with its potential to be used in many European industries - such as shipping, residential heating or replacing the use of coal in the manufacturing of steel, but the production of hydrogen-based energy is still limited and largely derived from fossil fuels. The EU hydrogen strategy proposes to make hydrogen production greener and sets a target to produce up to **10 million tonnes of clean hydrogen by 2030**, while expanding its use in sectors where it can replace fossil fuels.

The Role of Research & Innovation to enable an Hydrogen Economy

The development of a 'hydrogen economy' depends on striking a balance between increasing supply and demand. As new hydrogen applications emerge, the supply chain naturally becomes more complex. At the same time, we do see many improvements in the efficiency, reliability, cost, and safety of pro-cessing, storing, and transporting hydrogen.
Sustained research and development are essential to ensure that hydrogen technologies can become competitive at pan-European level. The EU research and innovation (R&I) framework programmes have supported in the past decade clean hy-drogen technologies, chiefly through the Fuel Cells and Hydrogen public-private partnership. We have invested close to **€1 billion on over 250 multi-partner projects** dedicated to the different challenges involved **in clean hydrogen research and innovation.** Horizon Europe, the new programme we are launching now, will step-up the public-private partnership with an increased budget supporting R&I activities, jointly with industry, on ad-vancing state-of-the-art, lowering-costs and increasing supply, storage and transport efficien-cy, widening the use to entire economy.

R&I key role to enable a hydrogen economy

A major objective of our R&I efforts will be to enable a hydrogen economy in Europe in which supply and demand generate a positive and sustained loop, in line with the Green Deal objectives. In other words, getting out of the standstill that characterises the introduction of a disruptive transformation: not enough hydrogen produced because there is no strong demand for it, while there is no strong demand for hydrogen be-cause not enough hydrogen produced.
We have devised several parallel strategies to break this hurdle where R&I has a key role. **To support the supply side and to promote clean hydrogen production, we need bigger, efficient, and durable electrolysers. This will require further coordinated R&I actions to maximise scientific output and reach new technological break-throughs.**

Higher production can also help develop more efficient industrial processes and develop economies of scale. To make this breakthrough possible, **a major recent initiative worth €1 billion, the 'Horizon 2020 European Green Deal Call', included a call for proposals to design a 100 MW electrolyser for hydrogen production** (currently the largest electrolysers can produce 20 MW).
A prime example of an energy-intensive sector is **steel production**, which emits on average 1.85 tons of CO_2 for every ton of steel produced. Greening this sector will require more re-newable energy resources and a smart integration and use of hydrogen technologies. Two recent EU-funded R&I projects play a role in this transition: **GrInHy and H2FUTURE**. GrInHy has developed the largest reversible solid oxide electrolyser in the world, and demon-strated its use on the surface treatment of steel. H2FUTURE has developed the largest low-temperature proton exchange membrane electrolyser of 6 MW.
Another strategy is **to link supply and demand**, creating an environment where they grow together. **Heavy-duty transport and urban mobility are excellent sectors for this approach.** What these sectors have in common is the fact that they either operate under a controlled route (trains, shipping transport, airplanes) or they are naturally restricted geo-graphically (public buses, taxis).
Two other such projects are **JIVE and JIVE2**, which brought almost **400 hydrogen-powered buses to European streets.** Hydrogen fuel cell buses are popular with both the public and transport operators, as they contribute to cleaner air in urban areas, and are much quieter than buses running on fuel. Their ability to travel up to 400 kilometres without refuel-ling also makes them a strategic choice for cities seeking greater sustainability.
Other projects have helped promote the adoption of **hydrogen-powered vehicles** in Euro-pean cities, bringing

over 1600 zero-emission cars and taxis to our streets. They have also significantly expanded the hydrogen network, having deployed **around 50 refuelling sta-tions in Europe**, kick starting a pan-European hydrogen fuelling station network.

Finally, **another challenge lays on linking supply and demand through a devel-oped infrastructure for hydrogen distribution and storage.** Depending on the local environment, distribution can be done through dedicated vehicles or by injecting hydrogen in-to the gas pipeline. The same is true for storage in dedicated tanks at different pressures, physical states, and temperatures.

European Hydrogen Valleys

We have also developed an approach that combines several challenges that need common multi-dimensional response. **'Hydrogen valleys' are EU regions, where several hydrogen applications are combined into an integrated ecosystem that covers the entire value chain.** Inspired in European communities which have become self-sufficient in their use of energy[2] the aim of the **EU-funded project 'BIG HIT'** was to demonstrate a fully-fledged hydrogen economy at a local scale, with its production, storage, distribution, and utilisation in heating, mobility, and power. As a result of this EU project, local resources that were previously used to import fuels are now being invested in the community - with hydrogen heating the buildings and powering the vehicles.

The project **HEAVENN** focuses on the Dutch city of Groningen making use of abundant off-shore wind energy, as well as onshore wind and solar resources, to produce hydrogen to manage the natural variability that these energy sources have. Hydrogen is transported through the gas infrastructure to deliver clean hydrogen to end-users, who can convert it into heat and power, as well as powering their transport vehicles.

Importantly, this initiative has a relevant role that goes beyond technological development. As they can be carried out in individual regions, they offer routes to economic growth and new skilled jobs. The success of these EU R&I projects is attracting international attention, and there is strong interest in replicating this model across the globe.

Under the umbrella of Mission Innovation, we have launched the Hydrogen Valley Platform[3] , which connects existing regional clusters with 30 other hydrogen valleys. This platform acts as a knowledge hub to raise awareness for local ini-tiatives.

Regulatory Framework and "guarantees of origin"

Beyond much-needed R&I support, **a successful European hydrogen economy requires an appropriate regulatory framework to support the development of new markets for clean hydrogen in context of strategic value chains such as manu-facturing industry or transport**. A regulatory framework including targets, boundaries but also incentives to convert current state-of-the-art to new, more sustainable hydrogen base technologies and processes will guide the transitions. While the renewable energy legislation can be a reference point for developing this framework, new techniques will also be needed to, for example, track the type of electricity used to produce hydrogen.

For example, the EU R&I **project CERTIFHY marked the start of a new green hydrogen market by launching the first-of-its-kind EU-wide "guarantees of origin" pilot scheme for green and low-carbon hydrogen**. Being able to certify and distinguish between clean hydrogen, low-carbon, hydrogen, and fossil fuel-derived hydrogen is an essential part of the transition ensuring we have environmentally sustainable hydrogen.Further steps will help to build these regulations so that we can bring the necessary innova-tions to life. This will need to be coordinated at an international stage.

Hydrogen and the General Public

R&I plays a central role in the safety of hydrogen, and many of the excellent projects we fund look

closely at the safety dimension, improved standards and on socioeconomic impacts. As the hydrogen economy turns more international, it is essential to have standards to facilitate a global hydrogen market, with standard rules on production and use across different industrial sectors. This ultimately leads to safer operations and rigorously tested products.

The Commission has strongly supported this research area with projects such as **HY-DRAITE, PRESLHY and HYTUNNELS-CS**, which have developed and provided input to several ISO standards. These transformations to our economies have impact on citizens in their professional contexts an also on everyday tasks like refuelling their car. the buy-in of the overall society is essential. The **HYACINTH project** has shown that, despite the promise of hydrogen technologies, they are mostly unknown to the wider public. It should be addressed by the research and innovation stakeholders since it can be a significant barrier to the adop-tion of hydrogen technologies.

The Future of Hydrogen

As hydrogen technologies inspire attention from all the EU and around the globe, all elements mentioned have their own role to play whether it is technological breakthroughs, expanded infrastructure, safety standards, social awareness, or transition caring for regional integration.

Each of those issues are relevant in the context of a functional hydrogen economy and their actions need to be coordinated and supported by R&I initiatives to achieve their full potential. **The EU is ready to support this initiative further through Horizon Europe, and the upcoming Clean Hydrogen public-private partnership.**

(*) Biography - Mariya Gabriel is the European Commissioner for Innovation, Research, Culture, Education, Youth and Sport. Under her leadership, the new Horizon Europe, Erasmus+, and the cultural strand of Creative Europe programmes (2021-2027) will be defined and implemented. Her main priorities are excellence in research, innovation and education (ERA, EEA, EIA); tackling the R&I divide in Europe; Europe as a leader in strategic innovation areas through the digital and green transition, with a particular attention for young people and regions. “No one left behind” and “Think out of the box” are her mottos.
She was elected as Member of the European Parliament (MEP) in 2009, 2014 and 2019. Mariya Gabriel is First Vice-President of the European People's Party (EPP), and, since 2012, Vice-President of EPP Women. Between 2017 and 2019, shel was European Commissioner for Digital Economy and Society.She is a board member of the UN youth programme Generation Unlimited (GenU). She is also known for her involvement in the fight for gender equality. In November 2020, she received the Annual Award of the Vienna Economic Forum "Partner of the Year 2020", rewarding her vision of a European knowledge strategy comprising the European Education Area, the European Research Area and the new Digital Education Action Plan. She holds a Master's degree in political sciences and international relations from the Institute of Political Studies (Bordeaux, FR) and a Bachelor’s degree in Bulgarian and French Languages from “Paisii Hilendarski” University (Plovdiv, BG).

1. COM (2020) 301 final: A hydrogen strategy for a climate-neutral Europe
2. An example is the Orkney Islands in Scotland, which in 2013 reached a point where they generated more wind energy from their turbines than they could consume.
3. www.h2v.eu

ENEA and hydrogen: a 30-year history

The R&D activities in ENEA in the hydrogen field began in 1989 and have never stopped. Through the Department of Energy Technologies and Renewable Energy Sources, ENEA is involved in R&D activities covering the overall hydrogen value chain, dealing with the development of processes, components and systems in the fields of hydrogen production, storage and end uses, from basic research on materials to applied research and demonstration in real environment conditions. Innovative applications always include technical and economic assessment and evaluation, simulation, prototype design and fabrication, and bench and field testing under selected operating conditions.

Nel campo dell'idrogeno l'ENEA ha una storia trentennale, iniziata nel 1989 con le prime attività di R&D, che proseguono tutt'ora. Il Dipartimento Tecnologie Energetiche e Fonti Rinnovabili è impegnato lungo tutta la catena del valore dell'idrogeno, attraverso lo sviluppo di processi, componenti, sistemi per la produzione, lo stoccaggio e gli usi finali, dalla ricerca di base sui materiali fino alla ricerca applicata ed alla dimostrazione su scala reale. Lo sviluppo di processi e tecnologie innovative include sempre valutazioni tecniche ed economiche, simulazioni, progettazione e realizzazione di prototipi ed attività di testing, a banco e in campo, in diverse condizioni operative.

DOI 10.12910/EAI2021-002

by **Giorgio Graditi,** ***Director - Department of Energy Technologies and Renewable Energy Sources***

Although in the last few decades hydrogen passed through cyclical waves of great enthusiasm and profound scepticism, the R&D activities in ENEA, which began before the 2000s, have never stopped. Now that hydrogen is indisputably affirmed as key factor to foster the energy transition, ENEA, thanks to the experience and skills gained over the years, can fully act as a pivot between research, innovation, experimentation, technology transfer and industrial development, at National, European and International level.

ENEA, through the Department of Energy Technologies and Renewable Energy Sources, is involved in R&D activities covering the overall hydrogen value chain, dealing with the development of processes, components and systems in the fields of hydrogen production, storage and end uses, from basic research on materials to applied research and demonstration in real environment conditions. Innovative applications always include technical and economic assessment and evaluation, simulation, prototype design and fabrication, and bench and field testing under selected operating conditions.

Alongside the technical-scientific activity, **ENEA, in this specific context, covers representative roles in National, European and International initiatives**: member of IEA-Hydrogen and IEA-AFC Technology Collaborative Programmes; member of Hydrogen Europe Research and the Clean Hydrogen Alliance and coordinator of the EERA Joint Programme on Fuel Cells and Hydrogen. At the national level ENEA is member of the Board of Directors of the Italian Association of Hydrogen and Fuel Cells and is serving as technical-scientific advisory to support the Italian Ministry of Economic Deve-

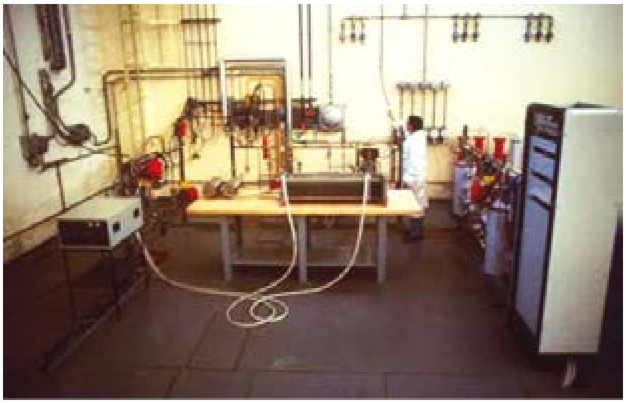


Fig. 1 Test Facilities for PEM FC up to 15 kW (ENEA Casaccia Research Center).

lopment in the framework of the Important Projects of Common European Interest (IPCEI) on hydrogen.

Hydrogen R&D Projects

In Italy, activities on hydrogen technologies, with specific interest on polymer electrolyte fuel cells, began in 1989 as part of a collaboration between ENEA and De Nora, which later became Nuvera Fuel Cells Europe. In the period 1994-98 the activities were conducted by Nuvera and ENEA, in collaboration with the Institute of Advanced Energy Technologies of National Research Council (Fig. 1). A few years later ENEA began a collaboration with a small company in Bologna, Roen-est for the development of cell components and stacks which resulted in a patent dealing with an innovative sealing system: Membrane Electrode Gasket Assembly (Fig. 2)
In the following years, attention gradually turned to the development of other technologies dealing with the hydrogen supply chain, from production systems to different types of fuel cells, such as molten carbonate fuel cells or solid oxide fuel cells. **Over the years, various pathways and methods for the production of hydrogen have been explored, both thermochemical and electrochemical, with carbonaceous matter and/or water as feedstock. Hydrogen conversion and utilization have been investigated too.**
Currently the **research is focused on advanced alkaline electrolysis, high temperature electrolysis, solar-assisted thermo-catalytic conversion of biogas and thermochemical water splitting for hydrogen production.** Regarding hydrogen conversion, different processes have been studied and experimented: "Power to Methane" for synthetic methane production via catalytic and biological methanation (carbon dioxide and carbon monoxide hydrogenation), liquid fuels production (Fischer-Tropsch synthesis products, methanol and DME). Regarding final uses several application are considered: in the thermal sector (hydrogen burners), in the power and CHP sector (high-temperature fuel cells and gas turbines) and in mobility (fuel cells).
R&D activities are mainly supported by the National Fund for Electric System Research under an agreement between ENEA and the Italian Ministry for Economic Development; in the years 2019-2021 the research program covers the overall hydrogen technological value chain from production to final uses. In particular, it is devoted to the development of:

- innovative hydrogen production technologies based on electrochemical and thermochemical routes such as high-temperature electrolysis, AEM (Anion Exchange Membrane) electrolysis, solar assisted reforming, thermochemical cycles.
- innovative hydrogen conversion technologies based on both catalytic and biological E-fuel production processes implemented at pilot scale with the construction of a 25 kWe PtG plant.
- hydrogen thermal uses in advanced combustion systems (burners, gas turbines).

Also at European level, on the topic of hydrogen technologies, ENEA is involved in several H2020 projects mainly co-funded by the Fuel Cells and Hydrogen Joint Undertaking (FCH JU).

Fig. 2 Stack PEM FC (ENEA-ROEN EST).

Fig. 3 High Temperature FC Experimental Facilities.

Several of these dealt with the development and validation of high-temperature fuel cells (SOCTESQA 2014-2017, NELLHI 2014-2017, SCoRed 2.0 2013-2017, qSOFC 2017-2020, INNOSOFC 2016-2019), other projects included the topic of high-temperature electrolysis (BALANCE 2017-2019, AD ASTRA 2019-2021) and still others have studied the operation of fuel cells with biogas and syngas (WASTE2GRIDS 2019-2020, WASTE2WATTS 2019-2021, BLAZE 2019-2022). The latest awarded projects concern the development of a fully fuel-flexible solid oxide fuel cell (SOFC)-based system for combined heat and power generation (SO-FREE) and the realization of a monitoring, diagnostic, prognostic and control tool (MDPC) for solid oxide electrolysers and reversible SOC stacks and systems (REACTT) (Fig. 3).

At pilot scale, two European projects coordinated by ENEA, CoMETHy (2011-2015) and PROMETEO (2021-2024), deal with the development of innovative hydrogen production systems, based on solar reforming and solar assisted Solid Oxide Electrolysis (SOE).

Demonstration Projects

One of the main roles of ENEA is to fill the gap between lab-scale and pilot plant installations, with the aim to assist industry in the first industrial deployment stage.

In this context, in the 1990 ENEA was involved in a first PtG project, realizing in the Casaccia Research Center a **demonstration plant (SAPHYS)**: hydrogen production was assessed by water electrolysis powered by intermittent renewable sources (photovoltaic); the produced hydrogen was stored and used to regenerate electricity by a fuel cell (3 kW Solid Polymer Electrolyte Fuel Cell). This prototype was identified as a promising application for stand-alone Photovoltaic Power Systems in remote areas. The project was funded by "FP3-JOULE 2 - Specific research and technological development programme (EEC) in the field of non-nuclear energy, 1990-1994".

Thirty years later, ENEA confirms its commitment and its involvement in the construction of demonstration plants in the hydrogen field. One of the projects that best represents this role by ENEA is the realization, at the **Casaccia Research Centre, of the first national Hydrogen demo Valley**, where comparative assessment and validation of integrated hydrogen technologies at demo or pre-commercial scale can take place.

The project is part of the international partnership initiative Mission Innovation, Challenge IC # 8 "Renewable and Clean Hydrogen" and is funded by the Italian Ministry of Economic Development.

The main objectives of the project in progress are: to evaluate technologies ready to contribute to the growth of a hydrogen economy; to increase awareness of hydrogen solutions within industry; to contribute to the policy makers' discussion on support mechanisms for hydrogen conversion and use in industry; to validate at a larger scale sustainable hydrogen micro-cogeneration, for the establishment of viable HRS business cases and resilient smart networks, before engaging in a First Industrial Deployment (FID) plant.

Utilization of the ENEA Casaccia Research Centre as technology "incubator" is logistically viable thanks to a large community (about 1000 people, 200 buildings, 100 hectares area) devoted to experimental validation of new technologies, the independent gas grid, the internal shuttle service, and the constant and high-level security and safety conditions, with an on-site Fire Brigade and safety protocols in place due to the nuclear reactors present in the Centre. In addition to these, highly specialised personnel (technicians/engineers/researchers) is available, able to operate multifunctional demo plants in response to various service requests and skilled in proposing innovative, optimized and sustainable solutions for the replication of technologies and systems in the market.

Support to national institutions and associations

In the Italian national framework, a **strategic alliance "hydrogen pact" has been finalized by Italian Manufacturers' Association (Confindustria) and ENEA.** The main goals of the joint agreement are:

- mapping the Industrial sector to identify the needs for hydrogen in industrial processes, applicable economic, environmental and efficiency criteria, and availability of adequate volumes of clean hydrogen.
- building a national database of industries that already use hydrogen in their production processes or that can use it to replace fossil fuels use.

Particularly, it is planned to identify the potential of industrial hydrogen chains, innovative solutions and possible operational scenarios by strengthening the collaboration between research and industry. Mapping of technologies, know-how, hard to abate sectors, technological evolution of hydrogen production and transport processes and of hydrogen using processes and potential of consumption and production capacity in the short, medium and long terms. Carry out an in-depth analysis of supply and demand, also concerning potential production and use in Italy of clean hydrogen and the investments needed to create a dedicated supply chain. Meet stakeholders of the hydrogen sector to build an open and continuous debate.

Through the agreement between Confindustria and ENEA, a closer and continuous relationship between research and industry is enhanced for the development of innovative technological solutions, projects and studies. This allows a wider perspective of a paradigm shift in energy systems, also through new project models and re-engineering of products and production plants.

ENEA has also signed an agreement with the Italian Ministry of Economic Development as a technical and scientific advisor for the IPCEI on hydrogen. The IPCEI is an instrument that aggregates several industries in a framework of Common European interest, supporting their investments in new products (R&D&I - research, development, and innovation) and in pre-commercialization (FID - First Industrial Deployment).

The IPCEI instrument recently supported two important supply chains through three integrated projects: the first on Microelectronics, followed by two distinct projects supporting the EU Battery sector. In 2019, the first call for manifestations of interest was issued also for an IPCEI on Hydrogen.

In this framework the collaboration between ENEA and the Italian Ministry of Economic Development allows to cooperatively develop activities and initiatives coordinating industry, national research and public administration in the effort to create an Italian hydrogen supply chain. Specifically, **ENEA contributes by providing technical-scientific studies, analyses, consultancy and assistance to support the Italian Ministry of Economic Development start-up, manage and complete the IPCEI.** ENEA also participates in working groups, commissions, national and European committees and round tables, and match-making event with European Commission, Member States and stakeholders, with the aim of supporting an Italian technical-scientific positioning for the implementation of the IPCEI regulation.

A new player at the service of the environment and the economy

Owing to a continuous European support to research, development and innovation, hydrogen technologies have transitioned from highly specialized applications to commercially available products. As a result, Europe is currently leading in several hydrogen technologies. However, many other countries and regions are equally ambitious about hydrogen and it is by no means guaranteed that Europe can maintain its leading position. The rapid development of a domestic market is therefore crucial to achieve climate neutrality by 2050 but also for preserving and enhancing EU industrial competitiveness, securing jobs and value creation in this new sector.

Grazie al costante sostegno dell'Unione Europea alle attività di ricerca, sviluppo e innovazione tecnologica le tecnologie dell'idrogeno, si sono evolute da applicazioni altamente specializzate, a prodotti disponibili sul mercato. Di conseguenza l'Europa è ormai leader in diverse tecnologie dell'idrogeno. Tuttavia, altri Paesi ed aree del mondo perseguono la stessa ambizione e non è affatto scontato che l'Europa potrà mantenere questa posizione di vantaggio. È quindi cruciale che il mercato interno cresca velocemente, non solo per raggiungere la neutralità climatica entro il 2050, ma anche per preservare e rafforzare la competitività dell'industria europea, garantendo posti di lavoro e valore aggiunto a questo nuovo settore.

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by **Laurent Antoni,** ***President of Hydrogen Europe Research***

In this new era of energy transition, Europe expects profound changes to achieve a climate-neutral Europe by 2050. In addition to the support and development of renewable energies in Europe over the last decades, **hydrogen is now recognised as a new player at the service of the environment and the economy.** Renewable electricity is expected to play a vital role in decarbonising the EU's energy consumption. However, it will not do it all through direct electrification, or battery solutions. **Hydrogen, as a versatile energy carrier and chemical feedstock, offers advantages that unite all of Europe's energy resources — renewables, nuclear, and fossil fuels — and enables innovations in energy production and end uses that can help decarbonise the most energy intensive sectors of our economy.**

The potential of hydrogen is being recognised worldwide, with strategies, plans and investments by government and industry ramping up in many countries, in particular in Europe. The year 2020 has seen the emergence of hydrogen strategies in many European countries and for the European Union as a whole. On 8 July 2020, the European Commission released the Hydrogen Strategy for a Climate-neutral Europe as part of the European Green Deal. It sets out an ambitious vision of how Europe can turn clean hydrogen into a viable solution to decarbonise different sectors over time. It identifies the challenges to overcome and provides a concrete policy framework for the European Clean Hydrogen Alliance to develop an investment agenda and a pipeline of concrete projects. The strategy defines a target of 1 million ton of hydrogen and an electrolyser capacity of 6 GW by 2024, and 10 million tons of hydrogen and 2x40

GW by 2030 and aims to create an enabling environment for the development of a secure, safe, affordable and just hydrogen economy in Europe.

Five main topics: technological and societal aspects

Over the past decades, owing to a continuous European support to research, development and innovation, hydrogen technologies have transitioned from highly specialized applications to commercially available products. This could not have been achieved without a strong commitment from industry, research and the public sector in Europe, in particular within the two FCH and FCH 2 Joint Undertakings. These private-public partnerships have been ensuring coordinated activities based on a common understanding and vision of the European industry represented by Hydrogen Europe (200+ members and 25 national associations), the European research represented by Hydrogen Europe Research (90+ members) and the European Commission with clear, quantified and focused objectives. As a result, **Europe is currently leading in several hydrogen technologies, and European companies and research institutions can be instrumental in advancing technological developments and industrial scale-up, contributing to cost-competitive renewable and low-carbon hydrogen.**

However, many other countries and regions are equally ambitious about hydrogen and it is by no means guaranteed that Europe can maintain its leading position. **The rapid development of a domestic European market is therefore crucial not only in terms of achieving climate neutrality by 2050 but also for preserving and enhancing EU industrial competitiveness, securing jobs and value creation in this new sector.**

Achieving the European hydrogen strategy will require significant additional research and innovation efforts with several research and innovation challenges to be addressed in the short and medium term, in particular in the next RTD framework Horizon Europe and the Clean Hydrogen JU. These challenges might be covering **five main topics** divided in **two aspects: a technological aspect and a societal one.**

Regarding the **technological aspect**, one could mention three main challenges:

- **Technology Readiness Levels** (TRL),
- **Manufacturing Readiness Levels** (MRL)
- **Preparation of the future.**

- **Technology Readiness Levels** (TRL)

Research needs to help industry to progress further in TRLs by bringing research results into commercial solutions while improving performance, durability and decreasing costs. It is aimed, in particular, at achieving @scale demonstrations and deployments in clean hydrogen production and in new applications of hydrogen as heavy-duty transports and industrial uses.

- **Manufacturing Readiness Levels** (MRL) - Research needs also to help industry to progress in MRLs ensuring its competitiveness at a global scale. Indeed, an enormous challenge lies ahead in upscaling currently available technologies to GW-scale factories of electrolyser and fuel cells required to drive forward the energy transition. This can be achieved by fostering cross-border RD&I collaboration and supporting a European RD&I ecosystem approach along strategic value chains, by connecting EU Hydrogen laboratories and infrastructures, setting clear performance standards and monitoring performance of subsidized pilots. These outcomes will be valorised in the setting up of several GW-scale factories in the frame of the Important Project of Common European Interest (IPCEI) under discussion.
- **Preparation of the future** - Finally Research needs to prepare the future through technological breakthroughs with new materials, new concepts, and at the same time to get rid of critical raw materials (CRM). Industry needs the continuous development of disruptive technologies and advanced materials all along the value chain. **Research and Innovation will be a key element for Europe competitiveness.** Among these challenges, three strategic research challenges can be mentioned: (i) low or free precious metals catalysts and critical raw materials for electrolysers and fuel cells, (ii) advanced materials for hydrogen storage (e.g. carbon fibres, hydrogen carriers…) and (iii) advanced understanding of the mechanisms of electrolysers and fuel cells performance/durability.

Regarding the societal aspect, two main topics appear:

- Education and training
- Increase of the public and policy stakeholders knowledge and acceptance or the Societal Readiness Levels (SRL).

- **Education and training**. There is a need in structuring interdisciplinary education and cross-sectoral training. **Europe needs to ensure a high skilled European workforce all along the hydrogen value chains: production, installation, operation and maintenance.** The first deployments are showing that this last point is of particular criticism. Trainers have to be trained and reskill or upskill an educated manpower the European industry will need in the coming years. This may also represent an opportunity to reemploy current workforce from declining industries and sectors.
- **Increase of the public and policy stakeholders knowledge and acceptance or in other words the Societal Readiness Levels (SRL).** This can be done by (i) intensifying the research on a better knowledge on all safety aspects, .e.g. underground parking, crossing tunnel (ii) continuing pre-normative research to ensure scientifically based standards and regulations and (iii) leveraging the increasing demand of information and expectation from the society towards a carbon-neutral Europe. **Carbon content becomes a pivotal parameter.**

A comprehensive, comparable classification and certification framework

These different points go beyond the only hydrogen technologies and cover the whole energy system. To give consumers the choice, by disclosing the origin of energies, there is a strong demand to develop a comprehensive, comparable classification and certification framework. It has to include information on sustainability as well as CO_2 and other greenhouse-gas footprints across the whole life cycle as well as their production and transport modes and the overall fuel mix and to ensure traceability. The carbon footprint needs now to take into account and not only the CO_2 emissions. Research is looking forward to continuing to contribute to ensure a scientific base approach.

In conclusion, clean hydrogen technologies have already reached a technological maturity allowing first commercial deployments. The high expectations put on hydrogen, in order to significantly contribute towards a climate-neutral Europe as well as towards an energy sovereign Europe, **request to scale-up and speed up massive production and deployments to show impacts at short term.** Hydrogen Europe Research and Hydrogen Europe are ready, fully mobilised and engaged to solve together with the European Commission and the members states these exciting and ambitious challenges.

The Industrial Policy and the IPCEI on hydrogen

Hydrogen represents a win-win opportunity for all Member States and through the IPCEI instrument they can provide the necessary public contributions to develop new hydrogen-related markets and products, creating new jobs opportunities and improving industrial competitiveness notwithstanding aid of State regulations. The IPCEIs play an essential role in ensuring that European industry progresses along this dual path of green and digital growth and transformation: EU Member States and companies are therefore now called upon to be the protagonists of the technological revolutions.

L'idrogeno rappresenta un'opportunità win-win per tutti gli Stati UE che, attraverso lo strumento dell'IPCEI, possono rendere disponibili i finanziamenti pubblici per sviluppare nuovi mercati e prodotti in questo settore, creare nuove opportunità di lavoro e rafforzare la competitività superando la problematica degli aiuti di stato. L'IPCEI svolge un ruolo essenziale affinchè l'industria europea possa proseguire nella duplice direzione di crescita e trasformazione green e digitale, con un ruolo da protagonista nelle rivoluzioni tecnologiche che abbiamo davanti.

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by **Mario Fiorentino,** ***Director General for Industrial Policy, Innovation and Small and Medium Enterprises - Italian Ministry of Economic Development***

Industry plays a crucial role in creating prosperity and sustaining a social model. Industrial policy is therefore an essential tool for the Authorities of each Country in ensuring welfare and shaping the citizens' lives. European industry, more than ever, is called upon to face challenging structural transformations linked to climate change, environmental degradation, accelerating pace of technological change as well as the unprecedented global health crisis that requires a re-thinking of economic and employment models.
To address these challenges and seize the opportunities of the transformation, the European Commission developed in 2017 **a new industrial strategy for Europe, with industrial policy initiatives directed towards innovation, digitisation and decarbonisation of our industry.**
The Strategic Forum for Major Projects of Common European Interest (IPCEI Forum)[1] - a high-level expert group, from representatives of the Commission, Member States, the world of Academic and Industry - developed in 2018 an important contribution to the EU's industrial future. The Forum focused on identifying value chains of strategic importance for the EU with the aim of strengthening Europe's competitive advantage and industrial leadership.

The Strategic Value Chains

The rationale of industrial policy interventions based on national markets and instruments is not sufficient as they are too small and fragmented to exert a significant impact at global level; the new approach is therefore based on strategic value chains, which involve markets in a logic of interdependence, sharing resources and cooperation, intra-EU but also in its international dimension.
These strategic value chains are interconnected and integrated industrial activities with great potential to contribute to Europe's green and digital transformation and to improve Europe's industrial competitiveness.
The Forum analysed several European industrial value chains and selected six strategic value chains where further joint and coordinated efforts are needed:

- Connected, clean and autonomous

vehicles
- Hydrogen technologies and systems
- Smart health
- Industrial Internet of Things
- Low-CO_2 emission industry
- Cybersecurity

These six strategic value chains are in addition to of the ones focused on "batteries" and "high-performance computing and microelectronics" already identified to disclose the way forward the IPCEIs.
In the identified strategic value chains, the European Union aims to stimulate the launch of major integrated projects on a European scale, to develop new and disruptive industrial processes, technologies and products; these integrated projects will create a European leadership on new products and technologies that will at the same time make it possible to address the industrial challenges linked to climate change, decarbonisation and digital development.
With the adoption of the new 2020 industrial policy strategy, the European Commission has set an ambitious and unprecedented goal of climate neutrality by 2050 for the European Union. In order to achieve this goal, which goes far beyond the already ambitious targets already fixed in the 2030 Agenda, the European Union has set itself the goal of embarking on a dual path of radical transformation: the green and digital transition.
In this context, **the IPCEIs play an essential role in ensuring that European industry progresses along this dual path of green and digital growth and transformation: EU Member States and companies are therefore now called upon to be the protagonists of the technological revolutions that will drive our competitiveness and economic development.**

The potential of the Strategic Hydrogen Value Chain

Hydrogen is an environmentally and climate friendly (zero emission) energy carrier. Produced from renewable energy sources, e.g. photovoltaic and wind power, or with low CO_2 technology, it has the potential to essentially replace fossil energy.
As underlined by the European Commission, hydrogen is currently the only alternative to fossil fuels capable of sustaining certain energy-intensive industrial applications (steel industry, building construction, chemicals, etc.).
Therefore, developing the strategic hydrogen value chain becomes essential for our green transition process: EU Member States are making huge efforts to meet the agreed emission reduction targets in sectors that could be decarbonised by the introduction of hydrogen.
Hydrogen therefore represents a win-win opportunity for all Member States: it is a challenge for stimulating new innovative and disruptive projects to develop new hydrogen-related technologies: through the IPCEI instrument each Member State can provide the necessary public contributions to develop new hydrogen-related markets and products, creating new jobs opportunities and improving industrial competitiveness notwithstanding aid of State regulations.
The whole hydrogen value chain will have to be invested in new innovative projects: production of hydrogen from renewable electricity with electrolysers; technologies to convert hydrogen into gases, liquids or chemicals with the aim of enabling the use of hydrogen-based or hydrogen-derived fuels on an industrial scale; adaptation of the natural gas network or construction of a hydrogen one and end-use applications, such as industrial processes, transport solutions (e.g. trains, heavy duty vehicles, maritime, aeroplanes), household appliances, etc.
Some hydrogen systems and technologies are technologically mature for large-scale implementation but are not cost-competitive yet, mainly due to lack of economies of scale.
EU-level support in coordinating and structuring large-scale initiatives could accelerate the deployment of massive hydrogen production and its usage beyond the RDI (Research, Development, Innovation).
In addition, the hydrogen value chain includes actors and industries from a wide range of sectors, Member States and regions: **coordination by the European Commission in cooperation with Member States, through the creation of a large Integrated Project of Common European Interest (IPCEI) could therefore be the most effective way for developing the potential of this strategic value chain**.

Why the IPCEI Instrument?

There are situations in which some investments cannot be feasibly sustained by the current market, in terms of risks and return of investment: this is the case of certain ambitious and complex projects characterised by a high degree of innovation, even more so if they require the involvement of several companies or Countries. Such investments involve a high degree of technological, financial or market risk, require coordination and cooperation efforts between several players in a value chain, but will generate spillovers beyond the investors, thus producing "positive externalities" for the community.
In these cases, the private investor is not available to take the full burden of the investment risk, and the credit market itself may not finance the project because it is considered too risky (or the risk compensation would be too high and make the investment cost prohibitive). In these cases, in order to **resolve these "market failures"**, it would be desirable to have public intervention by means of State aids from the various Countries involved in the project of common interest, as in the case of the IPCEIs.
In the case of the IPCEIs, state intervention produces a leverage effect of further private investment along the same value chain involved, triggering a virtuous effect of further projects that could not be carried out without the initial push of the large integrated project. Of course, given the single market and the competition on international markets regulated by the rules of the World Trade Organisation, any State subsidy/aid will be subject to a control of compliance with competition rules, in order to verify that the public intervention does not produce market

distorting effects or that such effects are limited and more than compensated by a prevailing public interest.
The IPCEIs' instrument is therefore regulated by the following legal basis:
A) Article 107(3)(b) TFEU (Treaty on the Functioning of the European Union), which provides that "aid to promote the execution of an important project of common European interest" may be considered compatible with the internal market.
B) The European Commission's IPCEI Communication (2014/C 188/02) which sets out the criteria for assessing public funding of IPCEIs.
As a general principle, in order for a project to be eligible for an IPCEI, it should meet the following requirements:

- make a concrete and clear contribution to one or more EU's objectives and lead to a significant impact on the EU's competitiveness and sustainable growth;
- involve several Member States working together to develop a major integrated project;
- the public contribution should be also accompanied by forms of in-kind investment by the beneficiaries themselves;
- the benefits should extend beyond the financing Member States and the sectors concerned, reverberating across the whole the European economy through positive spill-over effects;
- RDI projects should be highly innovative, going well beyond the state of the art;
- Projects involving *"First Industrial Deployment"*(FID) should allow the development of a new products or services with a high research and innovation content and/or the development of a highly innovative technological process;
- projects in the field of environment, energy or transport should be of major importance for the Union's environmental, energy or transport strategy or contribute significantly to the internal market (a possible hydrogen IPCEI is undoubtedly of major value in this respect).

Broad cooperation between Member States, the EU Commission and companies

The European Commission, when giving positive approval to an IPCEI, will verify that the positive effects of innovation, spill-overs and the achievement of key EU public policies prevail over the distortions that the aid granted may create in the each market sectors.
The IPCEI Communication allows public support up to 100% of the funding gap based on an extensive list of eligible costs, which are incurred during the RDI and FID stage, a phase during which the R&D content for product development before mass commercialisation is still very significant. Public incentives to cover costs during the mass production phase are never allowed.
In the preparation of a new IPCEI project, as in the case of Hydrogen, a broad cooperation between Member States, the European Commission and companies in the sector is necessary for discussing, coordinating and matchmaking; this approach will enhance the establishment of general mosaic/ framework of the integrated project on a European scale around which individual companies will be able to apply for their own well aligned projects to complete the European mosaic.
Forms of contribution through European programs and financial resources, to be added to those of each Member State, to balance the different countries' funding capacities, would represent the maximum expression of the European action's efficiency.
The Industrial Policy Direction of the Ministry of Economic Development is strictly endorsed in the IPCEI's establishment processes, having released this year the "EuBatIn" IPCEI (the second IPCEI on batteries) after the "Summer Battery" IPCEI and the IPCEI on "Microelectronics" during the last years, relying on this instrument as a great opportunity to develop our Industry, boost research and reach important innovation goals in the direction of the Twin Transition of the European Industrial Strategy.

Italian approach towards the IPCEI on Hydrogen

In the assessment of the panorama of industrial stakeholders in hydrogen technologies and systems, with the scope of outlining an European value proposition, France-Italy and Germany-Italy matchmaking events, and meetings with Member States, DG GROW and DG COMP of European Commission were organized to build a common program with shared objectives and based on a systemic approach to achieve the relevant European goals.
Additionally, in order to define the Italian value proposition for an IPCEI on hydrogen, expressions of interest including a first description of the specific project proposed by each player were called and round-table discussions organized among the Italian stakeholders. During these events, a more focused exchange of information took place around the proposed projects portfolios, defining the core innovative aspects and the possible interfaces with other (Italian or European) stakeholders in the attempt to place projects and players in consistent European hydrogen value chain that could be supported by an IPCEI.
A comprehensive database has been obtained connecting more than 150 national project proposals qualifying the maturity of the projects proposed by each stakeholder, a preliminary mapping was built around what are considered to be key players for short-term deployment within the Italian economic system. The described approach is aimed to build coherent and substantiated Italian position in the brokerage with the other Member States participating in the IPCEI on hydrogen initiative.

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The Mission Innovation main results and perspectives for clean hydrogen

Mission Innovation (MI) is a global intergovernmental initiative aimed at accelerating to accelerate clean energy innovation: 25 members on 5 continents are working to stimulate innovation with the objective to make clean energy more widely affordable. At the third MI Ministerial in 2018, members endorsed the addition of an eighth Innovation Challenge (IC) on Renewable and Clean Hydrogen, since MI recognizes the role of hydrogen in the energy transition. The Challenge is co-led by Australia, the EC and Germany with participation from Austria, Canada, China, France, India, Italy, Japan, Norway, Saudi Arabia, UK and USA. Its objective is to accelerate the development of a global market by identifying and overcoming key technology barriers to the production, distribution, storage, and use of hydrogen at gigawatt scale.

Mission Innovation è un'iniziativa intergovernativa globale composta da 25 membri di cinque continenti nata per accelerare e stimolare l'innovazione e promuovere la diffusione dell'energia elettrica da fonte rinnovabile. Nel 2018, in occasione della terza riunione Ministeriale di Mission Innovation, alle 7 Sfide Globali già approvate si è aggiunta come ottava sfida quella per l'Idrogeno verde e rinnovabile, riconoscendo il ruolo di questo vettore nella transizione energetica. Co-gestita da Austria, Canada, Cina, Francia, India, Italia, Giappone, Norvegia, Arabia Saudita, Regno Unito e Stati Uniti, l'ottava sfida si propone di accelerare lo sviluppo di un mercato globale identificando e superando le barriere tecnologiche alla produzione, distribuzione, stoccaggio e uso di idrogeno a livello di Gigawatt.

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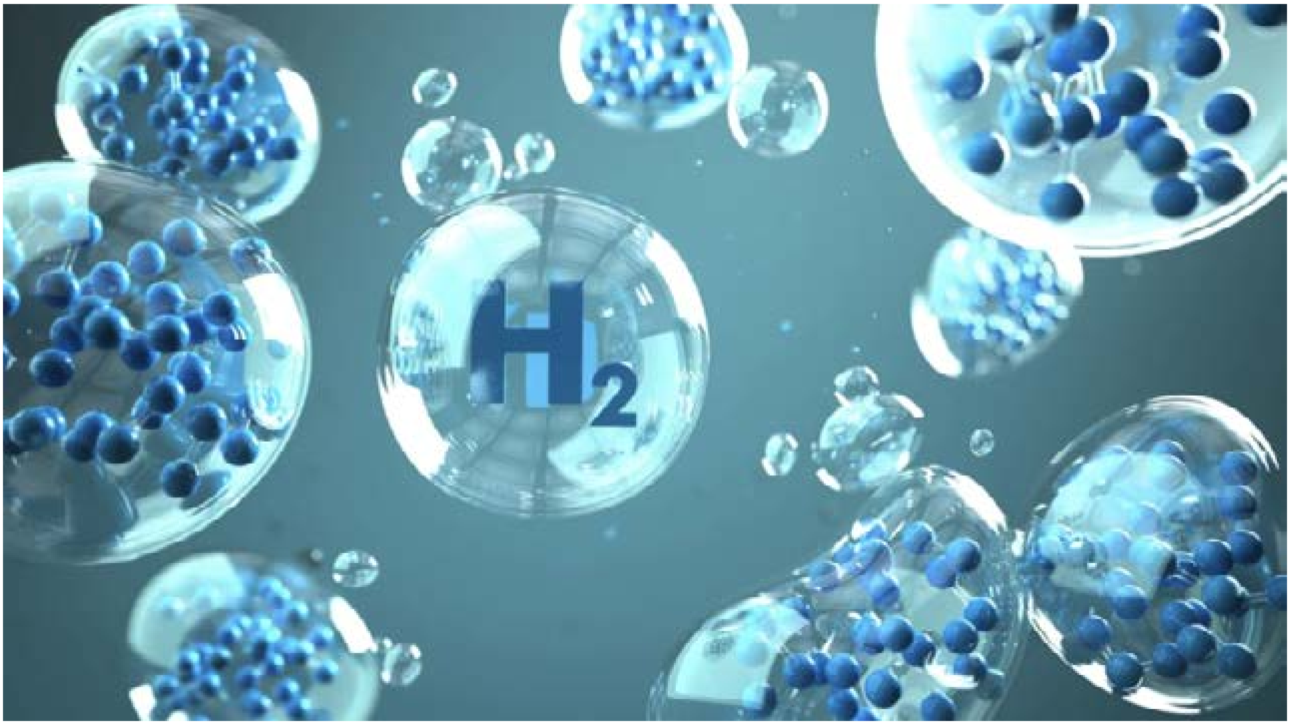
by **Marcello Capra,** *Ministry of Ecological Transition*

Mission Innovation (MI) is a global intergovernmental initiative working to accelerate clean energy innovation: 25 members on 5 continents are working to stimulate innovation with the objective to make clean energy more widely affordable. Mission Innovation members are continuing to work towards meeting their commitment to seek to double their investment in clean energy innovation over 5 years. Innovation Challenges (ICs) are global calls to action aimed at accelerating research, development and demonstration (RD&D) in technology areas that could provide significant benefits in reducing greenhouse gas emissions, increasing energy security and creating new opportunities for clean economic growth. The ICs cover the entire spectrum of RD&D: from early-stage research needs assessments to technology demonstration projects. Each IC consists of a global



network of policymakers, scientists and innovators working towards a common objective and built around a coalition of interested MI members. In 2016, MI members came together **at the United Nations Conference of Parties in Morocco (COP22) to endorse seven ICs. At the third MI Ministerial in 2018, members endorsed the addition of an eighth IC on Renewable and Clean Hydrogen since MI recognizes the role of hydrogen in the energy transition. The Challenge is co-led by Australia, the EC and Germany with participation from Austria, Canada, China, France, India, Italy, Japan, Norway, Saudi Arabia, UK and USA. The objective of IC#8 is to accelerate the development of a global hydrogen market by identifying and overcoming key technology barriers to the production, distribution, storage, and use of hydrogen at gigawatt scale.**

IC#8 has been set up to address the need for further technology improvements to enable hydrogen to be cost-competitive in the energy system: its participants are collaborating to identify and accelerate the key breakthroughs needed to achieve a cost-competitive hydrogen value chain and are collaborating with existing international co-operation forums including the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), the IEA Technology Collaboration Programmes and the Hydrogen Council.

The "Hydrogen Valley" concept

Members of IC#8 have identified focus areas where global research and innovation effort is likely to generate the most impact in the short term. The "Hydrogen Valley" concept, a geographical area – a city, a region, an island or an industrial cluster – where several hydrogen applications are combined together into an integrated hydrogen ecosystem, are one of the focus areas. The consumption of a significant amount of hydrogen and the coverage of the entire value chain in the "Hydrogen Valley" will offer a pathway for scaling up and making this technology a viable solution and will showcase the sectorial integration capability of hydrogen.

A two-day Antwerp workshop in 2019 gathered more than 80 attendees with interest in nascent "Hydrogen Valley" projects from Hydrogen Innovation Challenge member countries representing governments, industry and research community. Fourteen case studies were presented from all major jurisdictions exploring hydrogen as a future energy vector: Australia, Austria, Chile, China, EU, France, Germany, Italy, Japan, Netherlands, the UK and the US, with additional input from the Port of Antwerp and the Hydrogen Council. Italy presented the South Tyrol (Bolzano) Hydrogen Valley as an interesting example of Italian Valley at European level: hydrogen is produced by electrolysis completely from renewable sources for HRS.zsxc

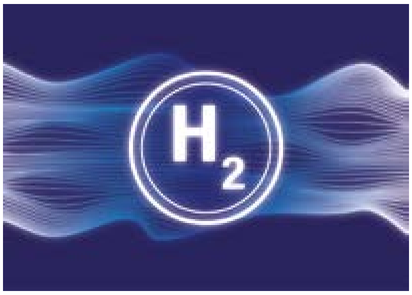
There is no one-size-fits-all solution when it comes to hydrogen valleys: different countries have different infrastructure and economic, geopolitical, and environmental circumstances. To facilitate knowledge sharing and reinforce global alliances around hydrogen valleys, **IC#8 is developing an online information-sharing platform on hydrogen valley projects in MI countries.** Information will be publicly available, but the platform will also allow contributing partners to take up direct contact with each other to share more detailed reflections on best practices and challenges.

New public-private innovation alliances

IC#8 is consolidating information on the latest technologies, lessons learned, and opportunities for collaboration related to the demonstration of integrated hydrogen solutions and infrastructure and distribution for hydrogen. For example, given that there are a limited number of research facilities that can conduct pressurized hydrogen testing for transport via pipelines, linking these laboratories to coordinate test conditions and sharing findings could help avoid duplication and accelerate deployment. In this way, IC#8 members and partners are combining complementary areas of expertise to fill information gaps and reduce duplication of effort through the IC#8 platform. **The development of the Hydrogen Valley Global Collaboration Platform and the work of the Hydrogen in the Gas-Grid Working Group are still in progress, but these initiatives are expected to support policymakers, industry stakeholders, and the hydrogen RD&D community in developing roadmaps, reducing the costs of implementation, accelerating future project delivery, and driving replicability.**

The second phase of Mission Innovation will build on the successes achieved whilst recognizing the need to shift the focus toward outcomes that will further accelerate the pace of innovation, and thereby facilitate countries' clean energy transitions by advancing the solutions and technologies needed to support national goals. **To achieve the shared goal of accelerating innovation, countries have agreed to develop a second phase that includes new public-private innovation alliances – Missions – built around ambitious and inspirational goals backed by voluntary commitments that can lead to tipping points in the cost, scale, availability, and attractiveness of clean energy solutions.** In this perspective hydrogen is expected to have a significant role also in the second phase of MI and a Mission "Hydrogen" is currently being defined on the basis of the results achieved in the context of the IC#8.

Following the Antwerp workshop,



the Italian Ministry of Economic Development set up The Hydrogen Table gathering the main national stakeholders in the value chain to encourage Italian companies and research organizations to actively participate in IC#8 activities. ENEA and the Ministry of Economic Development then signed in early 2021 a collaboration agreement in order to create the first Italian Hydrogen Valley to develop a national supply chain for production, transport, storage and use of hydrogen, focusing on research, technologies, infrastructures and innovative services. The project, conceived by ENEA, kicks off with a 14 million euro investment (in the frame of the Italian additional budget for the activities of Mission Innovation) to set up the first Italian technological incubator for the development of an hydrogen supply chain, in collaboration with universities, research institutes, associations and companies, to boost the energy transition and decarbonisation.

Hydrogen and fuel cell activities at the U.S. Department of Energy

At the U.S. Department of Energy (DOE), hydrogen and related technologies have been part of a comprehensive portfolio of activities for many years. Today fuel cells and hydrogen systems are becoming more available for multiple applications, but the primary barriers to widescale availability across sectors are still: cost, infrastructure and limited scale. To address these challenges, DOE's Hydrogen and Fuel Cell Technologies Office (HFTO) has a comprehensive portfolio of activities in R&D as well as enabling demonstration and deployment. DOE also has stewardship of 17 national laboratories across the U.S. with world-class, unique capabilities and over 50 Nobel Prize winners and experts tackling some of the most pressing energy challenges of our time.

Il Dipartimento per l'energia degli Stati Uniti (DOE), lavora da anni ad un ampio portfolio di attività sull'idrogeno e le tecnologie correlate. Ad oggi, le Celle a Combustibile e le Tecnologie della filiera Idrogeno stanno diventando sempre più mature per diverse applicazioni; tuttavia per una diffusione a più larga scala restano da superare barriere quali i costi, la carenza di infrastrutture e la limitata produzione. Per rispondere a queste sfide, l'Hydrogen and Fuel Cell Technologies Office (HFTO) del DOE sta portando avanti un insieme articolato di attività di R&D e di dimostrazione di tecnologie abilitanti. Inoltre amministra 17 laboratori negli USA con eccellenze riconosciute a livello internazionale, oltre 50 Nobel ed esperti impegnati ad affrontare le maggiori sfide energetiche del nostro tempo.

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by **Sunita Satyapal,** *Director - Hydrogen and Fuel Cell Technologies Office, U.S. Department of Energy*

Hydrogen is receiving increased attention worldwide for its role as a zero-carbon energy carrier that can impact hard-to-decarbonize sectors, as well as provide long duration energy storage for intermittent renewables like solar and wind. **At the U.S. Department of Energy (DOE), hydrogen and related technologies have been part of a comprehensive portfolio of activities for many years to enable emission reductions as well as resiliency, economic growth, and energy security.** While fuel cells and hydrogen systems are becoming more available for multiple applications like stationary power, transportation and industrial use, the primary barriers to widescale availability across sectors are still: cost, infrastructure and limited scale.

To address these challenges, **DOE's Hydrogen and Fuel Cell Technologies Office (HFTO) has a comprehensive portfolio of activities in research and development (R&D) as well as enabling demonstration and deployment**. DOE also has stewardship of seventeen national laboratories across the U.S. with world-class, unique capabilities and **over 50 Nobel Prize winners** and experts tackling some of the most pressing energy challenges of our time.

Market-driven targets to help the research community

HFTO has launched consortia with national lab core capabilities to address hydrogen production, storage, and fuel cells, and is funding industry and universities to join in these consortia to enable technology advances and address key targets.
These market-driven targets help guide the research community and are based on what is necessary to achieve parity with conventional commercial technologies or emerging advanced technologies in terms of cost, performance and other consumer expectations. For example, for transportation applications, the cost of hydrogen production must be less than $2 per kilogram (kg) and the cost of delivery and dispensing to the vehicle must also be less than $2 per kg, to be competitive with today's internal combustion vehicles. For large scale industrial and power generation applications, the cost of hydrogen must be less than $1 per kg due to the low cost of shale gas in the United States. However, today the cost of hydrogen production from electrolysis is about $5 to $6 per kg and cost must still be reduced.
In addition to R&D, to enable economies of scale, **DOE's HFTO launched the H2@Scale initiative (see Figure 1) to enable large scale production, storage and end use of hydrogen, catalyzing the development of infrastructure and further reduction in cost.** Producing hydrogen through electrolysis can enable greater penetration of intermittent renewables like wind and solar, as well as operation of baseload power plants, such as nuclear power. Hydrogen can also be produced from other diverse domestic resources in sustainable and carbon-free ways, including from fossil fuels with carbon sequestration.
The U.S. already produces 10 million metric tons of hydrogen, about one seventh of the global supply, and recent analyses shows the potential for a 2 to 4 fold increase in the economically viable production of hydrogen. End uses can include diverse areas such as the production of ammonia, chemicals and biofuels, as well as steel manufacturing, petroleum refining, transportation, and the power sector. By increasing the supply of hydrogen and co-locating end use at scale, we can pave the way for lower cost hydrogen infrastructure.
Infrastructure in the U.S. includes three large-scale geological caverns to store hydrogen, including the world's largest hydrogen storage cavern in Texas, over 1,600 miles of dedicated hydrogen pipelines, and nearly a dozen large scale liquefaction plants, in-

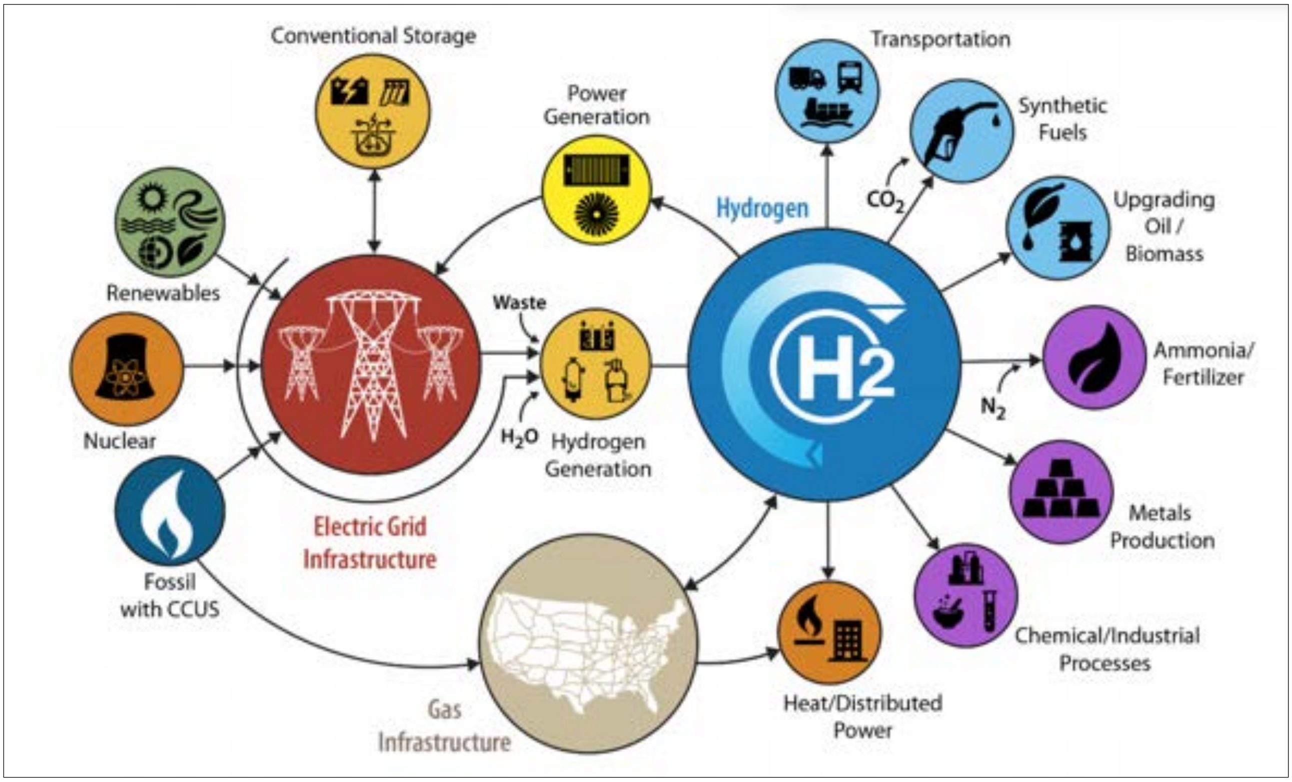

Fig.1 H2@Scale Concept: How Producing and Storing Hydrogen can Enable End Use Applications across Sectors

cluding those soon to be constructed. In terms of hydrogen fueling stations, approximately **45 commercial retail stations** are currently open, mostly in California with plans for up to 200 by 2025 to meet the projected growth in fuel cell vehicles.

One of the areas of growing interest is **heavy duty fuel cell trucks** and plans are underway by several industry players to develop such trucks for the transport of goods over long driving ranges. This will also enable a corridor of stations and infrastructure to be available for emerging truck fleets and help drive down cost. **And this also complements the strategies for large scale electric vehicle charging infrastructure for battery vehicles.**

Fuel cell forklifts and the importance of hydrogen safety

Perhaps the most noteworthy example of how DOE helped to catalyze an emerging niche industry in hydrogen was the case of fuel cell forklifts. By cost-sharing the demonstration of early forklifts a decade ago, the U.S. now has roughly 40,000 hydrogen fuel cell forklifts in warehouses at major companies and over 100 fueling stations just for this industry. Working with the developing industry has been critical.

The DOE program also emphasizes the importance of hydrogen safety, codes and standards. For instance, the program developed H2Tools.org to disseminate information and supports the Center for Hydrogen Safety (www.aiche.org/chs) which has numerous partners from industry and governments in different countries, to develop training materials and other safety resources. Such efforts are made available for global players to join, and to share information on lessons learned and best practices to accelerate global progress towards a carbon-free economy. While **hydrogen is just one part of a broad portfolio needed to meet our climate goals,** continuing to accelerate progress and impact the hard to decarbonize sectors will be essential to meet the challenging timelines ahead of us.

Australia's National Hydrogen Strategy

In 2019 the Council of Australian Governments' (COAG) Energy Council released a National Hydrogen Strategy (ANHS[1]) to address the hydrogen economy, and similar strategies have been following in most States and Territories in the Federation. A key difference with other national hydrogen strategies is the real prospect of becoming a major exporter of zero-carbon hydrogen and hydrogen derivatives to countries including Japan, South Korea and Germany who have already expressed strong interest in sourcing hydrogen from Australia. Australia's potential as a major renewable hydrogen exporter relies on: abundant and high-quality renewable energy resources; plentiful supply of low-cost land in areas of high renewable resource; and an existing, highly-developed energy export ecosystem.

Nel 2019 il Council of Australian Governments' (COAG) Energy Council ha pubblicato la National Hydrogen Strategy per arrivare ad un'economia dell'idrogeno, e strategie simili sono state adottate nella maggior parte degli Stati e dei Territori della federazione australiana. Una differenza essenziale rispetto ad altre Strategie nazionali è la prospettiva concreta di diventare un grande esportatore di idrogeno verde e dei suoi derivati, verso paesi come il Giappone, la Corea del Sud e la Germania, che hanno già espresso un forte interesse in questa direzione. Il potenziale dell'Australia si basa sull'abbondanza di fonti rinnovabili di alta qualità; grande disponibilità di terre a costi contenuti in zone ricche di risorse rinnovabili, ed un sistema di infrastrutture per l'esportazione di energia molto sviluppato.

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by **Ken Baldwin,** *Energy Change Institute Director - Australian National University*

Australia, like many countries, has developed a National Hydrogen Strategy (ANHS) to address the resurgent prospect of a hydrogen economy. The ANHS was released in 2019 by the Council of Australian Governments' (COAG) Energy Council, and has been followed by similar strategies in most States and Territories in the Federation. The ANHS examines how hydrogen can play an increasing role as an energy vector in various sectors of the economy, and how domestic hydrogen generation can contribute. The Strategy also examines the areas needing to be addressed in the development of the hydrogen economy, and the role of industry and governments (at all levels) required to make this happen. **A key difference with other national hydrogen strategies is that Australia has a real prospect of becoming a major exporter of zero-carbon hydrogen and hydrogen derivatives (such as ammonia) to help meet demand from countries including Japan, South Korea and Germany who have already expressed strong interest in sourcing hydrogen from Australia.** The reasons behind Australia's potential as a major renewable hydrogen exporter are threefold:

- abundant and high-quality renewable energy resources (some of the best in the world),
- a plentiful supply of low-cost land in areas of high renewable resource, and
- an existing, highly-developed energy export ecosystem.

Solar PV and wind are now the cheapest forms of electricity generation in Australia, with a levelized cost of elec-

tricity around US$30 per MWh[3]. In the most recent reverse auction in the Australian Capital Territory, the 14-year agreed feed-in tariff was below this level in real terms[4]. **Australia is now installing solar and wind at the most rapid rate per capita of any country, at a level 10 times faster than the world average**[5].

Cheap renewables and other comparative advantages

Cheap renewables therefore provide Australia with a clean energy cost advantage. In addition, some of the best solar and wind resources are co-located and complementary, such as in the northwest of the country where the wind often blows at night. These areas are largely desert environments, where land is relatively cheap. Therefore land-intensive renewable generation such as wind has relatively low land costs. Furthermore, these abundant renewable resources are often located side-by-side with major mineral deposits, such as Australia's world-class iron ore reserves in the Pilbara region of northwestern Australia. The export infrastructure for these minerals and the extensive oil and gas reserves of the northwest therefore provide a launch pad - the experience from which can be applied directly to hydrogen exports. Further, **hydrogen and renewable energy co-production onsite with world-class mineral reserves creates an enormous capability to value-add and create refined metals (iron, steel and aluminium) to generate a new export opportunity for green metals with embedded renewable energy.**

At the Australian National University Energy Change Institute[6] as part of our Grand Challenge *Zero Carbon Energy for the Asia-Pacific*[7] we have established the magnitude of the opportunities presented by these comparative advantages. We carried out calculations assuming that the world demand for Australian energy will remain the same, as will the demand for processed iron, steel and aluminium metals from its mineral exports.

We then take Australia's current energy exported in fossil fuels (coal and gas) and project that in future this will be exported as renewable energy. We assume that 20% of this energy will be exported as electricity (through high voltage, direct current undersea cables) such as is being proposed by Sun Cable's Australia-ASEAN Power Link[8] which has recently achieved major project status with the Australian Government. The remaining 80% we assume will be exported as hydrogen or hydrogen derivatives, such as the ammonia export terminal being proposed by the Asian Renewable Energy Hub[9] which has also achieved major project status. Under this scenario, Australia would export about 420 TWh per year of electricity direct to Asia, and about 50 Mt per year of green hydrogen while using 3,300 TWh per year of electricity in its production.

Next we assume that Australia's current iron ore and alumina/bauxite exports are processed onshore using renewable electricity and/or hydrogen reduction to produce green steel and green aluminium. This would generate a new export industry of 510 Mt per year of green steel and 18 Mt per year of green aluminium (compared to 6 Mt and 2 Mt domestic production per year respectively). Furthermore, it would require a further 2,300 TWh a year of renewable electricity for the refining processes and to create the necessary hydrogen. That brings the total renewable energy production needed for both energy and green metal exports to around 6,000 TWh per year. By comparison, this is almost 23 times Australia's current annual electricity generation of 264 TWh per year[10].

The Technology Investment Roadmap

The land area required is also significant. We assume a 50:50 ratio of solar PV and wind, with the land area dominated by the wind requirements. The 6,000 TWh per year of renewable electricity would need a land area of about 130,000 km² (or 1.7% of Australia's land mass). While this may appear large, it is similar to the area used for forestry and less than a tenth of the area used for agriculture[11], and is located in regions of relatively low land use.

A Crucial factor

A crucial factor is whether renewable hydrogen can be produced at sufficiently low cost to displace other energy sources and fit the projected demand trajectories. For example, Japan's 2017 Basic Hydrogen Strategy[12] projects US$1.30 per kg for the delivered cost of hydrogen by 2050. In a study performed by Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO) the cost of hydrogen production at the best Australia locations could be as low as US$1.60 per kg by 2025[13]. **The Australian Government has recently released a Technology Investment Roadmap[14] which has set a 'stretch goal' of producing hydrogen for $1.40 per kg.**

It remains to be seen whether Australia's comparative advantages in producing renewable hydrogen will be realised as technological and economic advances continue to drive down costs. Crucial to this process will be government planning and policy to help accelerate the adoption of renewables, as well as support the development of the nascent hydrogen economy. The Australian National Hydrogen Strategy and the Technology Investment Roadmap are important, but are just the beginning of the measures needed along the way.

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Japan's efforts to realize a hydrogen society

Japan has a long history of hydrogen and fuel cell technology development and is a world leader in this field, having achieved the commercialization of residential fuel cell power systems and fuel cell vehicles ahead of the rest of the world based on its many years of efforts. This paper introduces Japan's hydrogen energy policy and NEDO's technological development efforts.

Il Giappone ha lunga storia nello sviluppo delle tecnologie dell'idrogeno e delle celle a combustibile ed è un leader mondiale in questo campo. Dopo molti anni di sforzi è stato il primo paese che è riuscito a commercializzare sistemi alimentati a celle a combustibile per il settore residenziale e veicoli alimentati a celle a combustibile. L'articolo illustra la strategia del Giappone per l'energia da idrogeno e le attività di sviluppo tecnologico dell'organizzazione NEDO.

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by **Noboru Hashimoto**, *Panasonic Yamanashi University*

Japan's policy on hydrogen energy: past efforts regarding hydrogen and fuel cells

Japan has a long history of hydrogen and fuel cell technology development. Hydrogen production technology was carried in the Sunshine Project (new energy technology development plan) that started in 1974, and in the Moonlight project (energy saving technology development plan) from 1978 research and development of fuel cell technology (started in 1981) was promoted. Furthermore, in 1993, the New Sunshine Project started, which integrates the Sunshine Project and Moonlight Project, and in this program, the **International Clean Energy Network Using Hydrogen Conversion (WE-NET) has started.** This is a technological development for transporting and utilizing hydrogen produced from overseas renewable energy, etc., this will be the prototype of the hydrogen supply chain currently being worked on in Japan. After that, in the 2000s, efforts on establishing regulations and standards, that are indispensable for social demonstration and market introduction of residential fuel cell power systems and fuel cell vehicles, were made and all of them have been commercialized.

Positioning in the basic energy plan

Until now, hydrogen and fuel cells have been expected as promising technologies in the future, but fuel cells have been positioned mainly as one of the energy saving measures in the national energy policy. However, hydrogen was taken up in the 4th Basic Energy Plan revised in April 2014. Specifically, "**Hydrogen is expected to play a central role in future secondary energy in addition to electricity and heat**". Then the plan mentioned how to accelerate the realization of a society that utilizes hydrogen for daily life and industrial activities, that is "hydrogen society". In addition, it was pointed out that in order to realize a hydrogen society, it is necessary to develop hydrogen power generation technology and manufacturing, storage and transportation technology for stable supply of hydrogen, in addition to the development and spread of the Fuel cells. In the 5th Basic Energy Plan formulated in July 2018, "dramatic en-

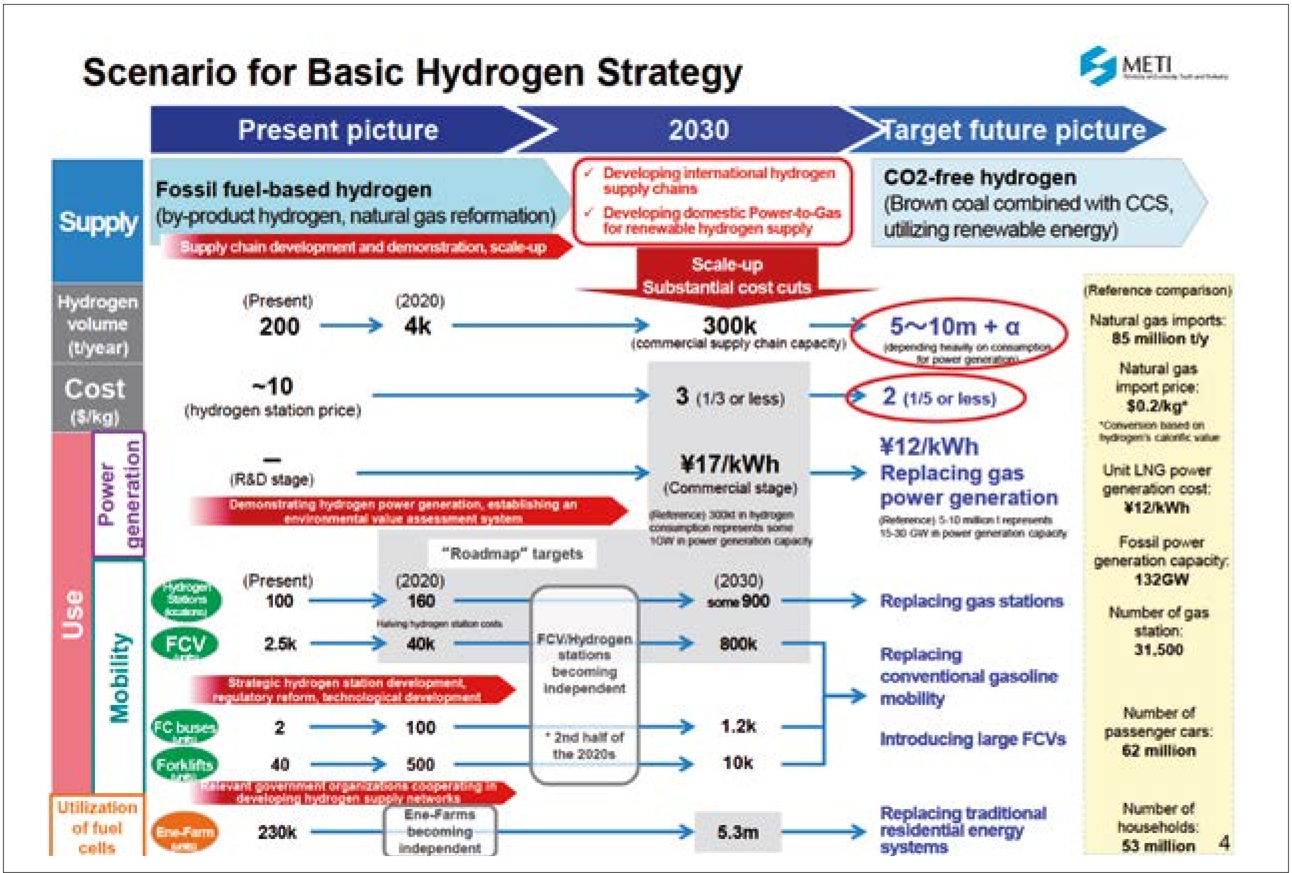

Fig.1 Scenario on hydrogen basic strategy

hancements of efforts toward the realization of a hydrogen society" is listed as one of the policy measures toward 2030, and under the expansion of renewable energy expectations, a new role of hydrogen like as energy adjusting capability to the energy systems is expected.

Hydrogen/Fuel Cell Strategy Roadmap

Following the Fourth Basic Energy Plan decided by the Cabinet in April 2014, the Ministry of Economy, Trade and Industry summarized **"Hydrogen/ Fuel Cell Strategy Roadmap"** showing the efforts of public and private stakeholders to realize a hydrogen society, in June 2014. This roadmap has three phases based on the time required to overcome technical issues related to hydrogen and secure economic efficiency.

Phase 1: Dramatic expansion of hydrogen utilization

Phase 2: Full-scale introduction of hydrogen power generation / large scale Establishment of a new hydrogen supply system,

Phase 3: Establishment of a total CO_2-free hydrogen supply system

These phases are carried step by step. Based on this roadmap, NEDO **promotes Power to Gas technology development** which includes the development of hydrogen power generation, hydrogen supply chain, and water electrolysis hydrogen production technology corresponding to Phase 2 and Phase 3. Furthermore, the roadmap was revised in March 2016 in light of technological progress and the introduction of fuel cell vehicles to the market, and concrete targets such as the number of fuel cell vehicles and the number of installation locations for hydrogen refueling station were added. In March 2019, the roadmap was significantly revised based on the direction indicated in the Hydrogen Basic Strategy and the Fifth Energy Basic Plan, which will be described later. In this revision, the structure has been changed corresponding to the basic hydrogen strategy, and numerical targets such as both specifications of elemental technologies and costs were clarified because the introduction targets shown in the roadmap was incorporated into the basic hydrogen strategy. In addition, specific actions (action plans) that should be taken to achieve this goal have been newly incorporated. At the same time, an **Evaluation Working Group** will be set up to grasp the progress of the roadmap. In the future, it is expected that measures will be progressed based on the goals and action plans shown in the roadmap.

Hydrogen basic strategy

The **Hydrogen/Fuel Cell Strategy Roadmap was formulated as a policy of the Ministry of Economy, Trade and Industry, but under the direction of Prime Minister Abe (at that time)**, ahead of the rest of the world the "Basic Strategy for Hydrogen" was formulated in December 2017 after the discussions by experts from industry, academia and government. After the entry into force of the Paris Agreement in November 2016, major countries have begun to announce ambitious plans and visions for 2050. **Under this circumstance, this strategy shows not only a direction and vision including targets that the public and private sectors should share for the realization of hydrogen society with a view to 2050 but also an action plan to the goal. As for the long-term vision, Japan aimed to realize carbon-free hydrogen and make hydrogen a new energy option, and set out to realize hydrogen cost equivalent to that of conventional energy.** In addition, the action plan includes the introduction target values for residential fuel cell power systems, fuel cell vehicles, hydrogen stations, etc., which have been shown in the Ministry of Economy, Trade and Industry's "Hydrogen/Fuel Cell Strategy Roadmap". Introduction target of a new application like as fuel cell buses and forklifts has also been added (Fig. 1). Furthermore, the Ministry of Economy, Trade and Industry and NEDO held a hydrogen energy ministerial meeting as a forum for ministers of major countries to discuss. The action policy of each country announced as the "Tokyo Declaration" in October 2018 was deepened and presented as "Global Action Plan" in October 2019. After that, **at the 3rd Hydrogen Ministerial Conference, a "Progress Report" was released that summarizes the progress of efforts by each country and institution, and the direction of future efforts was shared by the governments, international organizations, and industry working toward the realization of a hydrogen society.** Japan is setting out various policies toward the realization of a hydrogen society while appropriately grasping global trends and cooperating with the world.

NEDO's initiatives

NEDO, **as one of Japan's largest R&D project promotion organizations, promotes technology development projects in the hydrogen and fuel cell fields, mainly based on the policies of the Ministry of Economy, Trade and Industry.** Regarding fuel cells, NEDO is working on technological development of polymer electrolyte fuel cells (PEFC) targeting mobile objects and solid oxide fuel cells (SOFC) for stationary use. In addition, regarding hydrogen stations, which are indispensable for the spread of fuel cell vehicles, and proceeding with initiatives such as technological development to halve the installation and operation costs, review of regulations, and data acquisition for the formulation of new standards. Furthermore, **NEDO is carrying the technology development projects for the realization of hydrogen gas turbine power generation for the dramatic expansion of hydrogen energy use, the construction of an international hydrogen supply chain, and Power to Gas,** which is an energy system combined with renewable energy. Here, I will introduce the main initiatives at NEDO.

Fuel cell technology development

Regarding PEFC, NEDO developed electrode catalysts, electrolyte membranes, membrane electrode assemblies (MEA), which simultaneously realize the high efficiency, high durability, and low cost required for the autonomous spread and expansion of fuel cell vehicles after 2030, and various materials and components such as MEA constituent materials, high-precision performance prediction technology as a common basic technology, prediction technology for the fuel cell systems degradation, high-precision measurement technology (Evaluation methodology for MEA cell / material structure and performance up to high temperature and high-precision observation technology).
As for SOFC, NEDO promoted the development of cell stacks and systems that achieves both high efficiency (power generation efficiency of over 65%) and high durability (durability of 130,000 hours) in order to expand the use as a distributed power source. **All these projects were completed in 2019 with remarkable results.** In 2020, NEDO decided to deal with common issues in the industry based on the status survey of companies after the introduction of residential fuel cell power systems and fuel cell vehicles to the market, and from 2020, a new "Collaborative Industry-Academia-Government R&D Project for Solving Common Challenges Toward Dramatically Expanded Use of Fuel Cells and Related Equipment" has started. In 2019, NEDO planned projects targeting a basic technology in the cooperative area to realize a highly efficient, highly durable, low-cost fuel cell system (including hydrogen storage tanks, etc.) and technologies adapted to non-conventional applications. They will contribute to the independent spread expansion after 2030. NEDO planned a project targeting the technology to develop and solicited new implementers at the end of the fiscal year: 46 research groups were adopted.

Hydrogen refueling station

In order to respond to the issues for the spread and expansion of hydrogen refueling stations, NEDO is carrying technical development which contributes both to regulatory review and to reduction of maintenance and operating costs of hydrogen refueling stations. NEDO is also developing international standards relating to high-pressure hydrogen tanks for vehicles and the quality control methods of hydrogen. Regarding the review of regulations, NEDO is implementing issues such as identifying items for realizing labor-saving and unmanned operation, examining the optimum equipment configuration based on risk assessment, and acquiring various data to expand the applicability of general-purpose materials. As for a cost reduction, NEDO will study modularization and packaging based on standard specification conditions, study safety evaluation methods for extending the life of component equipment, and study high-pressure compatible long-life polymer component, electrochemical compressors, etc. In addition, **NEDO is proceeding with the development of a new hydrogen filling procedure (protocol) for heavy duty vehicles with a view to international cooperation with the United States and Europe.**

Hydrogen power generation/ Supply chain

In order to realize gas turbine power generation using hydrogen, NEDO is developing combustors for small size (several MW class) and large-scale (several hundred MW class) which will solve technical problems peculiar to hydrogen power generation such as suppressing NOx emissions during combustion, preventing burned out of combustor by flashback and countermeasures against combustion vibration. In order to promote the utilization of hydrogen power generation, the world's first system capable of 1 MW class hydrogen exclusive combustion/LNG co-firing has been installed in Kobe City, and technical verification is underway to supply both heat and electricity to the region.

Furthermore, regarding the construction of an international hydrogen supply chain that produces hydrogen by utilizing unused resources overseas and transports it to Japan, NEDO is proceeding with technological development using liquefied hydrogen and methylcyclohexane as hydrogen carriers. For methylcyclohexane, the world's first hydrogen transport test started in November 2019. Regarding liquefied hydrogen, major facilities such as a hydrogen transport ship and a hydrogen receiving base have been completed, and test operations are scheduled to begin in the future.

Power to Gas

Regarding the water electrolysis hydrogen production equipment, which is the key to Power to Gas, the main issues are upsizing, high durability, load followability, and cost reduction, however **NEDO is focusing on the analysis of the reaction mechanism including degradation and performance evaluation methods as a basic technology.** This technology is essential for the development of the main issues. On the other hand, for the system, small-scale development (hydrogen production capacity of about 5 to 30 Nm^3 / hour) started in 2014. Currently, we are proceeding with large-scale technology development (hydrogen production capacity of about 300 to 1,200 Nm^3 / hour) in Namie Town, Fukushima Prefecture and Kofu City, Yamanashi Prefecture. Of these, **the Fukushima Hydrogen Energy Research Field (FH2R)2, which is a test and research facility that will installs the world's largest 10 MW class electrolyzed hydrogen production equipment, is being developed for the project to be implemented in Namie Town, Fukushima Prefecture.** In addition to the production of hydrogen by making the best use of its own 20 MW photovoltaic power generation facility, it will verify its adjusting ability by changing the load of the entire system including the water electrolysis hydrogen production equipment.

Conclusion

In December 2020, following the policy that Prime Minister Suga announced in a statement of belief at the extraordinary Diet session that opened on October 26, 2020, that domestic greenhouse gas emissions will be "substantially zero" by 2050, "Green Growth Strategy for Carbon Neutral" was formulated. Hydrogen continues to be an important field in this growth strategy and a supplementary budget of 2 trillion yen is required for research funding for the next 10 years, and policy support is also expected.

The hurdles for the full-scale spread of hydrogen are not low, and there are many issues to be solved, but Japan will steadily advance the course of technological development toward the realization of a sustainable society.

Acknowledgments

I would like to thank NEDO for their cooperation in creating this article.

1. New Energy and Industrial Technology Development Organization, is a national research and development agency that creates innovation by promoting technological development necessary for realization of a sustainable society.
2. It is the largest solar hydrogen production plant ever built in the world

H2 Italy 2050, the European House - Ambrosetti study for Snam

Italy can become a hub and infrastructure bridge for hydrogen, using it to its advantage to reach European climate targets and create new forms of industrial competitiveness, also leveraging manufacturing potential and expertise in the natural gas supply chain. This is what emerges from the study *H2 Italy 2050: a national hydrogen value chain for the growth and decarbonisation of Italy*, carried out by The European House - Ambrosetti for Snam to examine the potential of the Italian hydrogen supply chain for the first time.

L'Italia può diventare un hub e un 'ponte infrastrutturale' per l'idrogeno, utilizzandolo a suo vantaggio per raggiungere i target europei sul clima e creare nuove forme di competitività industriale, anche facendo leva sul potenziale manifatturiero e sulle competenze nella filiera del gas naturale. È quanto emerge dallo studio *H2 Italy 2050: una filiera nazionale dell'idrogeno per la crescita e la decarbonizzazione dell'Italia*, realizzato da The European House – Ambrosetti per Snam per esaminare per la prima volta le potenzialità della filiera italiana dell'idrogeno.

DOI 10.12910/EAI2021-009

by **Valerio De Molli,** *Managing Partner and CEO of The European House – Ambrosetti*

On 21 April, the Council and the European Parliament reached an historic agreement on emission reduction targets: the commitment to climate neutrality by 2050 and a reduction of at least 55% of emissions by 2030 became law. Italy can use hydrogen to its advantage both to reach these decarbonisation targets and to create new forms of industrial competitiveness, leveraging its manufacturing potential and expertise in the natural gas supply chain. This is what emerges from the study **H2 Italy 2050: a national hydrogen value chain for the growth and decarbonisation of Italy, carried out by The European House - Ambrosetti for Snam to examine the potential of the Italian hydrogen supply chain for the first time.**

The study was presented as part of the Villa D'Este Forum of The European House - Ambrosetti that, together with Valerio De Molli, Managing Partner & CEO of The European House - Ambrosetti and Marco Alverà, CEO of Snam, saw the involvement of an Advisory Board composed of: Esko Aho, former Prime Minister of Finland and innovation expert, Steve Angel, CEO of Linde, Suzanne Heywood, Chairwoman and Acting CEO of CNH Industrial and Francesco Profumo, President of Compagnia di San Paolo.

Like the rest of the world, today Italy is facing a difficult relaunch phase. The changes that have disrupted everyday life and work over the past year are calling even more forcefully and urgently for the need to build a resilient, sustainable economic system.

Europe's challenge of becoming the world's first climate-neutral continent by 2050 is a historic opportunity. Seizing this opportunity means building a new social and energy paradigm and a massive industrial engine through significant infrastructure and innovation investments. To do this, it is necessary to make forward-looking choices today to build an integrated,

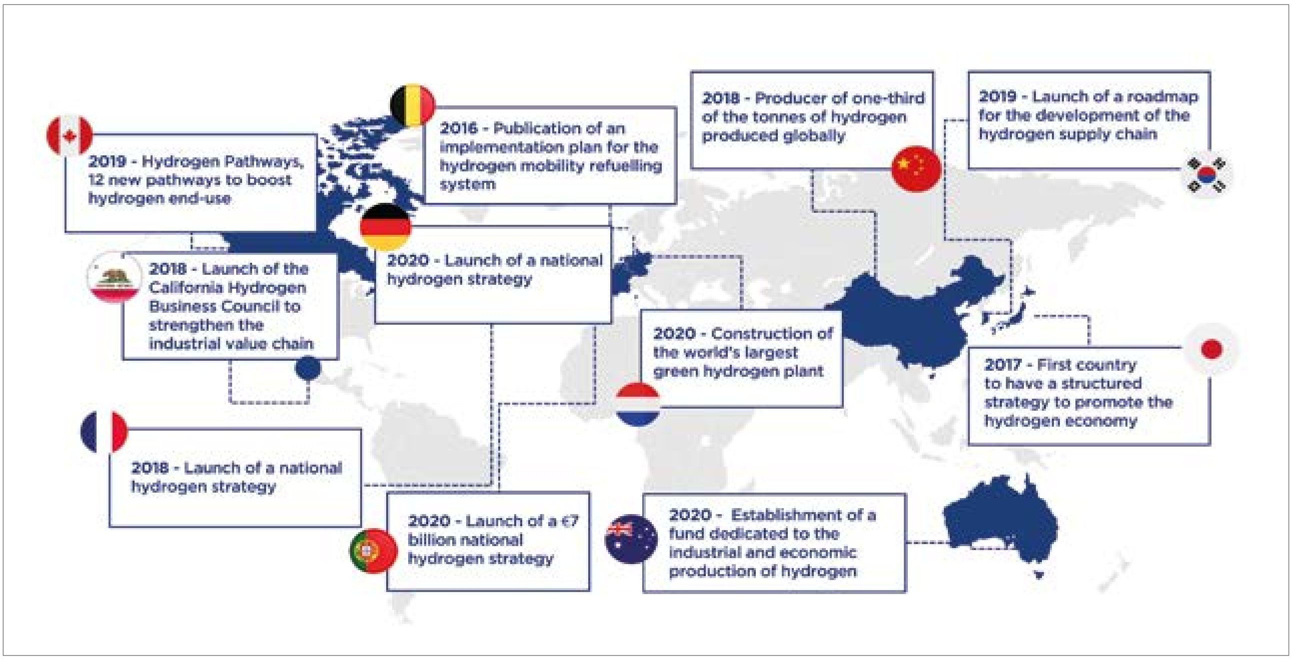

Fig.1 National strategies related to the world of hydrogen and launch year. Source: analysis of various sources by The European House – Ambrosetti, 2020.

more efficient and interconnected energy system that can make the most of the characteristics and benefits of each vector.

A key link for the sustainability of energy systems

In this context, hydrogen is a key link for the sustainability and functionality of future decarbonised energy systems. Its versatility and integration with other clean technologies for the production and consumption of energy are increasingly catalysing the attention and interest of governments. **The study of The European House - Ambrosetti analysed the national hydrogen strategies developed by the main OECD countries. Among these, Italy is one of the few that has not drawn up an advance operational roadmap for this energy vector aimed at exploiting its benefits.**
In a context of growing interest in hydrogen, the study examines the contribution of this energy vector to the energy transition process and estimates the economic, social and environmental impacts that it could have in Italy from its development to 2050. Thanks to its intrinsic characteristics, hydrogen can be considered an essential energy vector for the decarbonised future, in close synergy and complementarity with the electricity vector. In fact, it allows decarbonising end uses since it generates zero emissions and can be produced with processes having zero climate-altering emissions. This way, hydrogen can accelerate decarbonisation processes in a way that is complementary with other technologies, especially in sectors that still contribute most to climate change emissions today, from heavy industry (e.g. chemical and steel industry) to heavy and long-distance transport (e.g. heavy commercial vehicles and buses), from non-electrified rail transport to residential transport, for which various types of uses are examined, in particular for heating.

Moreover, hydrogen is able to offer advantages to the entire energy system, guaranteeing its flexibility and resilience, smoothing the peaks of electricity production from renewable sources and thus supporting the growing diffusion of non-programmable renewables also thanks to its distinctive ability to act as a link between the gas and electricity sectors. Used in a complementary way with other technologies, hydrogen can therefore contribute significantly to creating cleaner and more sustainable industrial processes, achieving zero-emission mobility and **reducing emissions from domestic heating, an environmental opportunity that could mean more than 97 million tonnes of CO_2 less for Italy, 28% of today's total emissions.** Furthermore, thanks to its unprecedented ability to act as a link between the gas and electricity sectors, hydrogen can guarantee flexibility to the energy system, advancing the spread of renewables.

Italy as a hydrogen hub and "infrastructure bridge"

The transport, storage and use of hydrogen have many synergies with the natural gas sector. This is why the current gas infrastructure can be seen as an accelerator that can allow faster penetration and first-mover positioning for Italy and its supply chains. In fact, hydrogen has the advantage of being able to be easily transported through the existing gas network, which is particularly extensive and widespread in Italy compared to other European countries. Moreover, the development of technologies for the production of green hydrogen and the increasing availability of renewable electricity in the coming years will strongly drive down the price curve for the production of hydrogen, thus achieving competitive cost levels with respect to the other alternatives.

The study shows how thanks to its particular geographical positioning and extensive gas network, Italy can aspire to the role of a European and Mediterranean hub, importing hydrogen produced in North Africa through solar energy at a cost that is 10-15% lower than domestic production, exploiting the greater availability of land for the installation of renewable energy and the high level of irradiation, and at the same time decreasing seasonal variability.

This way the country can become an **"infrastructure bridge"** between Europe and Africa, enabling greater penetration of hydrogen in other European countries as well. Furthermore, the Italian gas network can provide a launch pad for accommodating increasing percentages of hydrogen in the network through a series of targeted investments. Finally, the Italian energy system – characterised by a significant level of renewables and distinctive skills related to biomethane – is able to efficiently integrate hydrogen

The integration of hydrogen into the national energy mix can combine with the development and strengthening of an industrial supply chain capable of responding to future market needs, thus competitively positioning the country in the international landscape.

Policy proposals for GDP growth and new jobs

To assess hydrogen's potential to stimulate Italian industry, for the first time **the study "H2 Italy 2050"** reconstructed the entire supply chain of plants, components and equipment by analysing the role of this vector in all its phases: from production to transport and storage, up to multiple end uses and related services.

Using this innovative methodology composed of over 100,000 analytical observations, the study identified **90 technologies related to the hydrogen supply chain**. Based on this mapping and reconstruction it was estimated that **over the next 30 years the development of hydrogen in Italy could generate a cumulative production value of between 890 and 1,500 billion euros in the connected chains. Assessing the direct, indirect and induced effects, its contribution to the growth of national GDP could reach up to 37 billion euros by 2050.** This would be like adding a whole new industry equivalent in size to today's automotive supply chain to the country's economy. The effects on employment would also be extremely significant, creating between **320,000 and 540,000 new jobs by 2050.**

The realisation of these benefits depends on the definition of a concrete strategic vision and a national roadmap that proactively involves the gov-

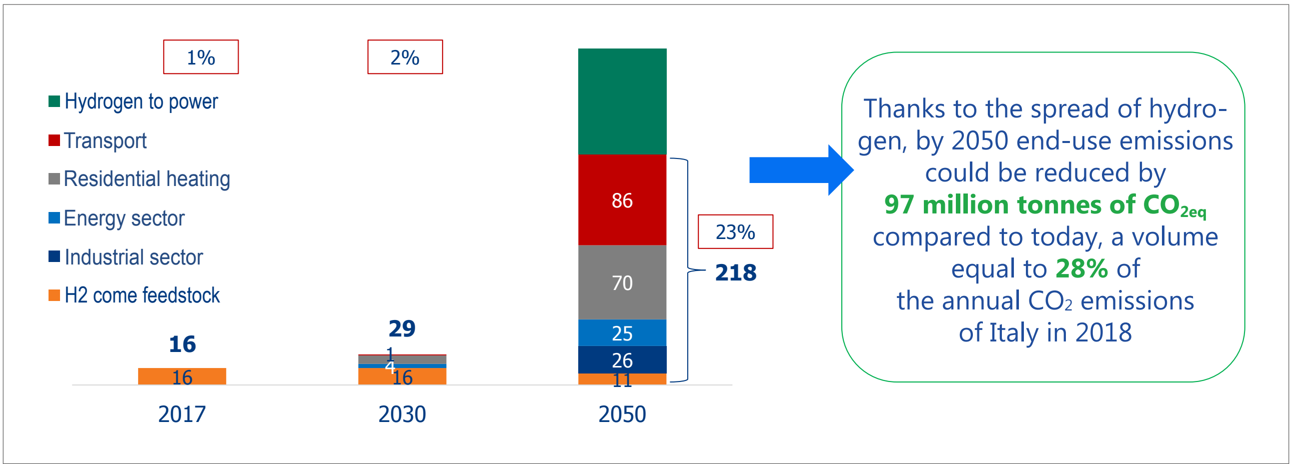

Fig.2 Potential evolution of hydrogen in final energy demand in Italy in the development scenario (TWh and % of total consumption), 2017, 2030 and 2050. Source: analysis of data from "The Hydrogen Challenge" and various sources by The European House - Ambrosetti, 2020.

ernment and the world of industry.
The "H2 Italy 2050" study identified six development guidelines to be implemented:

- **Make Italy the "conductor" of a European hydrogen strategy by defining a national vision, updating the INECP and participating more actively in the European Clean Hydrogen Alliance.**
- **Create an innovation ecosystem and accelerate the development of a dedicated industrial supply chain** through the conversion of existing industry, the attraction of new investments, the allocation of dedicated funds and the creation of favourable regulatory frameworks.
- **Support the production of decarbonised hydrogen** at a national level by leveraging incentive mechanisms similar to those used for renewables and promoting the creation of marketable guarantees of origin at a European level.
- **Promote the widespread use of hydrogen in final consumption** through the introduction of gradual mandatory shares of the energy mix and by promoting synergistic incentives in the ETS mechanism such as Carbon Contracts for Difference.
- **Encourage the development of specialised skills** both for new professional roles and to accompany the transition of existing specialists by promoting the emergence of appropriate training courses at various levels and across different disciplines.
- **Raise awareness among the public and the business world** of the benefits of using this vector through specially developed communications campaigns aimed at different stakeholders.

In summary, **hydrogen can be the best ally of renewable electricity to allow Italy to be a protagonist in the global fight against climate change and at the same time to promote new opportunities for development and employment for national industrial value chains**. As the study shows, thanks to its geographical position, the strength of the manufacturing and energy sector and a widespread gas network, Italy has the potential to become a continental green hydrogen hub, assuming an important role in the European hydrogen strategy. The hydrogen economy is therefore within reach and an opportunity that we cannot miss.

Hydrogen as an energy vector: towards an Italian strategy

Drawing a trajectory of hydrogen penetration in Italy is very hard: in fact, large margins of uncertainty exist about the evolution of the costs of the technologies involved and there are a series of barriers. Hydrogen production and use solutions need to start a virtuous path of increasing volumes and decreasing prices; transport and storage infrastructures are almost totally to be built; technical regulations are still incomplete; last but not least, the production cost of green hydrogen is around 5 times higher than fossil fuels, for the same energy content. But since the hydrogen penetration phase will be mainly driven by public policies, it will be possible to gradually address and overcome these barriers.

Delineare una traiettoria per la diffusione dell'idrogeno in Italia è molto complesso, tenuto conto degli elevati margini di incertezza sull'evoluzione dei costi delle tecnologie e delle barriere che ancora permangono. La produzione e l'utilizzo di idrogeno devono incamminarsi su un sentiero virtuoso di incremento dei volumi prodotti e riduzione dei prezzi; le infrastrutture di stoccaggio e trasporto devono essere quasi ancora del tutto costruite e la regolazione tecnica è ancora incompleta. Inoltre il costo di produzione dell'idrogeno verde è ancora 5 volte superiore a quello dei combustibili fossili, a parità di contenuto energetico. Tuttavia, considerando che la fase di penetrazione dell'idrogeno sarà prevalentemente a guida pubblica, risulterà possibile affrontare e superare gradualmente queste barriere.

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by **Maurizio Delfanti,** *CEO RSE- Ricerca sul Sistema Energetico*

The process of decarbonization of the economy has been adopted as an irreversible strategic choice by many countries, including the European Union; along the same line, President Biden has committed to the complete decarbonization of the United States economy by 2050. Renewable energy sources are the key to reach this objective, thus enabling the progressive phase-out of fossil fuels. This evolution shall be accompanied by an increase in the level of "electrification" of all types of energy consumption, so that important sectors, such as urban heating and private road transport, be adapted to use the electric vector instead of fossil hydrocarbons.

But this strategy alone will not reach the target, for two main reasons, and in particular:

- Electric renewables are largely composed of intermittent, non-programmable and barely predictable sources, such as solar and wind, thus requiring extensive flexibility resources, pending the risk to waste significant quantities of energy, during periods when the generation exceeds the demand, even for a long time (overgeneration);
- Not all end-use sectors are easy to be efficiently electrified, with special reference to high-temperature industrial processes and long-distance transport (mainly air and sea transport; but also

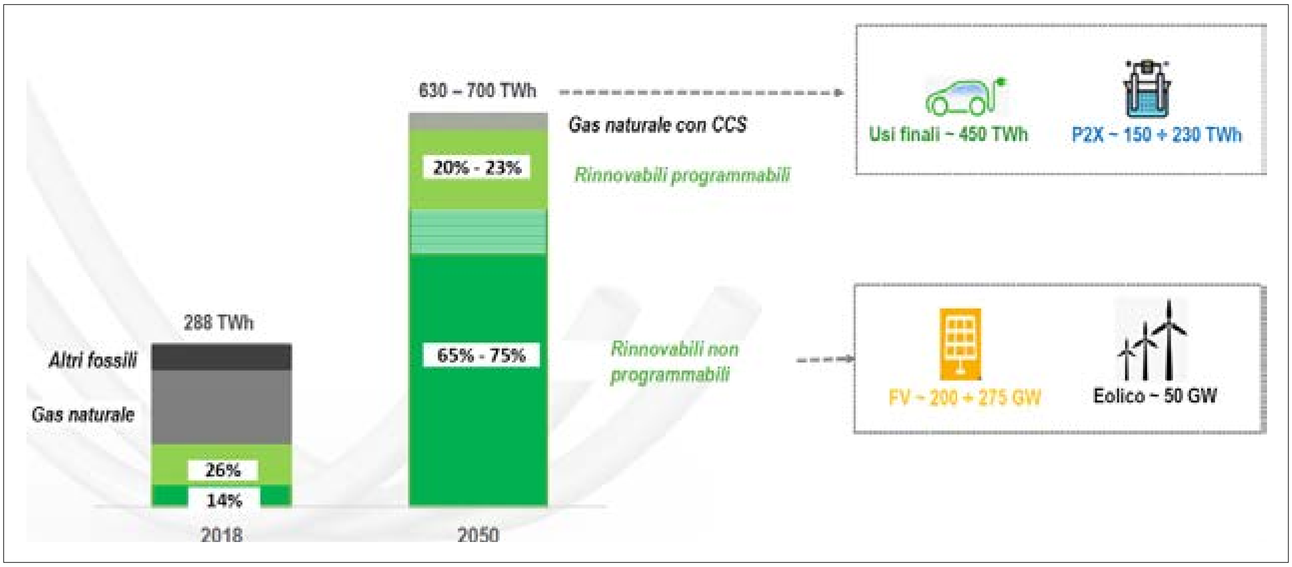

Fig.1 The Italian electricity system in 2050.

hard-to-electrify railways, and road freight).

Hydrogen, as an energy vector, will allow to overcome both these criticalities. In fact, high performance electrolysis systems to produce hydrogen in significant amounts will constitute the required high power, flexible electrical loads suitable to efficiently use the renewable energy produced during surplus periods, thus "transferring" it to other end-use sectors with virtually unlimited capability. **In several applications, moreover, the hydrogen vector represents an almost "perfect substitute" for fossil fuels. From the standpoint of end-uses, hydrogen can significantly improve the efficiency of several processes (for example, the use of hydrogen in a fuel cell reaches higher conversion efficiencies than those of an internal combustion engine powered by traditional fuels). On the other hand, we must not forget the logistical drawbacks of hydrogen: its low energy density makes long distance transport in gaseous form very inefficient; this makes it difficult to justify the expensive infrastructure required.**

The future of hydrogen in Italy

Drawing a trajectory of hydrogen penetration (i.e. the quantity of hydrogen use as a function of time, from now to 2050) is very hard: in fact, large margins of uncertainty exist about the evolution of the costs of the technologies involved. Scenario analyses, currently ongoing at RSE, are based on complex models of the entire Italian energy system (TIMES_RSE). In our approach, the path leading to a certain objective (e.g. net zero emissions at 2050) is determined according to a criterion of minimum overall cost.

Figure 1 **presents the possible evolution of the electricity mix in Italy from today to 2050.** The figure shows a strong increase (more than doubling) of the production of electricity, totally de-carbonized in 2050. The consumption of electricity in final uses is also much higher than today (increase of about 50%), due to the electrification of various sectors. A very significant share of electricity generated from renewable sources is reserved for "Power to X", which means the production of green hydrogen and its derivatives. **Under this scenario, between 10 and 15 % of final energy consumption would be constituted of hydrogen and fuels derived from it.**

The so-called "green" hydrogen, obtained by electrolysis from renewable sources, is the most suitable choice from the strategic standpoint, as it fosters the entire benefits of this vector (almost complete absence of greenhouse gas emissions; flexibility tool for the electrical system, with absorption of surplus production from renewable electricity). The main limitation of this solution resides in its cost of production, today around 5 times higher than fossil fuels, for the same energy content.

Looking at current costs of production, a possible alternative is given by "blue" hydrogen, which can be considered equivalent to "green" hydrogen in terms of CO_2 emissions. However, this type of hydrogen has some important limitations, namely: it does not use electricity, (and therefore does not contribute to the efficient exploitation of renewable electricity); the use of carbon dioxide currently occurs only in small quanti-

ties; finally, its stable and safe storage underground is possible in specific geographical areas.
Figure 2 depicts the path towards 2050: the increasing trend of hydrogen production and use accompanies, in a more than linear way, the reduction of carbon dioxide emissions.
By 2030, the level of hydrogen penetration is expected to remain marginal; nevertheless, an industrial strategy to gain expertise and manufacturing capacity in the hydrogen technology sector must include a somewhat accelerated path. In fact, in line with the experience of other energy technologies, **the hydrogen penetration phase will need to be supported by public policies for quite a long time.**
These policies could be designed to steer the demand growth (progressive use in "hard to abate" end-use sectors), and to support the production of green hydrogen in increasing quantities; these provisions should be consistent with the availability of growing amounts of renewable energy generated in excess in the power sector.

Barriers to overcome and some instruments

The development of hydrogen technologies encounters, like any new sector, a series of barriers: hydrogen production and use solutions need to start a virtuous path of increasing volumes and decreasing prices; transport and storage infrastructures are almost totally to be built; technical regulations are still incomplete; last but not least, the production cost is far from being competitive.
Since the hydrogen penetration phase will be mainly driven by public, this will make it possible to gradually address and overcome the barriers mentioned above.
As of today, economic stimulus measures are set to foster the economic rebound expected at the end of the present serious COVID 19 emergency. Instruments such as the National Recovery and Resilience Plan, the IPCEIs (Important Projects of Common European Interest) and the various national and European programs to support research and innovation include very significant quotas dedicated to hydrogen technologies. This will cover, at least in a first phase, the financial gaps, and will trigger new industrial initiatives.

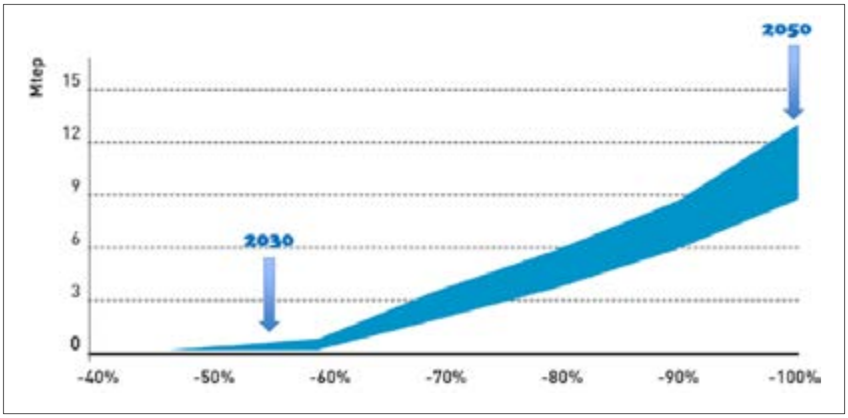

Fig.2 Hydrogen produced and reduction of greenhouse gas emissions (wrt 1990)

CNR contribution to national development of sustainable hydrogen technologies

The need to develop a green hydrogen infrastructure is now largely recognized in Italy as a crucial point to achieve the required energy transition. Hydrogen is the focus of intense research activities at CNR. A survey of projects is provided focusing on specific challenges that still need to be overcome for a wide scale diffusion of hydrogen technologies.

La necessità di sviluppare un'infrastruttura per l'idrogeno verde è oggi ampiamente riconosciuta in Italia come punto cruciale per realizzare la transizione energetica. L'idrogeno è al centro di intense attività di ricerca presso il CNR. Si riporta una rassegna dei progetti e le sfide da superare per una diffusione su larga scala delle tecnologie ad idrogeno.

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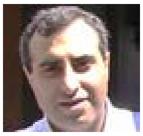

by **Antonino Salvatore Aricò,** *Director of CNR-ITAE - Institute of Advanced Energy Technologies*

Climate change is recognized as the most relevant current risk and, consequently, the most significant challenge we are facing; this makes it urgent to activate all possible strategies for mitigation and adaptation. Green hydrogen is considered an important solution to reduce GHG emissions and to achieve the challenging objectives in energy, transport, climate, economic and social policies. The Italian objectives in this field are essentially aligned to the EU hydrogen strategy targets. The need to develop large-scale hydrogen technologies and a specific H2 infrastructure is now largely recognized in Italy as a crucial point to achieve the required energy transition. This is testified by the strong interest that has been recently addressed in Italy to hydrogen at ministerial level. A research agenda on hydrogen has been recently published by the Ministry of Research (Srategia Italiana Ricerca Idrogeno – SIRI) [1] and a public consultation about the strategies to promote hydrogen technologies has been prompted by the Ministry of Economic Development (strategia nazionale idrogeno linee guida preliminari)[2].

A significant part of the renewable energy produced in Italy comes from hydroelectric, wind and photovoltaic sources, which are strongly influenced by weather conditions and therefore characterized by a high degree of intermittence. **If the share of energy obtained from renewable sources continues to increase in Italy, according to the recent trend, together with the need to implement EU directives, there will be a risk that a significant part of excess renewable energy may not be fed into the grid.** At the same time, it will be necessary to increase the fraction of alternative and renewable fuels in transport, at least to achieve the objectives agreed with the EU.

The solution to these problems can come from a wide deployment of electrolysers for the generation of hydrogen from renewable sources, providing both a network balancing service and promoting the diffusion of fuel cell ve-

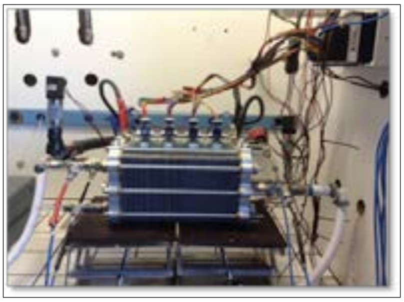

Fig.1 CNR ITAE-developed polymer electrolyte fuel cell stack prototype under laboratory testing.

hicles throughout the territory, especially if this is supported by adequate governmental incentives. Therefore, **it is widely recognized that, as soon as possible, an adequate infrastructure for hydrogen technologies will have to be built in Italy.** Beside transportation, hydrogen is widely considered as a means to allow a deep decarbonisation of buildings (heating and cooling) and industry. For microdistributed and combined generation of heat and power, solid oxide fuel cells can offer a concrete solution. Demonstration projects using SOFCs have especially dealt with the use of natural gas as fuel; a progressive transition to a hydrogen-rich stream for stationary generation is expected for the next years where a sustainable fuel, e.g. produced from gasification of biomasses, can progressively replace natural gas.

Wide-ranging research

Hydrogen is the focus of intense research activities at the Italian National Council of Research, in particular at CNR-ITAE Institute of Advanced Energy Technologies. ITAE's founder Professor Nicola Giordano was one of the Italian pioneers on hydrogen technologies by introducing fuel cells in Italy already in the seventies, in particular, phosphoric acid and molten carbonate fuel cells. **In the hydrogen sector, CNR performs wide-ranging research and development activities covering materials, components, technology and field-testing. CNR attitude is based on a synergy between basic and applied research, organised through a multidisciplinary approach.** The activity in this field covers several TRLs (Technology Readiness Levels), with consolidated experiences of coordination of TRL 6 demonstration projects (field-testing) and the development of pre-commercial prototypes (Fig.1).
CNR activity on hydrogen covers the sectors of sustainable mobility (Figs. 3,4) with demonstration of refuelling stations and hydrogen buses (PON I-NEXT) [3], development of integrated systems (PON CheapH2), naval applications (validation of hydrogen technologies for boats, PON TESEO) [4] and power-to-gas. The latter has been especially addressed in the context of European projects with coordination of FP7 FCH JU ELECTROHYPEM, ERANet SuperP2G and H2020 FCH JU HPEM2GAS projects [5,6,7]. Several research projects have aimed at studying the integration of renewable energy sources with electrochemical generation of hydrogen (FIRB RINNOVA) and its use in fuel cells for automotive applications (POR H-BUS). Integration efforts between hydrogen and batteries have been the focus of the FP7 FCH JU project ONSITE involving a cooperation between CNR and some national companies such as FIAMM and SOLIDpower.
In the field of hydrogen, CNR activity has been focused on the innovation of technologies through an advanced knowledge in materials science, micro and nanotechnologies, polymer science, system engineering and analysis of environmental sustainability. A strong cooperation between CNR and Italian stakeholders has been established. Just to mention a few, CNR-ITAE has cooperated with DE NORA, NUVERA, GAVAZZI SPACE and FINCANTIERI in the field of PEM fuel cells, with TRE on the integration of electrolysis systems with renewable power sources, with ENEL, PIRELLI Labs and SOLIDpower on solid oxide fuel cells, with SOLVAY SPECIALTY POLYMERS on membranes and membrane-electrode assemblies for water electrolysers. In the framework of the H2020 HPEM2GAS

Fig.2 HPEM2GAS power-to-gas plant in Emden, Germany. On the right, the high performance 200 kW electrolyser from ITM Power based on Solvay Aquivion® membrane and CNR-ITAE electrocatalysts (HPEM2GAS project).

Fig.3 Hydrogen filling station in Capo D'Orlando, Sicily (I-NEXT project).

project [7], coordinated by ITAE, an advanced Solvay Aquivion® membrane has been integrated into a 200 kW (80 kg H2/day) PEM electrolysis system developed in collaboration with ITM Power, to assess electrolysis operation at high current density (3 A cm-2) for power-to-gas applications (Fig. 2). This has allowed developing and testing a rapid-response, cost-effective and scalable power-to-gas plant, capable of absorbing the electrical power exceeding the capacity of a transport and distribution line. This new technology may considerably reduce the investments needed to build a new grid infrastructure. In this context, **hydrogen produced from water electrolysis can play a significant role as energy storage medium.** The new membrane has contributed to achieve a three-fold increase in electrolysis current density (resulting in a proportional decrease in capital costs) whilst maintaining cutting edge efficiency.

Back-up solutions for the stability of the grid

It is widely recognised that **the increasing penetration of non-programmable renewable energy systems will lead to a series of challenges related to the stability and flexibility of the electrical grid. This requires introducing back-up solutions able to effectively support the network energy mix**. In this regard, a solar-powered refuelling station has been installed in a Smart Grid landscape in Capo d'Orlando (Sicily) to refuel hydrogen vehicles. The aim of the I-NEXT project was the demonstration (at TRL6) of an innovative and flexible system for the simultaneous generation of hydrogen (20 kg/day), heat and power from RES (Fig. 3). In the framework of Mission Innovation: Challenge 8 Hydrogen, a MiSE-supported cooperation program, coordinated by ENEA and involving CNR has been planned. This program includes the further development of the hydrogen valley in Capo D'Orlando, with the involvement of Italian stakeholders. This hydrogen demo site potentially involves up to 40,000 citizens during summer time. The project aims at promoting hydrogen technology demonstration in the Sicily Region, as a means to favour energy transition towards a future clean energy hub centred in the Mediterranean Sea. Back-up power processes based on hydrogen are also the focus of regional projects like PO-FESR Sicily ELETRORIGENERA, coordinated by SALUPO. This is dealing with demonstration of reversible fuel cells in an industrial relevant environment.

Great relevance is expected to be addressed to the smart specialisation of regions within EU. It is worth to mention that the Sicilian Region, assisted by CNR, has recently expressed its intention to promote a European partnership in the field of hydrogen. In this regard, **Sicily may become a hydrogen hub in the Mediterranean area due to the possibility of connecting North Africa renewable hydrogen production with Italy and EU through a specific pipeline network.**

Specific studies carried out at CNR clearly indicate that a step-change in electrolysis technology development and a strong decrease of renewable electricity costs are required to economically produce hydrogen through electrolysis. This approach is currently addressed in the H2020 FCH JU ANIONE project coordinated by ITAE [8].

Technical bottlenecks

A game changer in this field would be the development of a new, efficient, practical and safe means to store hydrogen in appropriate carrier molecules with high volumetric and gravimetric energy density and its easier conversion back into hydrogen for re-electrification, heating purposes, industrial utilisation etc. Similar research needs are also necessary to reduce the costs of low temperature fuel cells for automotive applications. Hydrogen-fed PEM fuel cells are characterised by high energy density and low environmental issues; thus, their can have an important impact on the next generation energy system. However, this can only occurs through costs reduction. A transition to non-noble metal electro-catalysts and novel ion conducting membranes, covering a wide range of operating temperatures, are relevant aspects to address in future research programs.

In general, the main challenges to address for an effective utilization of hydrogen as energy carrier regard both the overcome of technical bottlenecks and an optimization of the energy cycle

Fig.4 CNR-ITAE hydrogen fuel cell city buses under testing on urban paths (I-NEXT, H-bus projects).

from RES to end use via hydrogen generation, storage, transport, conversion and consumption, which covers the whole chain of hydrogen and fuel cell technologies. As also stated in the SIRI agenda on hydrogen, significant progress in materials science, electrocatalysis and process development is needed to make hydrogen technologies efficient, practical and reliable for wide scale application in the next decades.

The present economic costs to implement hydrogen technologies appear still not easily affordable, compared to the expected returns. On the other hand, the significant benefits, in terms of environment, health, reduction of global and local pollution, enhancement of life-quality provide a clear idea about the positive impact of hydrogen technologies. In relation to this, an increased support for research, the implementation of focused demonstration programs, specific incentives and public support policies promoting the early market appear necessary for the Italian context. These aspects should be combined to a long-term strategic vision aimed at making hydrogen a future energy carrier.

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The RINA challenge to enable new hydrogen technologies

In the not-too-distant future, there will be a trend towards the production of green hydrogen from renewable energy obtained by electrolysis. In this area, RINA is committed to enabling new hydrogen technologies by experimenting with new materials thanks to a laboratory capable of testing materials for storage and transport at pressures of up to 1,000 bar. It is also closely cooperating with ENEA in order to integrate thermal conversion technologies for syngas and green hydrogen production.

In un futuro non lontano, ci sarà un interesse crescente alla produzione di idrogeno verde da fonti rinnovabili, ottenuto tramite elettrolisi. Il RINA è impegnato a promuovere e favorire la diffusione di tecnologie innovative con la sperimentazione di nuovi materiali, grazie a laboratori in grado di testare materiali per lo stoccaggio e il trasporto, con pressioni fino a 1000 bar. RINA ha inoltre avviato una stretta collaborazione con ENEA per attività di ricerca volte a integrare le tecnologie di conversione termica per la produzione di syngas e idrogeno verde.

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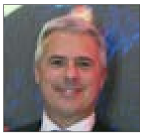

Andrea Bombardi,
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Antonio Lucci,
Senior Business Development Manager RINA

Following the 2015 Paris Agreement, targets were set for a 40% cut in CO_2 emissions by 2030 and zero greenhouse gas emissions by 2050. The IMO adopted these targets in 2018 and set out a strategy to reduce average carbon intensity by 40% by 2030 and cut overall CO_2 emissions by 50% by 2050. Ports and port infrastructures are essential for the EU, but as well as being strategic assets, they are also major sources of emissions. One ship moored at a dock for a day can produce as much CO_2 as 20 medium-sized cars in a year. Not to mention all the other activities carried out in the port including handling goods, cold storage, systems for providing continuous power or heating buildings, plus road and rail transport. **The first step in decarbonising ports is to improve the efficiency of infrastructure and processes related to logistics. However, in order to achieve the target, it is necessary to implement and optimise technologies that have not yet reached full maturity.** In a medium-term scenario, fuelling vessels with Liquefied Natural Gas (LNG) is a proven and available technology that would mitigate most emissions of pollutants such as sulphur, nitrogen oxides and particulates. Although these emissions would be significantly reduced, CO_2 emissions would not be: the maximum theoretical reduction in greenhouse gases would only be 20% compared to heavy fuel oil. The best solution would be to capture the CO_2 emitted both while sailing and while in port. This is an attractive but unrealistic scenario. Further contributions to reducing pollution could be made by modernising port infrastructure and renewing fleets. It would also be possible to improve the efficiency of buildings and install renewable power generation on site, such as photovoltaic and thermodynamic solar panels on roofs and façades, as well as hybrid propulsion for port logistics vehicles.

Cold ironing and port digitalization

In a medium-term scenario, it will be possible to implement cold ironing, a technologically mature solution that

reduces emissions from ships in port by connecting to the electricity grid on shore. This, together with port digitalisation or the use of hybrid ro-ro ships (roll-on/roll-off ships for transporting vehicles with wheels), would make it possible to eliminate overall emissions in port. At present, limitations of this solution are the scarce availability of renewable energy and the cost of electricity, which compared to the cost of generation on board is neither competitive nor sustainable. Hybrid power with batteries is a technology that can help to reduce emissions, but it is only economically viable for short distances. Technological advances could make its application wider in the future. **There are now ships, certified by RINA, that can produce zero CO_2 emissions in port. Their energy needs are met using batteries with adequate capacity.**

New hydrogen technologies

Hydrogen, along with its entire value chain, and ammonia deserve a special mention. As an energy carrier, hydrogen can store large quantities of energy. Its only emission is water, both when used as a fuel and in fuel cells. It is a particularly clean carrier for all maritime transport applications and for powering land-based logistics systems (forklift trucks....). In the not-too-distant future, there will be a trend towards the production of green hydrogen from renewable energy obtained by electrolysis. In this area, **RINA is committed to enabling new hydrogen technologies by experimenting with new materials thanks to a laboratory capable of testing materials for storage and transport at pressures of up to 1,000 bar.** Furthermore, new technologies that can combine material valorisation and hydrogen production are under development. RINA is also an advisor to the University of Cagliari within the IMPATTI-NO 2°Call project of the INTERREG IT-FR Marittimo Programme. In this technological strand, RINA is working on the valorisation of collected solid materials dispersed in port water (plastics, rubber, fibres, biomass...) and is cooperating with ENEA in order to integrate new thermal technologies processes aimed at the production of a syngas, hydrogen and valuable chemicals for port fuel and energy demand. These technologies are aimed at making port activities more sustainable and reducing CO_2 emissions. **RINA is currently closely cooperating with ENEA in order to integrate thermal conversion technologies for syngas and green hydrogen production.**

The objective is decarbonisation of industrial and transportation sectors. Ammonia obtained from green hydrogen could be a very promising fuel. It can be used in internal combustion engines and stored at room temperature. Issues of transport and logistics are well established. The downside is its toxicity and the absence of commercially available solutions for marine propulsion.

A roadmap for the green transition

Around the world, there are examples of applications and demonstrators of the most advanced technologies. Cold ironing systems are used in Los Angeles, Marseille (investment allocated not yet operative), Hamburg and Gothenburg. Projects and demonstrators using hydrogen as a power source for land-based logistics systems have been launched in Europe. The Port of Valencia will be the first in Europe to use hydrogen in its operations and plans to install a mobile hydrogen station to power container handling equipment. The first hydrogen-powered vessels are starting to be built (e.g. Port of Antwerp, Ferguson Marine Engineering is building the first renewables-based hydrogen ferry for Orkney, Norled-LMG Marin agreement for hydrogen-powered ferries and batteries in 2022). In Rotterdam, the Port Authority is working towards the introduction of a large-scale hydrogen network across the port complex, to become an international hub for hydrogen production, import, application and transport to the Northwest Europe. **Italy is still lagging behind. However, for the use of hydrogen in the maritime sector, studies and research are underway which will see Italy involved with the main national manufacturers.** RINA, which has been active in the port infrastructure sector for over 30 years, has launched and supports initiatives to develop new technologies in the field of port and naval engineering. The TecBia project involves the commissioning of a hydrogen-powered electric boat with fuel cells and hydride storage. RINA is involved in relation to the regulatory and safety aspects. **In the context of the ambitious scenario of zero CO_2 emissions by 2050, ports are the most suitable places to start the green transition. This is because they can positively influence the related infrastructures, cities, industries, transport and logistics systems. The Italian port infrastructure has the opportunity to play a strategic role. A process of innovation must be initiated and supported to overcome some critical issues.** A tariff system for electricity supplies from cold ironing should be promoted, making the exchange sustainable and advantageous compared to generation on board. It is also necessary to consider the freight transport chain as a whole and to integrate port and rail infrastructures in order to increase the competitiveness of the logistics chain. In this context, new technologies can be adopted that also leverage the recent collaboration agreement between RINA and ENEA. This was signed in the spirit of supporting and strengthening the growth and competitiveness of companies through the transfer of innovative technologies. **It is therefore essential to identify a roadmap for the green transition** through systematic and coordinated actions with interventions in the decarbonisation chain (hydrogen, renewables, CCS). This can be launched with the support of national and European funding and sustained over time thanks to the digital and green innovations that will make port infrastructures competitive and attractive.

Priorities for the development of a hydrogen value chain in Italy

In November 2020, H2IT, the Italian Hydrogen Association, released the report "Support tools for the hydrogen sector. Priorities for the development of the hydrogen supply chain in Italy". Born from the collaboration between 48 industry players, 12 research centers and 7 clusters and associations, the report contains the essential recommendations for creating the political and regulatory conditions to support the hydrogen sector in Italy. There are 51 priority actions and 66 policies indicated to the political institutions, divided into 7 different segments: production, transport, distribution and treatment, storage, mobility, energy uses; industrial, residential and feedstock uses, supply chain and transversal issues.

Nel novembre 2020 H2IT, l'Associazione Italiana Idrogeno ha diffuso il report: "Strumenti di supporto al settore dell'idrogeno. Priorità per lo sviluppo di una filiera dell'idrogeno in Italia". Frutto della collaborazione fra 48 imprese, 12 centri di ricerca e sette fra cluster e associazioni, il report indica le raccomandazioni essenziali per creare le condizioni politiche e regolatorie per supportare lo sviluppo di questo settore nel nostro Paese. Il report individua 51 azioni prioritarie e indica 66 azioni di policy alle istituzioni politiche, suddivise in sette diversi segmenti: produzione, trasporto, distribuzione e trattamento, stoccaggio, mobilità, usi energetici, industriali, residenziali e come materia prima.

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by **Luigi Crema**, *Vicepresident H2It, Director Center on Sustainable Energy – Fondazione Bruno Kessler*

Hydrogen has entered the political agenda of several countries at the international scale, including most of the EU Member States, and the European Commission itself, with the release of the European Hydrogen Strategy on last July 8th, 2020. All the strategies are looking to reserve relevant investments to the sector. The European Commission last July laid out its vision to promote green hydrogen up to 2050, which is expected to lure up to 470 billion euros in investments.

The future of the hydrogen supply chain in Europe in 2050 could reach a quarter of the share in final energy consumption, with a turnover of 820 billion euros a year, capable of creating approximately 5.4 million new jobs. A real revolution that in less than thirty years could change the society and economy of the Old Continent: if produced from renewable sources, through the process of electrolysis of water, hydrogen is free of both carbon and polluting emissions. A key solution to favor the decarbonization of the energy system and achieve climate goals. Indeed, several barriers are still present to reach an economic viability of green hydrogen and open the hydrogen sector in all its potential. **There is a need for a certain and simplified legislative framework and a long-term investment plan to develop infrastructure and finance research and innovation.**

H2IT Report on barriers and priorites in the hydrogen sector

For this motivation, in late 2019, H2IT, the Italian Hydrogen Association, started up a joint work for the analysis of the barriers and identification of the priorities in the hydrogen sector in Italy. After a year, in November 2020 we released the report **"Support tools for the hydrogen sector. Priorities for the development of the hydrogen supply chain in Italy ".**

We started from the analysis of the hydrogen sector as it is today. Hydrogen currently represents a modest fraction of the global and European energy mix. In our country, the total share of energy produced by hydrogen is around 1%, used by chemical, steel, and refining industries. However, it is still not clean hydrogen, but mostly produced from fossil fuels, with a release between 70 and 100 million tons of CO_2 each year across the EU. On the other hand, on the decarbonization targets, hydrogen is essential to achieve the goal of reducing emissions by 100% envisaged by 2050, made even more challenging by the potential new limit of 60% reduction by 2030. The path traced by the European Commission has set two main objectives: to reach by 2024 the capacity of 6 GW of electrolyser installed to produce 1 million tons of green hydrogen, and by 2030 40 GW for a production of 10 million tons in Europe. In other words, **in 2050, hydrogen could represent up to 24% of final energy consumption. Ambitious goals, like that set by the Ministry of Economic Development for Italy, which provides for a 20% hydrogen penetration in 2050.**

Collaboration between 48 industry players

Hence the motivation to develop the report by H2IT. **Born from the collaboration between 48 industry players, 12 research centers and 7 clusters and associations, the report contains the essential recommendations for creating the political and regulatory conditions to support the hydrogen sector in Italy.** This report was drawn up with the operators of the sector under the scientific coordination of universities and research centers, within seven working groups divided by segment of the supply chain, with the participation of the Italian Gas Committee as support to the tables regarding the technical standardization. The collaboration turned out fruitful bringing the experiences of companies within a scientific methodological approach, which allowed them to rationalize, integrate and communicate them in the best way through a single scheme. The approach was initially bottom-up by collecting information and experiences and then top-down guiding the collection of specific feedback. H2IT involved also external companies so that all sectors of the supply chain were represented in a broad manner to achieve a complete vision.

The work carried out addresses the entire supply chain, comprised of:

- **Production:** The technologies for production each experience different criticalities. It was decided to **divide the processes according to the carbon footprint**, a key issue for the decarbonization objectives, and according to the distribution logic, centralized or distributed.
- **Transport and distribution**: Hydrogen can be transported through pipelines or through logistics with dedicated vehicles. The problems currently in transport logistics are tackled, which are essential for connecting production to end uses.
- **Storage:** Hydrogen can be stored at high pressures in different ways, from gaseous phase with cylinders to storage in geological units (cavities in saline deposits and, potentially, in depleted hydrocarbon deposits and deep aquifers), in the form liquid or through dedicated carriers. The storage is crucial to ensure flexibility in the production of energy from hydrogen.

Long-term strategies

- **Mobility:** Hydrogen vehicles represent one of the most mature technologies on the market today. The development of hydrogen mobility is linked to the distribution of refueling stations throughout the territory. Not only light mobility, but heavy road, rail and maritime vehicles offer opportunities for decarbonization of the hard to abate transport sector.
- **Energy uses:** Fuel cells and gas turbines, two different technologies both capable of connecting two sectors, gas and electricity, whose installation still presents regulatory gaps.
- **Industrial, residential and feedstock uses:** This sector segment includes the use of hydrogen for the generation of electricity and heat, in the residential and industrial sectors, and as a raw material. The issue of green hydrogen is addressed to reduce the emissions of some processes that are difficult to electrify.
- **Transversal issues**: Some issues remain common to the entire supply chain as they are intersectoral and therefore dealt with from an integrated perspective.

We have involved the entire supply chain and leading to the elaboration of **51 priority actions and indicating 66 policies to the political institutions, divided into 7 different segments:** production; transport, distribution and treatment; storage; mobility; energy uses; industrial, residential and feedstock uses; supply chain and transversal issues.

Starting from these, H2IT suggests to the institutions some strategic priorities to break down the barriers to the development of the hydrogen sector in Italy, here represented in seven main points:

1. **Define the long-term strategic role of hydrogen:** it is essential to trace a clear direction that indicates specific actions and defined objectives to support the sector and enable investments. In the first phase of development, public support will be needed to cover existing economic

gaps through dedicated and stable support in the long term.

2. **Develop a clear legislative and technical-regulatory framework:** certain rules, simplified at the bureaucratic level and harmonized at an international level would allow companies involved in the entire supply chain to operate, on a European scenario, in favorable conditions also for investments.
3. **Guarantee the certification of renewable and low-emission hydrogen:** a certification system based on Guarantees of Origin to promote renewable and low-emission hydrogen, in line with European directives.

A primary role for research centers

4. **Supporting research, innovation, and training:** in this development phase, the role of research centers is primary, and they must therefore be supported with simplified accessibility funding for specific demonstration or research projects. The evolution of the sector will also require professionals specialized in a wide range of technical knowledge that can be created by investing in education, from high school to university to train future specialized technicians. An unmissable opportunity for a country that wants to restart by creating new employment opportunities.
5. **Develop a refueling infrastructure for mobility:** the construction of a network of refueling stations for hydrogen vehicles is the best solution to allow the circulation of fuel cell vehicles for both light and heavy road transport, but also dedicated to rail transport and transport in logistics hubs, such as ports and airports.
6. **Encourage strategic collaboration between Hydrogen Valleys projects:** it is a priority to identify the initial nuclei for the synergistic development of multiple end-uses and to develop different applications in logistics hubs (such as ports and airports) to encourage growth in demand, scale-up of devices and consequently reduce costs.

Raise awareness and inform public opinion

7. **Raise awareness and inform public opinion:** the development of the supply chain must be accompanied by information campaigns and educational projects on hydrogen technologies and safety procedures applied.

Italy has the potential to strategically position itself in all the reference sectors of the hydrogen supply chain: production, logistics and transport, industry, mobility, residential. We have large operators and companies that are decisive in opening the market, SMEs and innovative start-ups, research centers of international importance.

With this report, created involving 67 organizations active in the sector, we wanted to give our contribution to the development of a market that will become increasingly central in the national and European economy. To overcome the challenge of decarbonization, the time has come to develop a National Hydrogen Strategy that implements a broad plan of investments and reforms. H2IT, as the only voice in the Italian panorama, is ready to work together with the institutions by providing all the necessary skills to facilitate the decision-making process.

The report is just the latest of the many goals achieved in recent years by H2IT, an association that brings together large, medium, and small businesses, research centers and universities operating throughout the hydrogen value chain. In fact, since 2016 the association has supported the competent Ministries in the elaboration of the "National Plan for Hydrogen Mobility" updated in 2019, collaborated in 2018 with the Ministry of the Interior for the drafting of the "Technical Rule" of fire prevention for the design, construction, and operation of hydrogen distribution systems for motor vehicles and the Position paper "Italian Hydrogen Strategy and Fuel Cells" was released in 2019.

H2IT - Who we are

H2IT - Italian Association of Hydrogen and Fuel Cells brings together large, medium and small businesses, research centers and universities working in the hydrogen sector. It currently has about 70 members representing the entire hydrogen value chain from production to end uses, including companies that deal with hydrogen logistics for its transport, distribution and storage, companies that develop technologies such as electrolyser and fuel cells. Companies that develop components, systems for the use of hydrogen in the mobility, residential, energy production and industry sectors. Established in 2005, H2IT has set itself the goal of stimulating the creation of infrastructure for the use of hydrogen, being a spokesperson for the players in the sector and ensuring a leadership role for Italy in the world market.

The interviews

Snam is getting ready for the hydrogen revolution

The European Hydrogen Strategy and the national plans announced by Italy and some other countries are an important step in making it possible for hydrogen to contribute to the target of net zero CO_2 emissions by 2050. But in order to create a national and European supply chain, it is necessary to promote the scale up of technologies, the reduction of costs, the aggregation of consumption also through hydrogen valleys and solid cooperation between companies, institutions and the world of research.

La Hydrogen Strategy europea e i piani nazionali annunciati da alcuni paesi, inclusa l'Italia, sono un passo importante affinché l'idrogeno possa contribuire all'obiettivo di arrivare a zero emissioni nette di CO_2 al 2050. Ma per creare una filiera nazionale ed europea, occorre favorire lo scale up delle tecnologie, la discesa dei costi, l'aggregazione dei consumi anche attraverso le hydrogen valleys e una solida collaborazione tra imprese, istituzioni e mondo della ricerca.

Interview with **Marco Alverà,** *CEO Snam*

Mr. Alverà, what are the policies necessary for the development of a "hydrogen system" in Italy and Europe?

The Hydrogen Strategy launched by the European Union and the national strategies announced by some countries, including Italy, mark an important step in the right direction to enable hydrogen to contribute to meeting the target of making Europe the first continent to achieve net zero CO_2 emissions by 2050. In the case of Italy, for example, the strategy put into consultation in recent months calls for 5 GW of installed capacity for the production of green hydrogen and a first target of 2% of the energy mix by 2030, with an expected growth of up to 20% in 2050.
In order to accelerate the development of the value chain, we need policies that promote the scale up of technologies and the reduction of costs. For example, the Gas for Climate consortium recently proposed that the EU Commission introduce a binding target of 11% of renewable gases – of which 3% green hydrogen – for final gas demand by 2030. In our opinion, this is an example of an effective policy driver, as also the increasing use of the blending of hydrogen and natural gas in networks. It's also essential to create a national and European technological value chain in order to not miss out on opportunities, as it happened with the photovoltaic systems. For hydrogen this means building gigafactories that produce electrolysers, the components that make it possible to transform renewable electricity into green hydrogen.
Finally, to get the market going, it will be essential to aggregate consumption geographically by creating hydrogen valleys, also to optimise infrastructure. Cooperation

between companies, institutions and the world of research will be a key element in this process.

Speaking to the CEOs of the Hydrogen Council last January, EU Commission President Ursula von der Leyen stressed that "Europe takes clean hydrogen seriously: it is part of our future" and that achieving climate neutrality by 2050 requires investing in clean hydrogen. How can our country play a major role in a European hydrogen strategy? Can we become a green hydrogen hub and, looking forward, provide an infrastructure bridge with North Africa?

We do believe that Italy is ideally positioned – both in terms of expertise and geography – to play such a role. To begin with, we are one of the first three European countries in terms of thermal, mechanical and hydrogen production technologies. We have energy companies that are global leaders in their respective sectors and we possess extensive know-how in research, as also demonstrated by ENEA's recent initiatives.

"Italy is ideally positioned as a hydrogen hub"

Today we already are a gas hub on the Mediterranean, one of the key intersections for present and future energy supplies. The natural potential for hydrogen production from renewable sources is significant in Southern Italy and is enormous in North Africa. Our country can provide an infrastructure bridge to Germany, which will play a key role in the global hydrogen economy. In fact, in the coming years Berlin will have to abandon both nuclear and coal energy sources, and in order to do this successfully it will need a lot of hydrogen (from 90 to 110 TWh, based on estimates based on their national strategy). According to Bloomberg's New Energy Finance calculations, the cheapest way to import it by 2050 will be via gas pipelines running from North Africa through Italy.

Our network is getting ready for the hydrogen revolution: we estimate that about 70% of the pipes managed by Snam are already capable of transporting increasing percentages of hydrogen. We have also adopted internal rules on the supply of materials for new pipelines that allow not only the transport of natural gas and biomethane, but also, in the future, increasing percentages of hydrogen, potentially up to 100%. At the same time, we are also working on compression and storage plants.

Italy is working on a National Hydrogen Strategy to identify sectors where it believes it can become competitive in the short term and to verify the most suitable areas of intervention to develop and implement the use of hydrogen. What are Snam's proposals and vision? And what are the critical issues that may need to be resolved?

According to our forecasts, hydrogen will be able to become competitive in various sectors relatively quickly and sooner than expected. We imagine various steps: first, within a few years hydrogen will hit rail and heavy transport, from 2030 some industrial sectors such as refineries and some steel production processes, and finally from 2040 domestic heating and other applications. We're at the dawn of a new era: to get the European market going, we will need dynamic regulation and a level playing field to allow for the same conditions for all member states.

Cooperation between companies will be essential to enable the market to take off. For this reason, in addition to preparing its infrastructure for the transport and storage of hydrogen, Snam has also established partnerships with various operators in compliance with unbundling regulations, to pool respective skills and enable the development of the supply chain in Italy and Europe. We are already working with railway operators (FS Italiane and Ferrovie Nord), with engine suppliers (Alstom) and with energy suppliers (Eni and A2A) to develop refuelling infrastructure and make hydrogen rail mobility possible in Italy.

Snam is also working with other players that rely on our infrastructure upstream and downstream (suppliers and consumers of natural gas), based on their respective expertise, for projects and experiments aimed at applying hydrogen to decarbonise industrial processes (such as refining and steel) or for electricity generation. More specifically, together with Tenaris and Edison, we announced a project aimed at introducing green hydrogen and replace methane in some production processes at the Dalmine steel mill.

Snam was the first major player to experiment with introducing hydrogen into the gas network, in Contursi in the province of Salerno. Are there other initiatives under way, in Italy in particular?

The Contursi test was important because it revealed that the gas infrastructure will be able to transport hydrogen in increasing volumes in the coming years, helping Italy and Europe to meet the decarbonisation targets. Using the gas networks is the most competitive way to transport hydrogen: as calculated by Guidehouse in the European Hydrogen Backbone study, the interventions necessary to convert existing infrastructure to hydrogen transport only cost between 10% and 25% of what it would cost to build completely new networks.

"We are at the dawn of a new era"

As for new initiatives, the main one in our strategic plan – which requires investments for €150 million – is aimed at rail mobility projects that we have launched together with other partners to convert sections of the Italian network from diesel to hydrogen. In Italy, almost 5,000 km of network are still not electrified. The hydrogen train, which is already a reality in nearby Germany, can be an important opportunity for Italy too. As mentioned before, we are also working together with other Italian and foreign companies on experiments and projects to make our infrastructure and technologies available for industry and electricity generation.

What are the main lines of the Snam strategy for the energy transition and the Green Deal?

In our strategic plan to 2024 we set ourselves the goal of achieving carbon neutrality by 2040, with an intermediate target of reducing CO_2 equivalent emissions by 50% by 2030. Looking beyond the company, we are also committed to contributing more and more to the decarbonisation of the system, with over €700 million of investments planned in our new businesses for the energy transition, which include biomethane, sustainable mobility, energy efficiency and hydrogen. Leveraging these , we will help Italy to avoid emissions for over 600,000 tonnes of CO_2 as early as 2024.

Do you believe that the pandemic, as prominent proponents of the energy sector warn, will slow down the development and implementation of decarbonisation policies?

I think that the pandemic is proving to be a very complex challenge for everyone, including companies, but it also offers an opportunity to overcome inertia and face the future with greater courage and determination. As Italy's President of the Republic, Sergio Mattarella, underlined in his message, sent together with other Heads of State at the Climate Action Summit two years ago, climate change is the key challenge of our time and ours is the last generation that has a chance to fight it effectively. Europe aims to become the first continent with net zero emissions and Italy is at the forefront of this effort, as evidenced by the government's commitment to the ecological transition. The United States has re-entered the Paris Agreement and China has announced a net zero target by 2060. The global commitment to the climate fight is gaining traction once again and I hope that COP26 scheduled at the end of the year in Italy and the United Kingdom can bring concrete results, also for the development of hydrogen.

In your opinion, what strengths should be leveraged and what obstacles should be overcome in order to achieve the European objective of climate neutrality by 2050?

There is a strong commitment and sense of urgency on the part of the European Commission, as evidenced by the Green New Deal and the funds made available (starting from the Recovery Fund). The pandemic seems to have accelerated this trend. The signs are certainly encouraging, but we must be aware that the goal remains extremely challenging.
The electrification of end uses, accompanied by electricity generation from renewables, is a fundamental lever, together with energy efficiency. But this will allow us to decarbonise only 50-60% of the energy mix. New solutions are required. And a great connector like hydrogen can finally link the world of electricity with that of molecules in a view to sector coupling. As Italy's Minister of Ecological Transition Roberto Cingolani underlined in a recent lecture, "the challenge for technology is to develop solutions that solve numerous problems simultaneously". It's an opportunity that we can't afford to miss.

The turn towards green is irreversible, lesson learned from the crisis

With the last two Strategic Plans Eni has turned irreversibly towards the goal of becoming totally carbon neutral by 2050. The crisis has definitely taken us out of our comfort zones and convinced us that we must accelerate the energy transition. For this reason, over the next four years we will invest one billion euros in technological innovation and four billion euros to continue our industrial transformation as we move towards complete decarbonisation.

Con gli ultimi due Piani strategici Eni ha intrapreso una svolta irreversibile verso l'obiettivo di diventare totalmente carbon neutral al 2050. La crisi ci ha portato definitivamente fuori dalla confort zone e ci ha convinto che dobbiamo accelerare sulla transizione energetica: per questo nei prossimi 4 anni investiremo un miliardo di euro in innovazione tecnologica e 4 miliardi di euro per proseguire nella trasformazione industriale verso la completa decarbonizzazione.

Interview with **Claudio Descalzi,** *CEO ENI*

In recent years Eni initiated a transformation of its strategy and business model, moving towards sustainability and the reduction of carbon emissions. A green turning point that was also confirmed by its top-five ranking in the oil & gas sector according to the FTSE4Good Developed Index which measures the performance of companies in their attention to environmental, social and corporate governance. Mr. Descalzi, what is the origin of this choice and what does the future hold with respect to energy transition objectives and the Green Deal?

The Strategic Plan that we presented last year, together with the new developments that we introduced with the plan we just announced recently, represent an irreversible turning point for Eni: we have marked off the path that will lead us to becoming a leader in the production and sale of totally decarbonised products generated by industrial processes with net zero emissions. With a very important goal, which is the biggest piece of news from the recently announced plan: we will become totally carbon neutral by 2050.

> "The crisis has taken us out of our comfort zones"

But this new strategy is only possible because it builds on years of work that's already been done. In fact, anticipating an energy crisis, in 2014 we decided to assume the great responsibility of taking the lead in the fight against climate change, with the awareness that our industry had to play an essential role: we have

literally transformed the company, its internal organisation and its mission, now inspired by the 17 Sustainable Development Goals of the UN's 2030 Agenda. We have the most powerful supercomputing system in the industrial world and have developed and deployed numerous projects and technologies. These

"…we will produce green energy by developing renewable energy and natural gas, LNG, green and blue hydrogen"

are the foundations that we built our plan on, concrete and marked off by intermediate objectives announced to the market. And this while the pandemic forced us over the past year to work hard to rationalise investments and costs to protect the company's solidity. A crisis that has definitely taken us out of our comfort zones, convincing us that instead of slowing down we needed to accelerate, as evidenced by the billion euros that we will spend over the next four years on technological innovation, and the four billion euros that we will invest to continue our process of industrial transformation, moving towards complete decarbonisation.

From the point of view of results, what were the most successful initiatives under Eni's new strategy?

Our new strategy has some great strengths that I like to highlight: it's based largely on technologies that are already available, on projects that are already operational or implementable in the short term, it has intermediate objectives that prove its concreteness and it contains the mechanisms of value creation that fuel its implementation. Finally – and critically – it is based on the development of multiple strands of decarbonisation that are integrated with each other and that we will carry forward at the same time, since such challenging and important objectives are achieved pragmatically using different tools.

Tell us more.

In addition to reducing the carbon footprint of our upstream portfolio through efficiency actions, an increased use of gas, CO_2 capture projects and participation in REDD+ forest conservation projects, we will produce green energy by developing renewable energy and natural gas, LNG, green and blue hydrogen (starting from steam reforming of gas with the subsequent capture and storage of CO_2), ENI will produce biofuels in its biorefineries, as well as methanol and hydrogen from waste recovery projects, will engage in sustainable chemistry by exploiting recycled materials and renewable raw materials, and will produce biomethane from biogas upgrading processes. All this by being able to direct the decarbonised products we generate towards a vast domestic customer base in sectors that range from retail, commercial and industrial to sustainable mobility. And this is where the other big news from the recently presented Plan comes in. We will integrate our activities related to renewable energy within the Eni gas and electricity company: this way we will be able to make the most of our retail customer base, destined to reach over 11 million customers in 2024 and offering an increasingly complete range of decarbonised products.

What are your strengths and which areas need to improve?

We saw the first fruits of our strategy in 2020, with the excellent performance achieved by businesses related to the production and sale of decarbonised products, with the EBIT of Eni gas and electricity increasing by 17% and the processing of organic refineries growing by 130%, about 1 GW of generation capacity from solar and wind already installed or under development. And we estimate that over the course of the Plan the biorefining-marketing segment alone can generate €750 million of EBIT, while the integration between retail and renewables can yield €1.2 billion in EBITDA. In essence, notwithstanding the unprecedented situation we are experiencing we are still beating expectations, and if we were to identify any weaknesses along the way we are guaranteed to have all the flexibility we need to deal with them.

Looking globally, do you believe that the COVID-19 pandemic will somehow slow or even halt the decarbonisation process, as some prominent proponents of the energy sector have warned?

No, to the contrary, I believe that this crisis has catapulted us out of the routines that we were stuck in – of course I'm talking about developed countries – and has called into question all our traditional models. Lifestyles, levels of consumption, the way globalisation is conceived. It's now clear that globalisation means that vaccinating all Europeans against Covid would be of absolutely no use unless all Africans, all Indians, the Arab world and so on are vaccinated as well. Likewise, the most effective battles against climate change conducted at a European level would be a drop in the ocean if not associated with as many actions carried out globally: at this point we're all on the same boat when it comes to the great issues that underlie our existence. This is one of the great lessons that we must learn, and that's why institutions, economic actors, organisations and individuals must take advantage of the great mass of resources made available by the nations for this great global crisis and devote it to improving and accelerating policies aimed at saving our planet.

> "…Research, development and technological innovation are the foundation and accelerator of our new strategy: we are talking about more than 7,500 patents and 450 projects…"

Eni has stipulated and is stipulating numerous agreements with research institutions in Italy and abroad for the development of innovative and low-carbon technologies. What role does scientific research play in the Group's strategy, and what is the approximate value of the investments made and planned for the energy transition and decarbonisation?

Research, development and technological innovation are the foundation of our new strategy. They are both the foundation and the accelerator. We're talking about more

than 7,500 patents and 450 ongoing projects. In addition to our Ecofining technology, used in our biorefineries in Venice and Gela, and waste-to-fuel technology, used for the production of bio oil from the organic fraction of municipal solid waste (OFMSW) and which is evolving towards an industrial scale, we are expanding the use of plant biomass to produce bioethanol, advanced biofuels and biomonomers to be used as intermediate products for bioplastics, electronic components, cosmetics and agrochemistry. We are marketing high quality products from the mechanical recycling of post-consumer plastic waste, with a recycled content of 75%, and we are developing a pyrolysis technology to recycle mixtures of non-mechanically reusable plastics known as Plasmix.
For the capture and use of CO_2 we have an ongoing project for a pilot plant in Ravenna for the mineralisation of CO_2, which can be used for the manufacture of products that can be used in the construction sector. We are also developing another technology for the biofixation of carbon dioxide from algae, with a pilot plant in Gela in Sicily.

Why do you think a closer and more continuous relationship between the research system and the industrial system is important and how can this be promoted?

In light of these many examples I can say that we are fully committed, and indeed we are working with more than 70 universities and research institutes, among which ENEA is undoubtedly among the most prestigious. In fact, with ENEA we are pursuing the promising project on magnetic confinement fusion.

"…It is too soon to say if Italy can become a real hydrogen hub"

Other areas of focus that we are developing with ENEA concern Supercomputing (HPC), energy storage, concentrated solar energy, the exploitation of biomass, the identification of optimal solutions for the end-of-life management of technologies, including renewable ones such as batteries, and finally the recovery and recycling of waste products from industrial and municipal processes.
For us, the relationship between the research system and industry is essential with respect to the achievement of our objectives and should be incentivised so that it becomes a well-established part of the great system that the country needs at this time of pandemic and economic suffering. This relationship has a fundamental value for the entire national system, especially now that the ecological and energy transition process must be concretely initiated.

Let's talk about Italy. In your opinion, what are the main strengths and the critical issues to be resolved in order to achieve the European objective of climate neutrality by 2050?

Our country has many strengths: we have resources, skills and a great spirit of entrepreneurship and innovation. Our economic fabric is certainly made up of large companies with broad shoulders, but above all of small and medium-sized companies with a great capacity for innovation. The only major problem would be if we failed to work together as a system, bringing together the forces of the public and private sectors to pool our expertise. The challenge before us and the stakes involved are too great to be taken on separately by each of us.

In terms of innovative technologies, you are also focusing on frontier sectors such as nuclear fusion and hydrogen, the latter rapidly establishing itself as strategic for meeting the "zero emissions" objective. According to studies[1], by 2050 hydrogen will be able to cover 24% of final energy demand, will contribute to reducing 560 million tonnes of CO_2 and will generate a turnover of €820 billion/year and 5.4 million jobs. Furthermore, as underlined by Commission President Ursula Van der Leyen, hydrogen will be a priority for Next Generation EU. What is Eni's vision with respect to this element? And what are the prospects for Italy?

Historically, Eni has been the leading producer and main consumer of hydrogen in Italy.
We use hydrogen mainly as a raw material in traditional refining processes, as well as in biorefineries in Venice and Gela for the production of HVO biofuels, or "hydrotreated vegetable oils". As part of our strategy to decarbonise production processes, we have identified precisely in the so-called hard-to-abate sectors, including refining, the possibility of immediately reducing emissions by injecting the CO_2 captured from the chimneys of steam methane reforming plants into a safe storage site. This can be done in the Ravenna area where we

have one of the largest storage sites in the world.
This process, which will also allow us to obtain blue hydrogen, is based on safe technologies, tested and already used in many parts of the world, and represents the fastest way to concretely reduce CO_2 emissions without completely revamping existing industrial processes.
We are also working on projects to produce hydrogen from water electrolysis, using electricity generated from renewable sources (so-called green hydrogen), and, following a circular economy approach, also on technologies for the production of sustainable hydrogen from waste.
Indeed, we have joined the European Clean Hydrogen Alliance and are participating in the "Hydrogen for Europe" study together with 17 players in the energy sector, the purpose of which is to assess how hydrogen can contribute to achieving climate neutrality on the continent.
Promoting the use of low-carbon hydrogen in the decarbonisation process would undoubtedly make an important contribution to the reduction of emissions and move us along the path towards EU carbon neutrality by 2050, representing a solution to decarbonisation also in hard-to-abate industrial sectors where electrification is not currently a viable or definitive option. In this sense, the industrial initiatives that Eni intends to put in place to decarbonise its refining operations may offer benefits to entire districts, for which it may be possible to channel plant emissions to the same storage sites used by Eni.

Can we realistically become a hydrogen hub?

From the general point of view of the hydrogen strategy, I think it's too soon to say whether or not Italy will be able to become a real hub, but in order to become one we'll have to learn to see the various production technologies as complementary, not competing, and classify them in a shared manner based on their contribution to the reduction of greenhouse gas emissions. I believe that it is crucial to follow a technologically neutral approach, developing and applying all available and sustainable technologies from a low-carbon perspective, without excluding any of them. An effective hydrogen strategy must recognise and support the contribution of all forms of low-carbon hydrogen to decarbonisation, also in order to maximise resource efficiency and to implement principles of the circular economy.

One last question. Eni's green turn was very well received, but there was no shortage of accusations of "green washing". What's your response to this criticism?

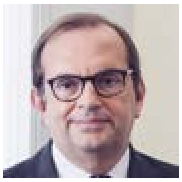
We respond with what we've done so far. The extensive reorganisation that we carried out last summer, which with the creation of the two new Energy Evolution and Natural Resources Departments revolutionised Eni's internal structure in order to best support its energy transition and decarbonisation strategy; the big change that we introduced with the new Plan, namely the integration of renewables into our gas and electricity sales company, an important step in our positioning as a leader in the retail sale of decarbonised products; the huge amount of investments already made and planned in the new plan for research, development and transformation; the pace of the intermediate objectives that we have set and communicated to the market for each business line related to decarbonised products; the plants already in operation, such as biorefineries, and the pilot industrial scale-ups already under way based on the most important technologies, such as waste-to-fuel. These are just a few examples of concrete initiatives and changes that testify to the transformation that is taking place, which is extensive and irreversible.

1. Hydrogen Roadmap Europe: A sustainable pathway for the European Energy Transition" and the recent report of H2.it

Five priorities to make Italy a hydrogen hub

To make Italy a hydrogen hub and overcome existing critical issues, action must be taken in five areas: support research; promote the production of hydrogen and its derivatives and stimulate demand for hydrogen and its derivatives. Legislative and regulatory shortcomings must also be addressed, authorisation procedures streamlined and information asymmetries eliminated to promote a culture of hydrogen, overcoming ideological approaches such as those often encountered for the different colours of hydrogen.

Per fare dell'Italia un hub dell'idrogeno e superare le criticità esistenti, occorre agire su cinque leve: supportare la ricerca; promuovere la produzione e incentivare la domanda di idrogeno e dei suoi derivati. Vanno inoltre colmati i gap legislativi e normativi, snellite le pratiche autorizzative e occorre eliminare le asimmetrie informative per promuovere una cultura dell'idrogeno, superando approcci ideologici come quelli che spesso si riscontrano per le diverse cromie dell'idrogeno.



Interview with Aurelio Regina, *Energy Delegate and Chairman of the Confindustria Energy Technical Group*

Hydrogen is increasingly establishing itself as a key element in the energy transition strategies of many countries and the EU Commission. President Ursula von der Leyen said that it will be a priority for Next Generation EU and that she wants to promote a European market with Hydrogen Valleys and Hydrogen Islands. According to studies, by 2050 this element will be able to cover 24% of final energy demand, will contribute to reducing 560 million tonnes of CO_2 and will generate a turnover of €820 billion/year and 5.4 million jobs. Chairman Regina, in light of all this, what is hydrogen's potential and what are the possible critical issues?

The strong acceleration of the Green Deal and European policies to combat climate change requires a rethinking of the entire energy paradigm and the exploitation of innovative technological options suitable for the decarbonisation of so-called "hard-to-abate" sectors, where direct electrification is not technically feasible or extremely expensive in financial terms. We see great potential for breakthrough technologies such as hydrogen in the decarbonisation of energy sectors that today use natural gas, or in the transformation of mobility, especially for heavy sea and air transportation. The biggest hurdle in the development of a supply chain for this element is the high generation costs, related to a low efficiency of the plants: green hydrogen can cost as much as seven times more than the natural gas it should replace. The lack of adequate liquidity, linked to the high cost of production, generates other barriers, namely demand that is still limited (currently concentrated in specific industrial sectors such as refining and chemistry) and the absence of a regulatory framework both for the use of infrastructure and for the installation of plants.

Since August 2020 you represent Confindustria in the European Clean Hydrogen Alliance, the association that brings together over a thousand representatives of the sector. How will you proceed in this context and what aspects will you focus on, also in view of the Green Deal?

Confindustria firmly believes in the potential of hydrogen. In fact we have followed the process of finalising the Community framework since before the definition of the European Strategy, published in July 2020. In August Confindustria was the first Italian employers' association to join the European Clean Hydrogen Alliance (ECH2A), the initiative of the European Commission that brings together public and private bodies, business associations and citizens to define the strategic priorities of the coming years for the promotion and development of hydrogen.

> "Confindustria firmly believes in the potential of hydrogen"

We consider it important to focus attention on the need to redesign the different phases of traditional production processes, from the re-engineering of products to the maximisation of the use of waste materials, from the rethinking of production plants to the hybridisation of thermal machines, all to ensure the reduction of the carbon footprint. The old continent will only be able to achieve carbon neutrality by 2050 through the exploitation of all sustainable technological options, from mature ones such as renewables and energy efficiency systems to evolving ones such as hydrogen or CCS/CCUS.

Let's talk about Italy. Last September Confindustria presented a comprehensive and detailed Hydrogen Action Plan aiming at the development of a national hydrogen supply chain. In your opinion, what are the main areas to focus on and what are the obstacles? Can we realistically become a hydrogen hub?

Confindustria promoted the definition of a Hydrogen Strategy by Italian institutions, presenting the Hydrogen Action Plan last September to the Minister of Economic Development. It's an organic vision of the topic that, starting from an assessment of the objectives/opportunities for Italy compared to other EU countries, analysed the main barriers to the development of an integrated supply chain to understand the future fields of application and potential markets for hydrogen, also with a view to transforming Italy into a hub. In summary, to solve the critical issues that I referred to just now, action must be taken in five areas:

- Support research by backing international research projects such as that of IPCEI, which saw 150 expressions of interest from Italian companies.
- Support the production of hydrogen and its derivatives, structuring a system that facilitates the installation of the plants and covers the incremental production costs with respect to the replaced fuel (in particular natural gas).
- Support demand for hydrogen and its derivatives through specific incentives to transform systems so they accept the new fuel for final energy uses.
- Clarify the regulatory and legal aspects, eliminating the current deficiencies in both legislation and technical standardisation and streamlining authorisation procedures, which currently make it difficult if not impossible to develop investments.
- Promote a culture of hydrogen, eliminating information asymmetries about the vector, and clearly present the risks, costs and benefits of the development of hydrogen in our country.

Remaining in Italy, you stressed that the National Hydrogen Strategy can represent a potential game changer for sustainability policies. What are the conditions for this to happen?

The use of gaseous fuels with low (zero) carbon emissions will only contribute to reducing greenhouse gas emissions if adequate volumes are available at competitive prices to meet the energy consumption of hard-to-abate sectors, interoperable transport and distribution networks, safe storage equipment and reliable end-use technologies, in synergy with expected electrification trends at a Community level. The National Hydrogen Strategy can be a game changer if it is able to define – consistent with the European framework – market-based policies and mechanisms aimed at facilitating the production and demand of new gases and their transport and distribution, but also the production of equipment along the entire value chain. We need a technology-neutral approach that fosters fair competition among technologies (P2X, storage, CCS/CCUS, etc.) and vectors (hydrogen, electricity, etc.) and assesses the savings of greenhouse gas emissions throughout the life cycle, overcoming ideological approaches such as those often encountered with respect to the different colours of hydrogen.

Recently you signed an agreement with ENEA to strengthen hydrogen research and innovation. Is the degree of cooperation between the industrial system and the world of research in Italy sufficient or do we need to increase our efforts, along the lines of other European countries such as Germany? And to what extent can investment in research lead to increased competitiveness?

Confindustria believes that dialogue with institutions, the world of research and civil society can produce the best ideas in every field of application. In recent months we launched three hydrogen-related initiatives in cooperation with ENEA, also involving other bodies relevant to the standardisation of the vector such as UNI and CIG. Contrary to what one might imagine, transferred know-how is not lost, and in the same regard we have opened up the meetings of the Energy Technical Group

"A technology-neutral approach is essential, fuelling fair competition among technologies and vectors"

to important institutional representatives. The initial meeting was attended by Stefano Patuanelli, then Minister of Economic Development, while the President of the Authority for the Regulation of Energy, Networks and the Environment (ARERA) Stefano Besseghini, and the European Commissioner for Energy Kadri Simson were invited to the subsequent meetings. Returning to the relationship with the world of research, we have launched a further study of the future national energy landscape, this time in partnership with CSR, with which we intend to map sustainable technological chains to understand their readiness and resilience in the current transition phase. The investments that we will have to make to achieve the new goals by 2030 are considerable, preliminary estimates put the figure at an excess of an additional € 500 billion over the next 10 years, and the development of skills through the dialogue and consultation of all stakeholders will be central for the correct allocation of funds, starting from those of the National Recovery and Resilience Plan (NRRP) aimed at restarting the Italian economy after the pandemic.

More generally, what are the main themes of Confindustria's strategy to achieve the objectives of decarbonisation, combating climate change and sustainability in the context of post-pandemic relaunch strategies?

Confindustria is strongly committed to promoting the sustainable development of the industrial system, capable of ensuring the transition to a low-carbon economy and the availability of safe, environmentally friendly and cost-competitive energy for the domestic manufacturing sector. Essentially, there are four main themes of our strategy regarding the energy transition in the post-pandemic Recovery and Resilience Plan that can be divided into two lines of intervention, related to the two technological pillars that the fight against climate change is based on, namely renewable sources and energy efficiency.
The first concerns the decarbonisation of the electricity sector through the promotion of active participation of industrial consumers in the energy transition and the development of projects in transportation and distribution networks.
The second concerns the decarbonisation of the gas sector by enabling the diffusion of new sources and new vectors through infrastructure projects and contributions to the supply chain.

"In order to reach the new goals by 2030, over €500 billion of investments will be needed according to the Italian Integrated Energy and Climate Plan"

The third concerns the decarbonisation of transportation by supporting the energy transition of fuel sources and vectors in the sector, in line with the government guidelines for sustainable mobility.
The fourth concerns the promotion of energy efficiency

through integrated projects in synergy with the digitisation of production processes for economic recovery and the environment.
The common thread of all the policies to enable a relaunch is the elimination of bottlenecks in the bureaucracy, like unsustainable authorisation procedures that, instigated by the NIMBY effect (Non In My Back Yard), block the installation of plants for the generation of clean energy.

Speaking of the pandemic, according to some authoritative representatives of the energy sector the crisis we are going through could mark a strong halt in investments in technologies and projects for the energy transition. Are such fears justified?

Climate and energy policies are central to the country's economic growth. In fact, they profoundly influence companies' competitiveness factors, but at the same time they can prove to be a great opportunity for investment and technological advancement. The National Recovery and Resilience Plan (NRRP), in line with the Integrated National Energy and Climate Plan (INECP), will allocate a large part of the funds for the relaunching of the Italian economy to achieve the new ambitious greenhouse gas reduction targets set out in the EU Green Deal. For this reason we believe that a complete halt to integrated transformation along the entire energy supply chain is unlikely, and this chain will stimulate investments that clearly have slowed in 2020 and 2021. However, crucial events to understand the future of global climate ambitions will be the G20, which will be held in Italy next fall, and COP 26, managed in partnership between our country and the United Kingdom. Achieving the European medium- and long-term decarbonisation objectives can only be effectively translated into the energy transition of sectors of the economy through the diffusion of green technologies enabled by a new energy market and global cooperation in the fight against climate change. In the absence of real international convergence, unfair competition from areas less sensitive to environmental issues could undermine not only the achievement of the Paris Agreement, but also the very survival of the European manufacturing industry.

Renewables, green hydrogen and digital networks to save the climate

Enel will invest around €190 billion over ten years, leveraging the development of renewable energies, increasingly digital, flexible and resilient networks and the progressive electrification of final consumption. In order to combat climate change and create a chain of sustainable value over time it is also necessary to focus on green hydrogen, boosting innovation, economies of scale and industrialisation in order to achieve a parity of costs with polluting hydrogen within 3-5 years.

Enel mobiliterà investimenti circa per 190 miliardi di euro in dieci anni, facendo leva sullo sviluppo delle energie rinnovabili, delle reti, sempre più digitali, flessibili e resilienti e sulla progressiva elettrificazione dei consumi finali. Per combattere il cambiamento climatico e creare una filiera di valore sostenibile nel tempo, occorre inoltre puntare sull'idrogeno verde, spingendo sull'innovazione, sulle economie di scala e sull'industrializzazione, per raggiungere, nel giro di 3-5 anni, la parità dei costi con l'idrogeno inquinante.

Interview with Francesco Starace, ***CEO of Enel***

After having been the focus of alternating waves of great enthusiasm and deep scepticism in recent decades, hydrogen is establishing itself as a key element for the energy transition in the policy agendas of many countries. According to a study presented by H2IT, the hydrogen sector could create a turnover of €820 billion per year and about 5.4 million new jobs in Europe by 2050. Given these facts, in your opinion what policies are needed to develop this energy vector?

Today hydrogen is a popular topic in the media and beyond. Green hydrogen represents an opportunity for utilities as the demand for renewable energy is increasing and it could provide flexibility to the network. Despite this, today it is still difficult to foresee the magnitude of the transformation that it could engender in the business of utilities and industry in general.
The production of hydrogen should not be seen as an end in itself, but rather as a tool for achieving climate neutrality. However, in order for it to become a vector of sustainable energy in the future its heavy carbon footprint must first be eliminated, and precisely for this reason it is essential to focus on the production of hydrogen from water electrolysis, with electrolysers powered by electricity from renewable sources, resulting in so-called green hydrogen. This will make possible the sustainable and competitive decarbonisation of hard-to-abate sectors such as energy-intensive industries, aviation and maritime transport.
Currently it is a very expensive technology, but we think that in the next 3-5 years – thanks to economies of scale and a focus on innovation, aggressive industrialisation and great ambition – we can achieve a parity of cost of green hydrogen with the current polluting hydrogen, provided we reduce the cost of electrolysers by a factor of six. This may seem like a lot, but in the past we have seen many industries succeed in doing this, for example batteries and solar panels. All this must be accompanied by the right policies.

Enel is one of the signatories of "Choose Renewable Hydrogen", the initiative launched in summer 2020 by WindEurope and SolarPower Europe, and is among the members of the European Clean Hydrogen Alliance. What are the priorities at a European level for developing a hydrogen supply chain and using this vector for the decarbonisation of the economy, also as part of the Green Deal and the Recovery Fund?

A rapid, ambitious deployment of renewable energies in Europe is the main enabling factor for the creation of a value chain linked to the production of green hydrogen with zero CO_2 emissions that is competitive in terms of costs and able to support the creation of new industrial opportunities.
From a regulatory point of view, the European Union (EU) should promote an international certification standard that attributes additional economic value to green hydrogen compared to hydrogen produced by fossil fuels. Creating a clear, complete terminology (taxonomy) linked to the different production processes based on both climate performance (CO_2 emissions) and the origin of the input/raw material (renewable, non-renewable) is essential to avoid ambiguity and allow end customers to make informed choices.

"A rapid, ambitious deployment of renewable energies in Europe is the main enabling factor for the creation of a value chain linked to the production of green hydrogen"

At the same time, it is essential that the legislative framework allow market players to quickly launch projects for the development of electrolysers for the production of hydrogen, introducing initiatives to accelerate and support forward-looking business models in Europe, and allow forms of sectoral integration, that is, based on green hydrogen intended for customers operating in the hard-to-abate sectors.
The EU should also support the development of a European green hydrogen supply chain and promote R&D funding to improve the efficiency of electrolysers and increase their production capacity.
At a national level, countries should introduce a regulatory framework that recognises and promotes the hybridisation of hydrogen production units in renewable plants, allowing access to ancillary service markets (for the provision of services such as frequency regulation or secondary and tertiary reserves).

The Ministry of Economic Development has worked on a National Hydrogen Strategy to identify sectors where it believes this element can become competitive in the short term and to verify the most suitable areas of intervention to develop and implement the use of hydrogen. What are Enel's proposals and vision in this context? Can we become a hydrogen hub?

Enel shares the basic approach of the Italian National Hydrogen Strategy focused on green hydrogen, which we believe should be the only solution supported by governments as it is capable of promoting a sustainable value chain over the long term. We welcome the targets of satisfying 2% of final demand for hydrogen energy and installing 5 GW of electrolysers by 2030. We share the promotion of a high-potential integrated system model where demand and supply are concentrated locally (known as hydrogen valleys), despite the local factors that will influence the choice of the mix of models for the production, transport and storage of hydrogen. Moreover, we support a model for the development of a supply chain that can improve the security of the supply and reduce the dependence of the EU and its Member States on imported fossil fuels through the creation of local supply chains that maximise the socio-economic benefits in terms of industrial development and employment. With regard to the end uses of hydrogen, we promote a strategy that rewards only efficient uses applied to hard-to-abate sectors and substantiated by cost/benefit analyses in order to avoid capital-intensive structural investments.

At an operational level, you have launched projects in the United States and Latin America in partnership with major players, including Eni. Are there other initiatives under way, in Italy in particular?

Our goal is to increase our green hydrogen capacity to over 2 GW by 2030. Enel Green Power is engaged in the research and development of projects for the production and use of green hydrogen obtained from water electrolysis, with electrolysers powered exclusively by renewable elec-

tricity. The Group has launched a study of new business models that include the supply of green hydrogen for the decarbonisation of industrial sectors, with partnerships and projects already under development in Chile, the United States, Spain and Italy. In Italy, for example, we are working on several initiatives that include a partnership with Eni and another with Saras for the production of green hydrogen for use in refineries and biorefineries.
In parallel with these initiatives, in Catania we are developing an innovative project – a hub – to test new technologies and accelerate the development and industrial validation of all components of the green hydrogen production chain.
In the development of new technologies, employing a model of partnership and open innovation allows us to shorten the learning curve and accelerate the pace for the benefit of the system and the country.

More generally, what are the main lines of Enel's strategy for the energy transition?

Enel's goal is not only to create value for the Group, but to generate sustainable growth that creates value for all: customers, companies, the environment and shareholders. With our latest 2021-2023 Strategic Plan we also unveiled our vision for the next ten years, underscoring what kind of utility we would like to become.

"Covid-19 took us on a journey into the future, showing us a reality that we will have to deal with sooner or later"

The issues that lie at the heart of our strategy are based on the growing role of renewable energies, the development of increasingly digital, flexible and resilient networks and the progressive electrification of final consumption. Over the next ten years we will invest around €190 billion. Over €150 billion will be invested directly by the Group through the traditional business model – so-called "ownership" – with more than 90% divided between renewable energy and networks. On the other hand, employing a stewardship model to catalyse third-party investments, 50% of the total will be allocated to renewables and the other half will be divided among fibre optics, transport electrification and flexibility.
A changed energy mix in 2040, the result of the growing development of renewables, will make digital networks the backbone of the new energy world. This will go hand in hand with the implementation of storage systems to improve the flexibility of the electricity system and an increasing focus on electrification, especially of public and private transport, with the consequent need for a charging infrastructure plan that meets the needs of users. It will be critical to harmonise the development of all these technologies as it is essential that they proceed in lockstep, because one cannot grow without the other.

Prominent proponents of the energy sector have raised an alarm about the possible decline in investments for the energy transition due to the pandemic. Do you believe that this emergency will somehow slow or even halt the development and implementation of decarbonisation policies?

Covid-19 took us on a journey into the future, showing us a reality that we will have to deal with sooner or later. We are now seeing what it means to emit less CO_2 and we are even more aware of the great importance of having resilient networks. We have direct experience that it is possible to decarbonise the energy sector without particular management difficulties, and when the pandemic is over no one will be able to say that this is not possible. The way had already been mapped out and we had already started down the path, a path that leads to a safer society because it depends less on fossil fuels and is more compatible with the planet, with better air quality and which contributes to combating climate change. The pandemic has given us a greater awareness of the importance and cost effectiveness of decarbonising the economy, and it is no coincidence that precisely during the year we have just gone through several

countries made a stronger commitment to this path. For example, we saw China, Japan, South Korea and South Africa all make commitments to reduce their emissions in the coming years, and the United States also announced its return to the Paris Agreement. Even the financial community – especially given the climate of general uncertainty that we are experiencing – is looking for stable investments, and consequently is increasingly aware of the importance of sustainability for the creation of lasting economic value in the medium to long term. In his annual letter to CEOs, companies and clients, Larry Fink, CEO of BlackRock, pointed out that 2020 was a historic year for sustainable investments, with a momentum that grew globally despite the thinking of many who posited that Covid-19 could slow this trend. This demonstrates that the world is inevitably moving in this direction, and to get out of the economic and social crisis and at the same time combat the climate emergency governments are implementing recovery plans that are sustainable, innovative, resilient and that also take into account social equity.

For many years you were CEO of Enel Green Power, an international leader in renewable sources. In your opinion, what strengths should be leveraged and what critical issues should be overcome in order to achieve the European objective of climate neutrality by 2050, or in other words to eliminate CO_2 emissions?

The energy transition that we are experiencing is being concentrated into a reduced time space and therefore is perceived by all. Moreover, at this particular moment it is being further accelerated by turbulent changes involving not only the energy sector, with oil & gas companies having to reinvent their businesses and utilities that can benefit from the transition, but also other industries such as the automotive sector with the production of electric cars. The development of renewable energies has proved extremely resilient to the challenges posed by the Covid-19 crisis. The pandemic has slowed the economy and energy consumption, but this does not apply to renewable sources, which are the only ones that have seen record growth. In 2020 renewables accounted for almost 90% of the increase in total installed energy capacity worldwide, reaching a record level of almost 200 GW (for example, about 18,000 MW of photovoltaic capacity were installed in Europe). This was driven by the fact that, in addition to their obvious benefit to the environment, renewable sources are economically more competitive than fossil fuels.

But where are we with regard to European objectives?

Unfortunately we are well below the growth levels needed to achieve them. If you stop and think about ESG policies (Environmental, Social and Governance), you realise how important the environment is and that the Green Deal is therefore the right way forward. You also realise that society – namely unemployment, job creation and cultural change – is important, but what really needs to happen is a change in governance. This isn't just an Italian problem, indeed it extends to all of Europe, and it doesn't concern the generation of ideas, the design of works or the need to find funds, but rather the ability to make projects actually happen. If you look at the historical trend of installing new renewable capacity at a European level, you can see that in the years 2009-2019 about 190 GW were installed, of which most were installed in the early years of the decade, with an average of about 18 GW/year in the latter five years. Over the next 10 years it will be necessary to install an additional capacity of about 300 GW (with an average installed capacity of about 28 GW/year) – an increase of at least 50% in line with the targets set by the National Energy and Climate Plans (NECPs) of the individual States – but which will need to be further revised with the increase of the emission reduction target to 55% by 2030 (compared to 1990 levels).

“The simplification of authorisation procedures and the acceleration of investments are two key aspects”

The NRRPs (National Resilience and Recovery Plans) can play a fundamental role in the realisation of investments in decarbonisation, networks and for the electrification of final consumption, decisive levers for the Green Deal and NECPs. In order to allow them to reach their full potential, we must focus on two key aspects: simplification of authorisation procedures with the goal of streamlining and speeding up the processes and steps currently required to obtain permits for the construction and operation of plants, and acceleration of investments focused on sustainability and decarbonisation, including through simplified procedures for the authorisation of renewable plants.

Development perspectives on low-temperature electrolysis

Water electrolysis is a pivotal technology to boost the hydrogen economy and to decarbonize energy and industry processes. Electrolysers, in addition to the production of hydrogen and oxygen, allow to implement renewable energy storage, through the integration of the electricity grid and the gas network. There are various technologies for water electrolysis, but the most interesting are certainly the membrane one (PEM and AEM) for the possibility to produce hydrogen directly under pressure: a fundamental aspect to favorite the use of hydrogen as energy vector and storage system. ENEA collaborates with Industry, Universities, Research Centres to promote the development and marketing of innovative electrolysers.

L'elettrolisi dell'acqua è una tecnologia fondamentale per favorire la crescita di un'economia a idrogeno e per decarbonizzare i settori energetici e i processi industriali. Gli elettrolizzatori, oltre a produrre idrogeno ed ossigeno, favoriscono la penetrazione delle fonti rinnovabili, attraverso l'integrazione tra la rete elettrica e la rete del gas. Esistono diverse tecnologie di elettrolisi, ma le più interessanti sono quelle a membrana (PEM e AEM) per la possibilità di produrre idrogeno direttamente in pressione: un aspetto fondamentale per favorire l'uso dell'idrogeno come vettore energetico e come "mezzo" di accumulo. ENEA collabora con industria, università ed enti di ricerca per promuovere lo sviluppo commerciale di elettrolizzatori innovativi.

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by **Alfonso Pozio, Francesco Bozza, Giuseppe Nigliaccio, Marzio Platter, Giulia Monteleone (*)**

Why the electrolysis? Chemical storage consists in transforming the excess electricity produced by the renewable source into chemical energy contained in a combustible substance. The process that allows this transformation from electricity to chemical energy is precisely electrolysis in which electric current splits water into oxygen and hydrogen. **Electrolysis is one of the best known and simplest methods used for the production of pure hydrogen, both on a small and large scale, starting from water, that is, from an extremely abundant primary source.**
The electrolysis of water occurs when a direct current is passed between two electrodes immersed in an aqueous electrolyte giving rise to the electrolytic decomposition of the water according to the global reaction. $2H_2O + \text{electric energy} \rightarrow 2H_2\uparrow + O_2\uparrow$.
Low temperature electrolysis technologies can be roughly divided according to the type of electrolyte which can be an alkaline liquid electrolyte (AE) or a cationic (PEM) or anionic exchange polymer membrane(AEM) [1]. During electrolysis, the water molecule is broken down to form hydrogen and oxygen. In PEM electrolysis [2, 3], the H^+ cations produced at the anode (by the water molecule) move to the cathode through a solid electrolyte, a polymeric acid membrane. H^+ cations combine to the cathode forming hydrogen, while oxygen is formed at the anode. In AEM and AE electrolysis occur the same reactions but the charge carrier are the OH^- anions moving through a polymeric alkaline membrane or an alkaline solution (Fig.1).
In all the case the membrane (PEM and AEM) or the porous septum (AE) have the function of separating

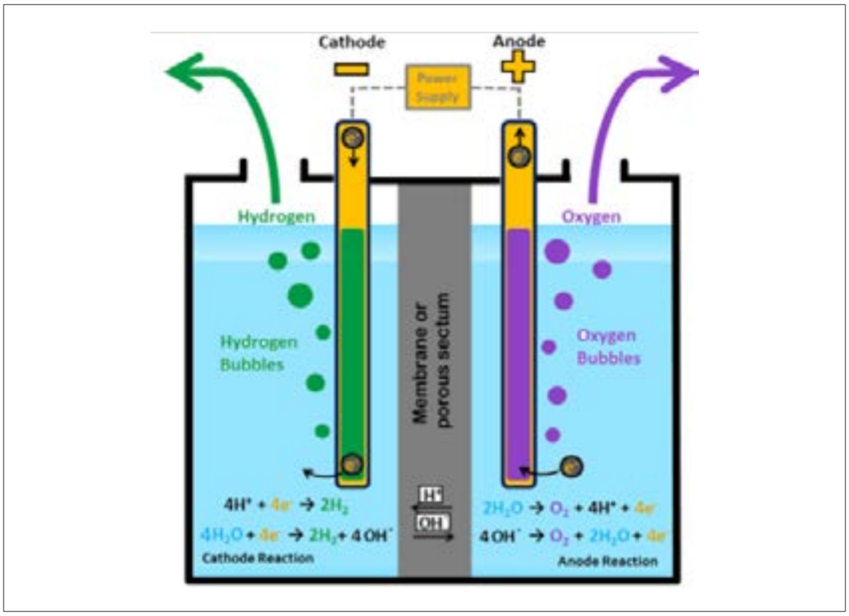

Fig.1 Simplified diagram of an electrolysis cell with alkaline or acid charge carrier.

the hydrogen and oxygen produced in the reaction [4]. Several cells of the type shown, connected together and placed in a single container, constitute an electrolyser. The electrodic catalysts will be selected depending on the acidic or alkaline environment. Typically precious metal of platinum group (PMG) are used in the PEM technologies while transition metals as Ni, Co and Fe are used in the AE and AEM systems.

Typical alkaline water electrolysis (AE) operates at a current density of about 400 mA cm^{-2}, at moderate temperatures of 70–90 °C, with a cell voltage in the range 1.85–2.2 V, and conversion efficiencies in the range 50–70%. **The advantages of alkaline electrolysis are mainly the followed: not depend upon a noble metal catalyst for the hydrogen production and easily handled due to the relatively low temperatures.**

The PEM electrolyzer can operate at a current density of 2000 mA cm^{-2} at 90 °C, at about 2.1 V. The kinetics of the hydrogen and oxygen production reaction in PEM electrolysis are faster than in alkaline electrolysis due to the acidic nature of the electrolyte and the metal surface of the electrodes. PEM electrolysis offers safety due to the absence of caustic electrolyte. One of the advantages of PEM electrolysis is the possibility of using high pressure on the cathode side, while the anode can be operated at atmospheric pressure.

AEM electrolysis: a developing technology

AEM electrolysis is a developing technology. It summarize some advantages of both technologies, low cost catalysts such as liquid alkaline, compactness and high pressures such as polymeric. Many research organizations and universities are actively involved in this research, largely due to its low cost and the high performance it offers.

The specifications, advantages, and disadvantages of the different low temperature electrolysis techniques are summarized in Table 1 and 2.

Research and development activities in ENEA

ENEA's activities on green hydrogen production are addressed to all the three categories of low-temperature electrolysers, mainly concentrating to catalysts production, electrode and membranes materials development, methods of preparation of electrodes and assemblies for PEM and AE electrolysers [5, 6, 7, 8].

Catalysts and membranes characterization activities are carried out in order to optimize the electrochemical aspects of the polymeric devices. Moreover, research are also addressed to the characterization of components for the production of hydrogen under pressure, with and without a differential between anode and cathode. The possibility of using hydrogen as energy storing system or vector requires gas compression [9]. In fact, hydrogen of all fuels is the one with the lowest volumetric energy density (6.8 MJ/L for 700 bar compressed hydrogen compared to 32 MJ/L for gasoline) (Fig. 2). So, **in all the above electrolyser technologies, the hydrogen operating pressure plays a decisive role [10]. The development of a system for the production of hydrogen under pressure, which also allows to increase the energy performance of the device, would allow an improvement in the overall efficiency of the production and storage system. This represents an important milestone and the growth of this technology would constitute a real technological breakthrough, guaranteeing a better penetration of electrolysis technology from renewable sources.**

To obtain high pressures, two alternatives are possible: the use of AE coupled to hydrogen compressors and the sizing of polymer electrolysers (PEM and AEM) for massive hydrogen production. Both options are technically feasible but economically and/or energetically not very convenient. Hence

	Alkaline	PEM	AEM
Electrolyte	**20-30% KOH**	Acid membrane	Alkaline membrane
Charge carrier	**OH^-**	H^+	OH^-
Temperature (°C)	**65-100**	70-90	50-70
Pressure H_2 (bar)	**25-30**	30-80 760	~30
Catalyst	**Ni, Co, Fe**	Pt, Ir, Ru	Ni, Co, Fe
Current density mA cm^{-2}	**200-500**	800-2500	200-500
Durability (h)	**90.000**	<20.000	NA
H_2 purity (vol%)	**99.3-99.9**	99.9999	99.99
Current efficiency	**50-70.8**	48.5-65.5	39.7
Production $Nm^3\ h^{-1}$	**1-760**	0.265-30	0.25-1
Energy consumption kWh Nm^{-3}	**4.5-7.5**	5.8-7.3	5.2-4.8
Power (kW)	**2.8-3534**	1.8-174	1.3-4.8
System cost (€ kg-1)	**1300-800**	2000-1200	NA
Technology status	**Mature**	Mature for small scale	R&D

Table 1 Comparison of main low temperature water electrolysis technologies.

the need to improve the technology of PEM and AEM electrolysers.
Operation under pressure requires the use of thicker and stronger membranes and internal gas re-combinators to keep critical concentrations (mainly H_2 in O_2) below safety thresholds (4 vol.% H_2 in O_2). Lower gas permeability across the membrane can be achieved by incorporating various fillers within the membrane material, but this normally leads to less conductive materials.
The critical point in this technology is the development of membranes capable of obtaining high current densities, with a mechanical stability such as to withstand high pressures for thousands of hours, ensuring the necessary purity of the hydrogen produced. According to what has been said, the current commercial standard provides for devices that operate with a pressure of 20-30 bar, even if there are manufacturers that have certified devices in their catalog that can work even at higher pressures. If the operating pressure of the electrolyser were to reach values close to 70 bar, hydrogen could be accu-

Alkaline (AE)	PEM	AEM
	Advantages	
Mature technology	Higher performance	Non-noble metal catalyst
Non-PGM catalyst	Higher voltage efficiencies	Non corrosive electrolyte
Long term stability	Good partial load	Compact cell design
Low cost	Rapid system response	Low cost
Megawatt range	Compact cell design	Absence of leaking
Cost effective	Dynamic operation	High operating pressure
	High operating pressure	
	Disadvantages	
Low current densities	High cost of components	Laboratory stage
Cross-over of gas	Acidic corrosive components	Low current densities
Low dynamic	Possible low durability	Durability
Low operating pressure	Noble metal catalyst	Membrane degradation
Corrosive liquid electrolyte	Stack below Megawatt range	Excessive catalyst loading

Table 2 Advantages and disadvantages of alkaline, PEM and AEM electrolysis [7].

mulated, eliminating the first stage of gas compression which is the one that consumes the most energy. Furthermore, mechanical compression could be completely eliminated for some applications, such as the introduction of gas into the network, with great plant and energy advantages.
A different approach is that the two electrolytic compartments operate under pressure and without pressure differential. In this case the system exerts equal pressure on both sides of the membrane, which allows the use of thinner membranes.
According to a theoretical analysis, as pressure increases, the volume of gas bubbles developed during electrolysis decreases. This facilitates the transport of water, decreases ohmic losses in the catalytic layer and improves the electrical contact between the layer and the current collector. This in turn facilitates the transport of water, decreases ohmic losses in the catalytic layer and improves the electrical contact between the layer and the current collector.
In addition, by raising the pressure, it is possible to perform electrolysis at temperatures above 100 °C, thus reducing energy consumption due to a decrease in membrane resistance and overvoltage.

Projects and perspectives

The low temperature electrolysis technologies can play a key-role for the entire hydrogen supply chain, since they allow the production of electricity from renewable sources to interact effectively and efficiently for the production of a gaseous energy vector with zero CO_2 emissions. This makes it possible to accumulate, in the form envisaged for gaseous fuels, large quantities of energy and for a very long period. In this sense, the role of hydrogen, seen as an electrical energy storage system, is complementary to the role and use of batteries. The hydrogen thus produced can be injected, for low percentages, directly into the natural gas network. Subsequent use, mixed with natural gas, for example in vehicles, can present significant advantages in reducing emissions [12, 13].Furthermore, the hydrogen produced in this way, in combination with CO_2, can be used for what are defined as e-fuels; fuels characterized by low CO_2 emissions

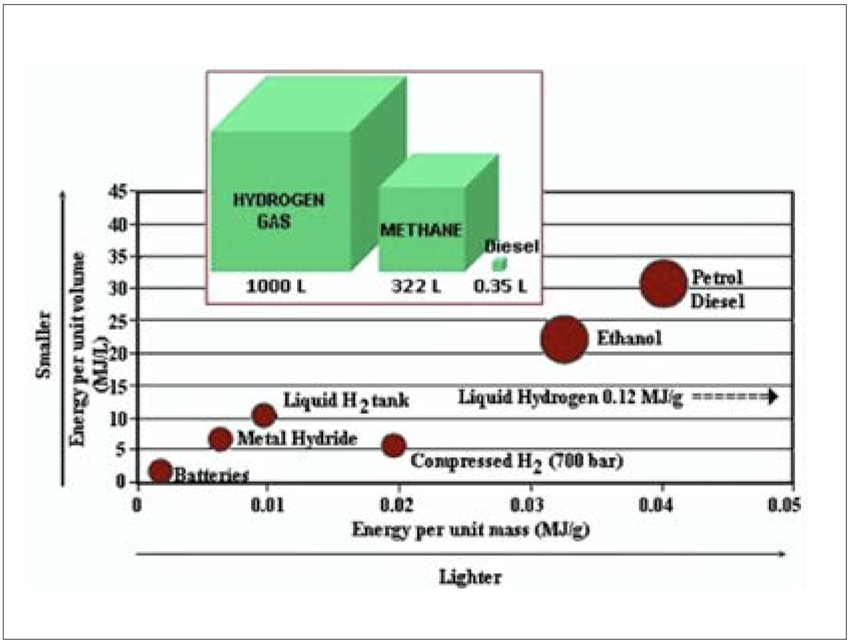

Fig.2 Energy densities of various energy storage materials and technologies, illustrating the respective volumetric and gravimetric densities []. The insert refers to volume gases at atmospheric pressure.

in the production - use cycle and which may be compatible with the users already present. One example is synthetic methane, produced from hydrogen and CO_2 and fully compatible with existing natural gas infrastructures.

Actually, AE electrolysis is the most industrially widespread and technologically mature technology. The main applications are aimed at the on-site production of hydrogen for industrial use with plants of up to hundreds of Nm^3/h with operating pressures up to a maximum of 25-30 bar. Lately, under the increasing pressure of the use of renewables, the size of these systems has increased and today modules up to 800 Nm^3/h are on the market. Major producers of alkaline electrolysers include Nel (Norway), Thyssenkrupp (Germany), McPhy (France), IHT (Switzerland), Hydrogenics (Canada), Teledyne Energy Systems (USA), Asahi Kasei (Japan), Toshiba (Japan). 50% of the world market of this class of electrolysers is in China which is able to produce machines of the AE type at about 200 USD / kW equal to -80% of the cost of the European ones. About this technology, the main objective is to reduce energy consumption to the theoretical limit of 3.6 kW/m^3 in order to reduce the cost of hydrogen. The fundamental points to be addressed in the research field are: 1) the cell engineering in such a way as to minimize the separator/electrode gap by reducing the ohmic drop and develop a more compact design, 2) the development of the electrolytic cell (catalytic coatings of the electrodes, increase in electrode area, decrease in degradation). As regards the management of the overall system, it is necessary to improve the dynamic behavior to electrical loads.

As highlighted above, polymer electrolyte electrolysers (PEMs) have several advantages over AE including the possibility of obtaining theoretically much higher hydrogen pressures thanks to the separating polymer membrane [14]. This last point allows to eliminate or reduce expensive compression systems. On the other hand, the high cost of materials as well as the need to use totally deionized water represents a limit to development. Therefore, although they can reach large sizes (eg: 2 MW ITM plant with single modules of 14 Nm^3/h in two blocks of 15 modules each) in fact today they are produced mostly for hydrogen production of a few Nm^3/h. There are few industrial companies that produce large polymer electrolysers in consideration of the heavy investments necessary for their development: ITM Power Ltd. (UK), Nel (Norway), Proton Energy Systems (USA), Toshiba (Japan).On both technologies, there are industrial companies in Italy operating on sizes of tens of Nm^3/h for AEs, which can be modulated up to MW power and a few liters/h for polymers. The main objective in this case is to reduce the costs related to the materials used.

The fundamental points to be addressed in the research are therefore: 1) reduction of the load of noble metals (or replacement with non-CRM metals), 2) replacement of titanium with less expensive metals and/or suitable protective coatings, 3) development of efficient membranes and alternatives to commercial ones but with reduced costs, 4) the development of a cell and system engineering to guarantee high pressures without degradation of the system.

Finally, in the prototype or small-scale commercial phase, there are alkaline membrane electrolysers AEM which should summarize some advantages of both technologies, low-cost catalysts such as liquid alkalis, compactness and high pressures such as polymeric ones [15]. Very few Italian companies operate in this sector. Basic research on various aspects is required on this technology: 1) development of a mechanically stable and performing anion membrane capable of guaranteeing suitable purity of hydrogen, 2) development of anodic and cathode catalysts and of the related membrane coating methods (CCM), 3) development of cell and system engineering to guarantee high pressures.

ENEA with the aim of promoting the development and marketing of innovative electrolyser collaborates with Industry, Universities, Research Centres, and is also involved in national project as the Electrical System Research program (RDS) with the financial support of Minister of Economic Development [16]. With regard to membrane for high pressure, ENEA develops research activities relating to the balance of plant of PEM systems; in the past, activities developed on small PEM system have reached pressure of about 60 bar, and with an improvement in energy performance compared to operation at atmospheric pressure [17]. This pressure value represents the target to be able to think of an injection of hydrogen into a gas network without the use of additional compression systems. Starting by these results, recently ENEA develop a proof or concept [18], in collaboration with national electrolysers producers. Last, in order to develop a regional supply chain for hydrogen, various research projects were also launched [19, 20].

Conclusions

The green hydrogen was universally acknowledged with a key-role for the decarbonization of the energy sector since it could be injected, at low percentages, directly into the natural gas network (blending) or directly used in several industrial application or in mobility sector.

The low temperature membrane electrolysers (PEM and AEM) are the most interesting technologies for green hydrogen production from RES, thanks to the characteristics of compactness, ease of use, low maintenance and high-pressure operation.

The high cost of hydrogen production from electrolysis is still due today to the cost of electricity supply and of the technology. For this reason, there is a need to focus on reducing the production cost and increasing the performance and durability of electrolysers, to achieve further cost reductions in hydrogen production. The achievement of cost targets will depend on innovation that will lead to technological improvements and better adaptation for different technologies and system designs in each specific application.

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Solid oxide cells: a pivotal technology for hydrogen generation and use

The increasing penetration of variable renewable energies poses new challenges for grid management, in particular on: the efficient storage of excess renewable power, the integration of different energy grids and infrastructures (e.g. electrical, natural gas, transport fuel), and the decarbonization of transportation fuels. Solid-oxide systems are the key enablers to increase the penetration of variable renewable energy, and to allow for flexible coupling of different sectors as well as the decarbonization of transport fuels and chemical industry. In the last 15 years, ENEA consolidate knowledge, skills and procedures on this pivotal technology, exploring technical feasibility, sustainability, system integration and business opportunities.
The paper describes the Solid Oxide Cells in the actual and future energetic scenario, describing the main advantages and drawbacks, and the principal research lines and R&D challenges in which ENEA is involved.

Il crescente utilizzo delle fonti rinnovabili intermittenti comporta nuove sfide per la gestione della rete, in particolare per quanto riguarda lo stoccaggio dell'energia elettrica in eccesso, l'integrazione fra le diverse reti e infrastrutture (ad esempio, elettrico, gas naturale, carburante per il trasporto) e la decarbonizzazione dei carburanti per il trasporto. Le celle a ossidi solidi sono elementi-chiave per accrescere la penetrazione delle fonti rinnovabili intermittenti e per rendere flessibile l'integrazione di diversi settori oltre che la decarbonizzazione dei combustibili per il trasporto e dell'industria chimica. Negli ultimi 15 anni, ENEA ha consolidato conoscenze, competenze e processi relativi a questa tecnologia strategica, esplorando la fattibilità tecnica, la sostenibilità, l'integrazione del sistema e le relative opportunità di business. Nell'articolo sono descritte le potenzialità delle Celle a Ossidi Solidi nello scenario energetico attuale e in quello futuro, i principali vantaggi e le criticità oltre che le principali linee di ricerca e sfide di R&S in cui ENEA è coinvolta.

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by **Francesca Santoni, Davide Pumiglia, Andrea Monforti Ferrario, Massimiliano Della Pietra, Stephen Mc Phail (*)**

As the evolution of the energy system moves from the use of fossil fuels to low-carbon energy sources, the integration of growing shares of intermittent renewable sources into a legacy power infrastructure constitutes a significant challenge. The higher the share of renewables, the more flexible and interconnected the energy distribution grid needs to be. In this scenario, electrolysis technologies play a crucial role, being the core of power-to-X (PtX) solutions, where X can be a secondary vector such as hydrogen, syngas, or synthetic fuels, or other chemical commodities. This allows the abundance of renewable power to be transformed into other usable streams, effectively decarbonising the corresponding industrial processes, diversifying the end use of renewable energy carriers and increasing the overall flexibility – and value added – of the energy system.
Among the different electrolysis technologies, the Solid Oxide Cell (SOC) is attractive both because of unrivalled global conversion efficiencies - over 90% (electrical + thermal) - and because it can operate in reversible mode, switching between hydrogen production mode or power storage (SOE, solid oxide electrolysis) and power generation (Solid Oxide Fuel Cell, SOFC) as required. These properties make them **a**

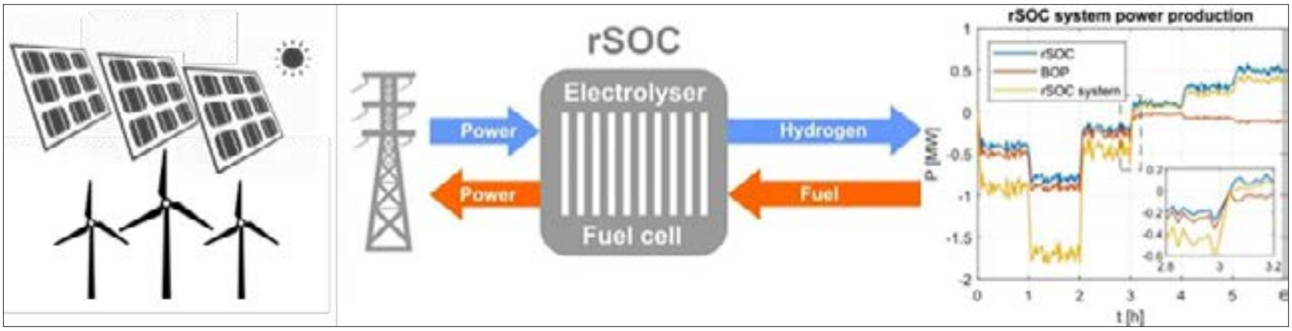

Fig.1 Simple schematic of an r-SOC system for RES balancing. (K. Motylinski et al. Energy Conversion & Management 228 (2021))

pivotal technology for hydrogen production, distribution and consumption, simultaneously balancing the electricity grid (Figure 1). **Solid oxide technology has undergone tremendous development and improvements over the last decades.** Their intense development has led to the growth of various industrial realities throughout Europe, ranging from individual cells' development and production to the construction and commercialization of small-sized modules (a few kW) up to module of hundreds of kW. Despite these advances, **research and development challenges remain, tied to necessary cost reduction and lifespan enhancement, for wide deployment to be achieved.**

Research and development activities in ENEA

The main activity carried out in ENEA related to SOC technology has always been the testing and characterization of solid oxide cells on a laboratory scale, conducted in the framework of European research projects (H2020, FCH-JU, etc ...). The ABI Laboratory is equipped of different test benches for SOCs testing, shown in Figure 2. Each of them can be adapted and customized to each project's requirements.

Testing and characterization of solid oxide cells samples, supplied by the leading manufacturers in Europe, is carried on at the level of button cells (1-10 cm^2), single cells (up to 100 cm^2) and laboratory scale power modules (short stacks, 5-6 single cells connected in series).

On these samples, the main studies are focused on: (i) the evaluation and quantification of the electrochemical performance by simulating the different operating conditions with respect to the scope of a specific project,[1 (ii) the study of the material degradation phenomena, induced by particular operating conditions or by the presence of contaminants in the fuel gas, and, last but not least,[3-4] (iii) the definition of experimental procedures for the qualification of the performance of commercial cells and modules. Typical outcomes of experimental SOC testing and characterization activity is summarized in Figure 3.

All these activities allowed to consolidate knowledge, skills and procedures in line with those currently present in the other European research centres, with which the laboratory has collaborated, but also to develop more advanced investigation methodologies such as the analysis of the Distribution of Relaxation Times (DRT) or the development of localized gas sampling for *in-operando* chemical and electrochemical reactions monitoring.

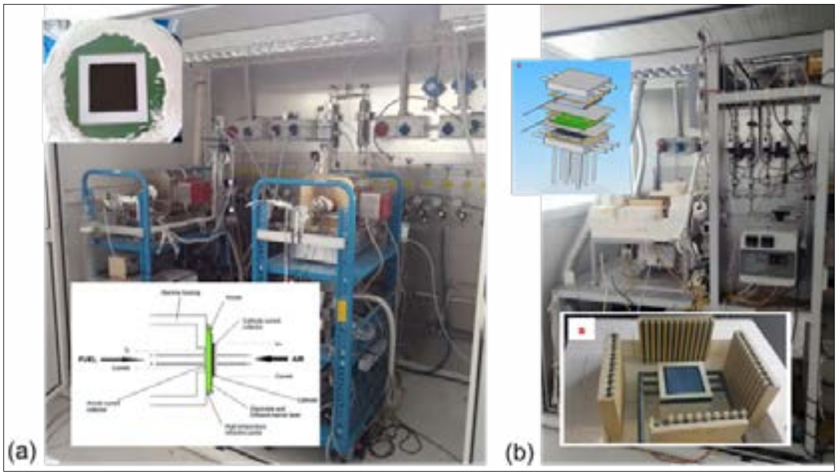

Fig.2 ABI laboratory test benches for SOC button cells in (a) and for single cells and short stack in (b)

Cross-cutting activities

Other activities conducted by the laboratory and related to SOC technology are the Life Cycle Assessment (LCA) studies and the standardization of experimental procedures in liaison with

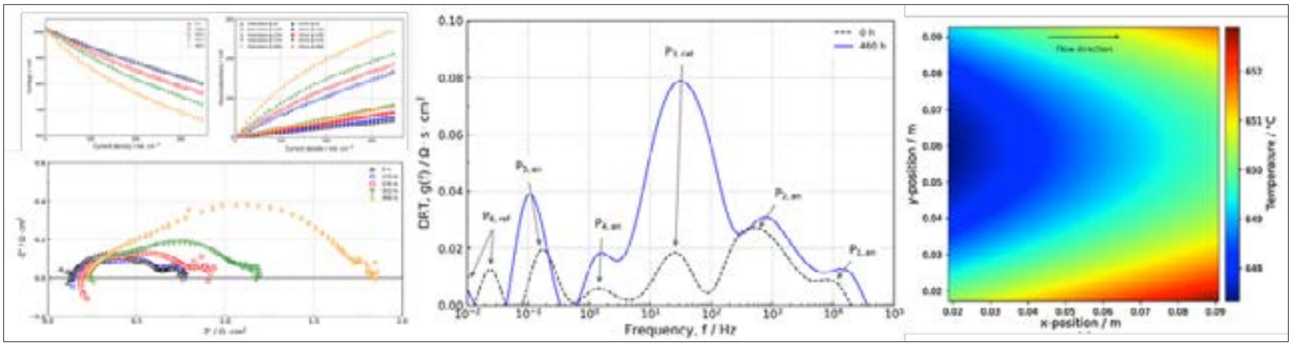

Fig.3 Example of SOFC electrochemical characterisation performed in ABI. D.M. Silva-Mosqueda et al. Applied Energy 235 (2019) 625–640

standardisation bodies (IEC). Moreover, the ABI laboratory carries out other cross-cutting activities such as the definition of new regulatory standards and the provides support to national and European institutions for the development of road maps, strategic industrial plans and KPIs for project financing platforms in the field of solid oxide cells and their applications.
Considering the technological maturity level reached by SOCs, and given the particularly favourable moment for their next market penetration, both in the production of power but, above all, in the generation of hydrogen, the aforementioned laboratory skills could be put at the service of two future strategic activities:

- **the development of large-scale SOC systems** through the creation of a **Testing Hub laboratory** capable of testing, validating and certifying the performance of prototypes or commercial SOCs devices of industrially significant size (kW-scale). Such activity would make available to companies interested in the production of SOC modules the infrastructures and skills necessary for the validation of their systems, simulating a relevant application environment, with the ultimate goal of placing **ENEA as a certification center of electrolysis and fuel cell systems;**
- **the development of "next generation cells" with a great application potential,** such as Proton-Conducting Solid Oxide Fuel Cells (H-SOFC). These cells can work at lower temperatures respect to SOCs, limiting, in this way, the impact of thermally activated degradation processes, and, at the same time, allowing the use of less expensive materials for their integration in the power module. The most important factor for which they are considered **strategic for future applications** is that they can act as separators, concentrators and electrochemical compressors of H_2, with a selectivity not comparable to other known systems, making them **very attractive for H_2 mobility applications and for the direct injection of H_2 produced by electrolysis into the existing natural gas network.**

ENEA's projects, perspectives and comprehensive network of research

The SOC is a high-temperature technology, operating at 600-800°C, and which is the reason for the high conversion efficiencies in both operating modes. **It is especially promising in industrial contexts, where steam is available as a process stream and can be directed towards the generation of hydrogen at unmatched efficiencies in an SOC.** For example, the steel industry is particularly interested in utilising hydrogen for the production process to replace coal and carbon-containing reagents for iron ore reduction, high-temperature treatment and other process steps. Other **chemical industry** processes apply as well. **Working flexibly, the SOC can give rise to innovative business propositions where price arbitrage** of renewable power connected to the grid can provide adequate revenue streams, or where energy communities want to progressively emancipate themselves from grid connection. ENEA is active on all these fronts, exploring technical feasibility, sustainability, system integration and business opportunities. **ENEA has built up a comprehensive network of research and industrial partners in this process, articulated in a number of European projects**:

- AD ASTRA (FCH JU, 825027) and SOCTESQA (FCH JU, 621245) projects, focused on the development of validated test protocols for SOFC and SOEC stacks, building on multiannual experience of key research institutions in Europe in the field, among which ENEA, responsible for the projects' liaison with Standards-developing organizations such as IEC, CENELEC and ISO;
- NELLHI (FCH JU, 621227), INNOSOFC (FCH JU, 658813) and qSOFC (FCH JU, 735160): this concatenation of projects, in collaboration with Elcogen, progressed from the development of a high-performance 1-kWe SOFC module to the creation of a market-ready 60-kWe SOFC system and improved designs of components for mass production;

- WASTE2WATTS (FCH JU, 826234) and BLAZE (H2020, 815284) are based on the utilization of alternative fuels (biogas and bio-syngas) in a SOFC system for small-to-medium scale CHP applications in farms and organic waste processing facilities;
- BALANCE (H2020, 731224): aimed at the development of an European regenerative solid oxide cell (Re-SOC) stack benchmark, for the reversible generation and storage of renewable power in a unique SOC stack. Based on an EU-wide survey, this project also defined a European common agenda to develop and implement this strategic technology solution.

The most recent EU projects, coordinated by ENEA, started in 2021: SO-FREE (FCH-JU, 101006667) focused on the development of a versatile (fuel-flexible), SOFC-based system for combined heat and power (CHP) generation, and PROMETEO (FCH-JU,101007194) based on the integration of SOEC technology with renewable (solar) sources. Furthermore, the engagement of the Laboratory is further increased by the membership and participation in the International Electrotechnical Commission's Technical Committee on Fuel Cells (IEC TC105), the International Energy Agency's (IEA) Technology Collaboration Programme on Advanced Fuel Cells, the European Energy Research Alliance's (EERA) Joint Programme on Fuel cells and hydrogen, the International Partnership for Hydrogen and fuel cells in the economy (IPHE), Hydrogen Europe Research, the Clean Hydrogen Alliance and the national association H2IT.

Conclusions

The European long-term strategy (EU Commission 773-2018) provides the achievement of Carbon Neutrality by 2050, through an increase in renewable electricity generation, a drop in oil and coal consumption and the increment of biomethane and hydrogen usage. In this frame SOCs technologies will play a central role, acting as a vital link between the electric, gas, and thermal grids and providing fuel for the transportation sector. Moreover, it is especially promising in industrial contexts, where steam is available as a process stream and can be directed towards the generation of hydrogen at unmatched efficiencies in an SOC. The experience and European collaboration network on SOCs technologies accumulated over the years by ABI laboratory in ENEA, allow to position itself among the future specialists in the energy transition processes, continuing research and development activities to achieve further performance enhancements and cost reductions on cell, stack, and system level.

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MCEC, a promising, innovative and versatile technology

To achieve long-term climate neutrality targets by 2050 as imposed by the EU [1], transition technologies capable of efficiently exploiting unavoidable CO_2 streams, in synergy with renewable energy sources, must be further investigated and deployed in the global energy sector; in such a context, hydrogen is an energy vector that can effectively contribute to the energy transition due to its wide applicability, both in terms of sector and scale [2]. In this scenario, electrochemical systems can connect gas and electricity networks, providing the opportunity to integrate clean technologies into industrial processes and to reduce their environmental impacts. Among them, high-temperature fuel cells using molten carbonate electrolysers represent a promising technology to valorise CO_2-rich waste streams, which are typically available in industrial plants, by their conversion into high-value hydrogen or H_2/CO syngas. ENEA is among the first organizations worldwide having started a deep and comprehensive investigation of the MCEC technology. Thanks also to the pioneristic activities carried out in ENEA laboratories, the interest on MCECs technology is growing fast, involving industrial partners as end users and technology uptakers but also research institutions at Italian and European level. What is expected to obtain in the next future is to build a supply chain able to take out from the laboratories the technology to apply it in relevant industrial context.

Per raggiungere gli obiettivi di neutralità climatica a lungo termine da qui al 2050, come imposto dall'UE [1], le tecnologie di transizione in grado di sfruttare in modo efficiente i flussi di CO_2 inevitabili - in sinergia con le fonti energetiche rinnovabili - devono essere ulteriormente studiate e diffuse nel settore energetico globale; in tale contesto, l'idrogeno è un vettore energetico che può contribuire efficacemente alla transizione energetica grazie alla sua ampia applicabilità, sia in termini di settore, sia di scala [2]. All'interno di questo scenario, i sistemi elettrochimici possono collegare le reti del gas e dell'elettricità, fornendo l'opportunità di integrare tecnologie pulite nei processi industriali e di ridurre il loro impatto ambientale. Tra queste, le celle a combustibile ad alta temperatura che utilizzano elettrolizzatori di carbonati fusi: rappresentano una tecnologia promettente per valorizzare i Fumi di combustione o gas esausti ricchi di CO_2, solitamente disponibili negli impianti industriali, attraverso la loro conversione in idrogeno ad alto valore o syngas H_2/CO. ENEA è tra le prime organizzazioni al mondo ad aver iniziato una profonda e completa ricerca sulla tecnologia MCEC. Grazie anche alle attività pionieristiche svolte nei laboratori ENEA, l'interesse nei confronti delle tecnologie MCEC sta crescendo rapidamente, coinvolgendo partner industriali come utilizzatori finali e sostenitori della tecnologia ma anche istituti di ricerca a livello italiano ed europeo. Quello che ci si aspetta di ottenere nel prossimo futuro è la realizzazione di una filiera in grado di portar la tecnologia fuori dai laboratori per applicarla nel contesto industriale di riferimento.

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by **Massimiliano Della Pietra, Stefano Frangini, Luca Turchetti (*)**

Architecture and engineering of molten carbonate electrolysis cells (MCECs) are based on the well-proven and mature Molten Carbonate Fuel Cell (MCFC) technology, which started to operate commercially from 2007 for applications in the prime and premium power generation market of large stationary systems [3]. The typical power size of MCFCs ranges from several hundred kilowatts up to 3-4 MW, with several power plants with a capacity of 10-60 MW already installed worldwide [4]. The difference between MCEC and MCFC is the direction of the redox reaction only [5]. Figure 1 schematizes the reactions occurring inside a MCEC (a) and a MCFC (b), respectively.

Water, carbon dioxide and electricity are required in electrolysis mode to perform the reduction reaction in the fuel electrode (FE), where H_2 and carbonate ions (CO_3^{2-}) are produced, as expressed by Eq. (1):

$$H_2O + CO_2 + 2e^- \rightarrow H_2 + CO_3^{-2}$$

Carbonate ions are transported through the electrolyte to be oxidized at the oxygen electrode (OE), producing carbon dioxide and oxygen, as reported by Eq. (2):

$$CO_3^{-2} \rightarrow CO_2 + 0.5\ O_2 + 2e^-$$

Thus, the global reaction is expressed by Eq. (3):

$$H_2O + CO_{2,fe} \rightarrow H_2 + 0.5\ O_2 + CO_{2,oe}$$

Molten Carbonate Electrolysis Cells based on the flat design of MCFC cells typically operate in the range 600-650°C. No flow is strictly required at the OE inlet; nevertheless, since CO_2 is a highly corrosive gas, feeding a gas stream, generally air mixed with a little amount of carbon dioxide, is beneficial to sweep out the formed gases, thus avoiding unrestricted degradation of the electrode.

As shown by Eq. (3), the overall process carried out in MCECs is the electrochemical water splitting of water with simultaneous CO_2 transfer (without net generation) from the FE to the OE. Therefore, if the system is fed with renewable power and CO_2 is separated from the OE outlet stream and recycled to the FE feed, MCEC electrolysis can be used as a green hydrogen production method, with some advantages compared to more consolidated processes: MCECs require a lower power input to produce 1 Nm^3 of hydrogen (3.5kWh/Nm^3) than low-temperature water electrolysers, because they can be operated with lower cell potentials (~1,2 V vs 1,6-1,8 V); furthermore, compared to solid oxide steam electrolysers, MCECs operate at significantly lower temperatures (600-650 °C vs >700 °C).

Equation (3) also shows that MCECs are characterized by the unique ability to act as an integrated CO_2 separator during their operation. Therefore, MCECs can be used to separate a part of the CO_2 from the off-gas and concentrate it at the OE, making it is easy to capture as pure CO_2, for instance, after using the electrochemically produced CO_2-O_2 gas mixture (see reaction (2)) in an oxy-combustion process. Similarly, MCEC can be used to exploit CO_2-rich waste streams typically available in industrial environments, by converting them at the Fuel Electrode compartment into high-value syngas products, which can be reused in the industrial plant or elsewhere for different applications, like producing synthetic fuels or chemicals such as methanol.

The research on MCEC is still lying at fundamental levels, with almost no studies on scaled up systems. The main challenge for the implementation of the MCFC technology for electrolysis applications is the identification of structural and functional materials with sufficient corrosion resistance when exposed to the higher potentials and CO_2-rich electrolysis atmospheres.

Research and development activities in ENEA

As mentioned above, the research in the field of MCEC is still at an earlier stage compared to other types of electrolysers, although this technology

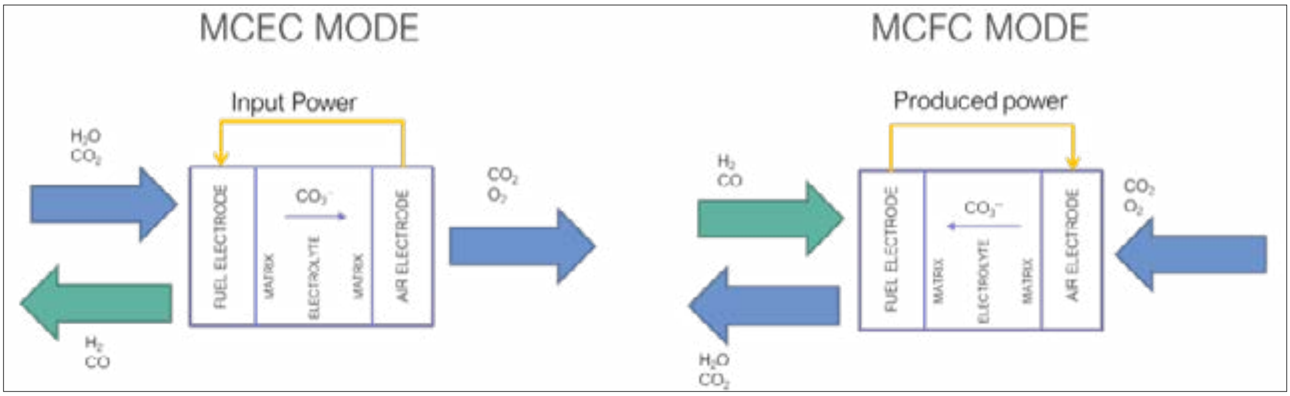

Fig.1 Working principles of MCFC/MCEC technology

represents an attractive sustainable option for generating green hydrogen or synthetic fuels from CO_2-rich waste streams. Several issues need to be tackled to implement a reliable MCEC technology, starting with a better understanding of the degradation phenomena affecting cell materials, in order to improve the cell tolerance and stability to the harsh operating conditions. Furthermore, the development of reversible MCECs, i.e. systems that can work efficiently in both electrolysis and fuel cell operation modes, is another important target. **ENEA is among the first organizations worldwide having started a deep and comprehensive investigation of the MCEC technology, with two main research lines:**

- Reverse operation of MCFC: focused on the study of the electrochemical phenomena occurring inside a molten carbonate fuel cell operated in reverse mode for the optimization of the operating conditions.
- Low-temperature MCE (~ 500 °C): based on a new process patented by ENEA, focused on the study of degradation phenomena affecting structural and functional materials at such lower temperatures and on the development of a new cell for these operating conditions.

For both research lines, ENEA is also studying the integration of MCEC systems with concentrating solar power (CSP) plants, which may feed the process with renewable heat and power, for a fully green hydrogen production [15]

Low temperature MCE

Production of pure hydrogen with MCEC cells is not an easy task since the steam electrolysis is challenged by side reactions such as CO_2 electrolysis and the reverse water gas shift reaction (RWGSR), the latter one consuming the hydrogen produced at the Fuel Electrode forming carbon

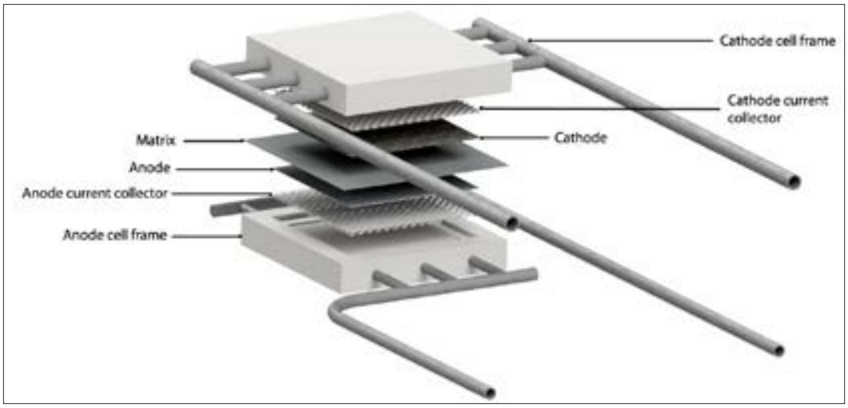

Fig.2 Working principles of MCFC/MCEC technology

monoxide according to Eq. (4):

$H_2 + CO_2 = H_2O + CO$

Equilibrium conditions are rapidly established at 600-650°C in presence of the Fuel Electrode of nickel, which is a highly effective RWGSR catalyst. Furthermore, carbon monoxide may be also produced by direct CO_2 reduction in molten carbonate salts, although CO_2 electrolysis is slightly more energy demanding than steam electrolysis [6]. As this energy gap decreases with temperature and becomes negligible above 600°C, this gives the opportunity of producing pure hydrogen in molten carbonates by lowering the temperature below 600°C and conducting the electrolysis under well controlled potential and current conditions. Based on these concepts, **the development of an innovative molten carbonate steam electrolysis system working efficiently at around 500°C, is under scrutiny at ENEA.** This activity builds on previous studies [7] and on the consideration that lower operating temperatures may be beneficial for the process manageability, safety and economics. The development of more efficient electrolysis cell designs compatible with intermittent and dynamic uses as those present in hydrogen energy storage systems (Power-to-Gas systems) is also under attention. For instance, molten carbonate cells with a tubular cell design has been recently investigated [8]. Results indicate that rapid start-up and improved mechanical stability can be achieved with tubular MCC systems, which would be highly relevant for implementing a molten carbonate electrochemical technology to be used in Power-to-Gas systems. Development of stable anode materials for replacing traditional MCFC nickel anodes, which exhibit substantial corrosion at around 500°C, is the primary objective of current experimental efforts [9].

Reverse operation of MCFC

The possibility of using MCFC in reverse mode to produce hydrogen instead of electric power has been deeply investigated in ENEA laboratories. The main goal of the experimentation carried out was to evaluate the electrochemical performance of MCFC/MCEC device. To tackle this challenging objective, ENEA team assembled and tested an MCC single repeating unit (fig. 2) of relevant size (81 cm^2), to move one step forward the state of the art (previously similar tests have been carried out only on 3 cm^2 cells). Experimentation carried out in ENEA facilities consisted of an accurate an extensive matrix of tests performed by varying all the oper-

ating conditions one by one, while diagnosing the state of health of the device continuously. The results of the experimental campaign shed light on the real feasibility of using MCFC/MCEC systems, increasing the know-how on a technology that can represent the missing ring between the capture and utilisation of CO_2, thus closing the carbon loop.
Next steps in this R&D field in ENEA will be to bring together the two above-mentioned research lines, joining results and know how to overcome the major issues identified and develop the next generation MCEC systems.

Projects and perspectives

Interest for MCE processes is developing following three main application directions: low-carbon manufacturing, energy storage via CO_2 capture and chemical conversion.
The possibility of enabling low-carbon and sustainable manufacturing technologies for the production of high-value chemicals (i.e., carbon nanotubes) [10] and key commodities (i.e., iron, cement) [11,12] via molten carbonate electrolysis is at the basis of recent studies [13,14], which also take into consideration the possibility of an easy integration of MCEC technologies with CSP systems, aiming to increase the overall efficiency and sustainability of the production processes.
Chemical energy storage of intermittent renewable energy sources via hydrogen or syngas production is another field with significant opportunities for MCEC processes. Energy storage applications is the main subject of interest and research studies in ENEA laboratories, on MCEC processes.
In particular, ENEA interest is directed to the development of MCE processes for hydrogen production from steam in CO_2/H_2O gas mixtures (wet CO_2) aiming to valorise carbon dioxide exhaust streams usually produced in industrial environments (e.g. refining processes, biogas upgrading) closing, in this way, the carbon cycle by producing renewable fuels. These application scenarios are particularly attractive since MCECs are able, on one hand, to capture CO_2, when operated in fuel cell mode, in an effective way (capture efficiency > 90%) and, on the other hand, to utilise it, operating in electrolysis mode for efficiently producing syngas (conversion rate <3.5 kWh/Nm^3) compared to the state of the art.
ENEA's activities in this field are currently carried out within the implementation plan 2019-2021 of the Italian Electric System Research programme, funded by the Italian Ministry of Economic Development. The main goal is taking the technology from TRL 3 to 4. In parallel, a strong network composed by research entities, SMEs and industries is taking form both at Italian level and European one, where ENEA plays an important role as know how collector and EU proposals coordinator.

Conclusions

Molten carbonate steam electrolysis is a promising and versatile process that can be used to produce green hydrogen or as a carbon utilization system to obtain synthetic fuels (gas, liquid) or chemicals (e.g. methanol).
Thanks also to the pioneristic activities carried out in ENEA laboratories, the interest on MCECs technology is growing fast, involving industrial partners as end users and technology uptakers but also research institutions at Italian and European level. What is expected to obtain in the next future is to build a supply chain able to take out from the laboratories the technology to apply it in relevant industrial context.

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A new generation of renewable powered reforming processes

Most of the world hydrogen production is obtained by steam reforming of methane, a thermocatalytic process carried out at high temperatures (>800°C) associated with high greenhouse gas emissions. The environmental impact of this process can be significantly reduced, even possibly achieving net-zero emissions, if the required high-temperature heat is provided with solar energy and renewable feedstocks such as biogas are used. An innovative steam methane reforming process of this type, operating at relatively low temperatures (<550°C), has been developed by ENEA in cooperation with Italian and European partners; the lower operating temperature allows to supply the process heat by means of molten salts, fostering the integration with concentrating solar technologies using the same liquid to capture and store solar heat up to 550°C. The research led to the development and experimental validation of a prototype reformer heated with molten salts, which achieved similar efficiencies compared to the conventional process, despite the lower operating temperatures. This result is obtained through to the combination of a specifically designed catalyst with a membrane to recover the produced hydrogen, which allows to integrate hydrogen production and separation into a single compact process unit.

La maggior parte della produzione mondiale di idrogeno è ottenuta mediante azioni di reforming con vapore di metano, un processo termocatalitico effettuato ad alte temperature (>800°C) associato ad elevate emissioni di gas serra. L'impatto ambientale di questo processo può essere significativamente ridotto, anche raggiungendo possibilmente emissioni nette zero, se solo il calore necessario ad alta temperatura fosse fornito dall'energia solare e se fossero utilizzate materie prime rinnovabili come il biogas. Un innovativo processo di reforming con vapore di metano di questo tipo, operante a temperature relativamente basse (<550°C), è stato sviluppato da ENEA in collaborazione con partner italiani ed europei; la temperatura operativa più bassa permette di generare il calore di processo per mezzo di sali fusi, favorendo l'integrazione con tecnologie solari a concentrazione che utilizzano lo stesso liquido per catturare e accumulare il calore solare fino a 550°C. La ricerca ha portato allo sviluppo e alla validazione sperimentale di un prototipo di reformer riscaldato con sali fusi, che ha raggiunto efficienze simili rispetto al processo convenzionale, nonostante le temperature di funzionamento più basse. Questo risultato è ottenuto grazie alla combinazione tra un catalizzatore specificamente progettato ed una membrana per recuperare l'idrogeno prodotto: così facendo, si permette di integrare la produzione e la separazione dell'idrogeno in un'unica unità di processo dalle dimensioni compatte.

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by **Alberto Giaconia, Giampaolo Caputo, Luca Turchetti, Giulia Monteleone (*)**

Today's global annual hydrogen production is estimated to be around 70 million tons [1], mostly obtained by the steam reforming of methane (natural gas), a process based on two chemical reactions:

$CH_4+H_2O \rightarrow CO+3H_2$
(ΔH^0_{298K} = +206 kJ/mol, SMR, 850-950°C)

$CO+H_2O \rightarrow CO_2 +H_2$
(ΔH^0_{298K} = -41 kJ/mol, WGS, 200-450°C)

Figure 1 shows a simplified block diagram of the process. The Methane feed is cleaned-up (the typical contaminants of natural gas are removed) and mixed with steam. The first reaction is the steam methane reforming (SMR) reaction, a heat demanding catalytic reaction carried out at high-temperature in gas-fired industrial furnaces, where methane and steam are converted to a mixture of hydrogen and carbon monoxide. After cooling, this outlet mixture is sent to a set of reactors where the "Water Gas Shift (WGS) reaction takes place, with the conversion of CO to CO_2 leading to additional hydrogen production. The produced hydrogen is then separated (usually by "pressure swing adsorption", PSA) and the off-gas (unreacted CH_4 and CO) mixed with additional methane and burned in the SMR furnace. The process is associated with high CO_2 emissions (up to 12 kg per kg of H_2 produced) coming from two sources:

- CO_2 produced with the reforming reactions;
- CO_2 from fuel combustion.

The carbon footprint of the reforming process can be significantly reduced by replacing the gas-fired furnace with a concentrating solar thermal system providing high-temperature renewable heat: in this way, combustion is avoided with savings in methane consumption and CO_2 emissions. Figure 2 shows the solar reforming concept, where the flue gas is not present and the chemical reactions are the only source of CO_2 (5.5 kg per kg of H_2 produced), which can more easily be captured compared to the conventional process, in a "blue hydrogen" production strategy. Even more interestingly, if a renewable feedstock like bio-gas or bio-methane is fed to the reactor instead of natural gas, the whole process becomes "net-zero emission" and green hydrogen is produced.

Solar reforming can be seen a renewable-powered fuel upgrading process that converts the methane contained in the feed into a decarbonized gas with a higher energy content. Figure 3 shows the net increase of the calorific value of produced hydrogen fuel (LHV_{H2} = 244 kJ/mol) compared to methane (LHV_{CH4} = 802 kJ/mol): the 22% increase is obtained by "embedding" solar energy in the product.

Over the last 25 years, there has been an extensive research and development effort worldwide on the solar reforming of methane [2,3]. The major challenge in the development of solar reformers is the integration with concentrating solar technologies, which can be achieved through different methods. The first approach, followed in the early development stage of this technology, is the "direct solar reforming", i.e., receivers/reactors were used to capture and convey

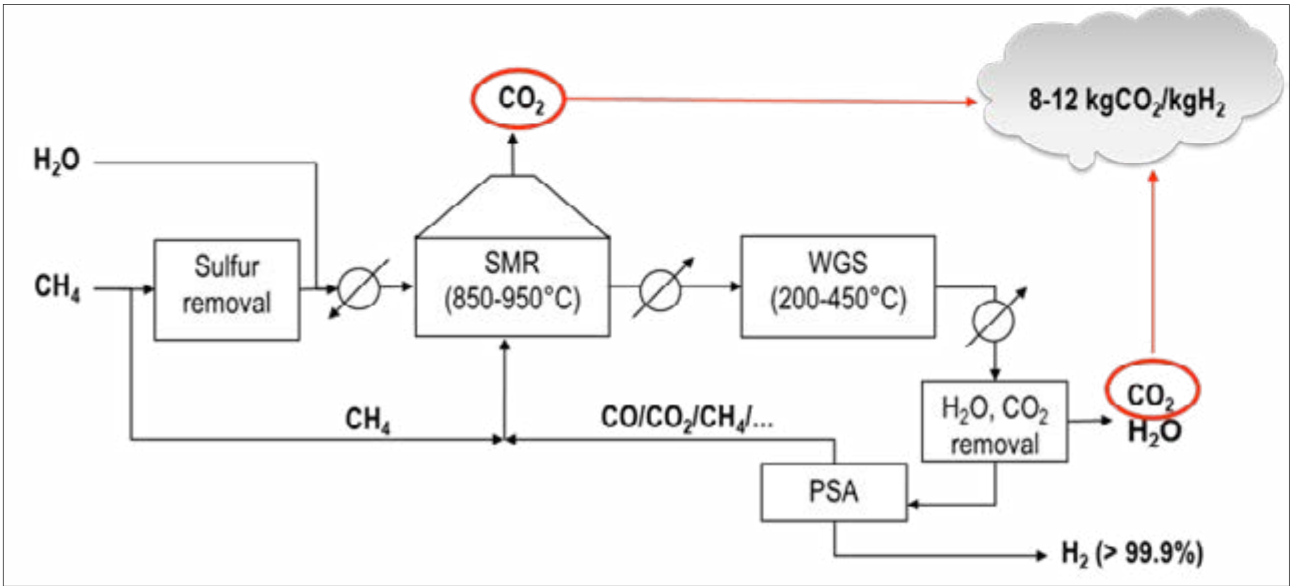

Fig.1 General scheme of a conventional steam methane reforming process

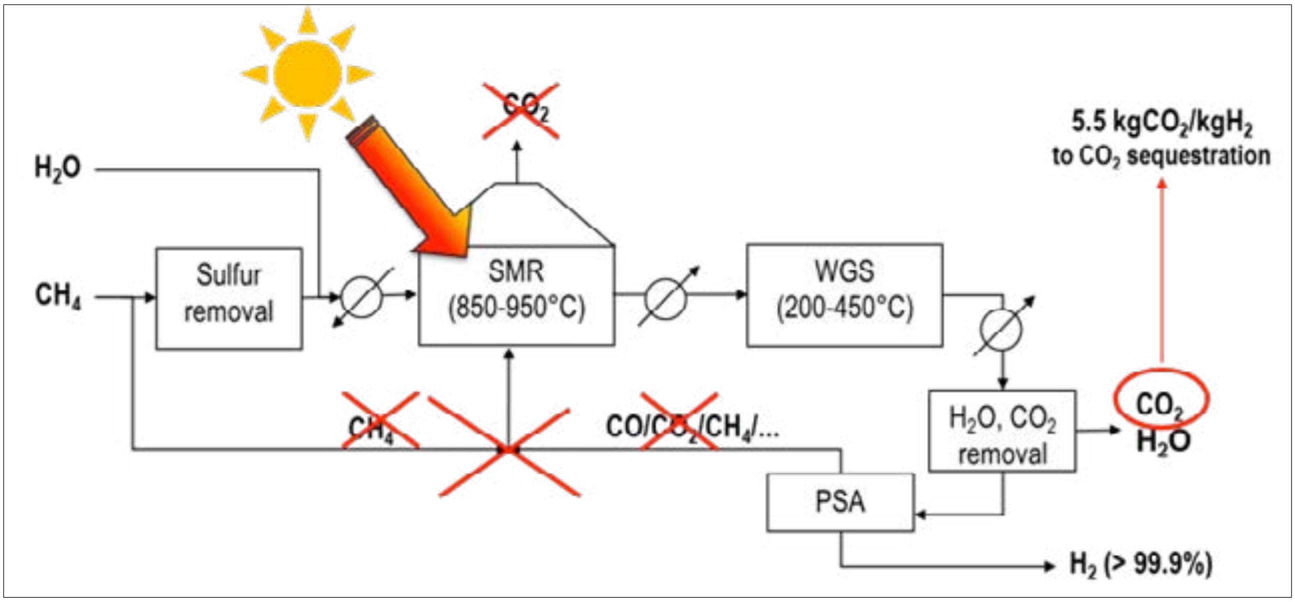

Fig.2 General scheme of a solar steam methane reforming process

the incoming highly concentrated solar radiation to the catalytic reaction zone operating at temperatures close to conventional reformers (>750°C) [2]. In this case, the main challenge is the management of transients that affect the operation of the reactor and downstream units, both on a short (cloud passages) and daily timescale. Such transients cause thermal cycling of the receiver reactor components, including catalysts and structural materials, fluctuations in the product gas composition and require daily startup and shutdown operations. All these issues could be more easily managed by using a thermal energy storage (TES) system; however, no consolidated TES solution is currently available for temperatures above 550 °C.

Research and development activities in ENEA

Recently, ENEA has patented and developed a new solar reforming technology consisting of a low-temperature membrane steam reformer [4,5] which can be easily coupled with mature concentrating solar technologies that make use of a molten salts mixture as heat transfer fluid (HTF) and TES medium up to 550°C [5]. Such mixture, often called "solar salt", contains sodium and potassium nitrates (60%wt. $NaNO_3$, KNO_3 40%wt.) and has several outstanding positive features, including low cost, high heat transfer/storage capacity and minor environmental and safety issues [5].
Figure 4 shows a conceptual scheme of the molten salt heated membrane reactor integrated with a concentrating solar plant with a two-tank TES system.
The membrane reformer consists of a shell-&-tube arrangement heated with the molten salt coming from the high-temperature TES tank [5,6]. The TES system overcomes the issues dealing with the mismatch between the fluctuating solar resource and the steady thermal duty profile of the chemical plant and allows to supply the process heat even overnight and during cloudy periods. Additionally, the continuous flow of the HTF in the shell of the reactor keeps the reactor hot in stand-by periods and minimizes start-up/shut down times.

The integration of a membrane inside the reaction chamber allows the continuous removal of hydrogen from the catalytic section, so that significant methane conversions can be attained despite the low operating temperatures (<550°C).
Moreover, the operation at such lower temperatures allows, with the adoption of suitable catalyst formulations, to carry out the endothermic SMR reaction (1) and the exothermic WGS reaction (2) in a single reactor, with consequent advantages in terms of overall thermal efficiency and process

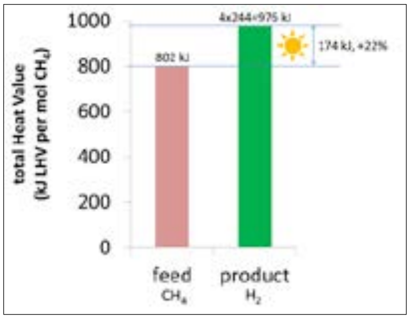

Fig.3 Energy balance of solar steam methane reforming process in the solar fuel perspective

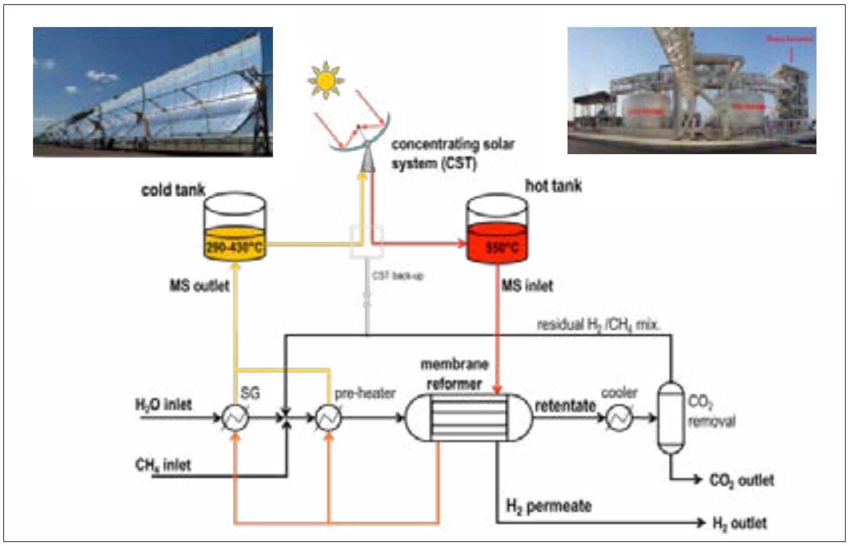

Fig.4 Conceptual scheme of the solar methane reforming heated with molten salts

intensification. **The development of this innovative technology required to face several R&D challenges.** After studying relevant process schemes for the combination of Concentrating Solar Thermal (CST) plants with a membrane reformer [5], a prototypal system heated with solar salt has been developed in the project CoMETHy [7]. First, basic components such as the catalysts for the low-temperature steam reforming and hydrogen-permeable membranes were identified and validated [7-11]; it is worth noting that the selected catalysts proved effective for the steam reforming of methane, biogas and ethanol, making the proposed technology flexible respect to the usable feedstock and suitable to produce 100% green hydrogen. Then, the catalyst/membrane assembly was tested by ENEA's partners in lab-scale SMR reactors [12,13]. Finally, a pilot membrane reformer to produce up to 3 Nm³/h of pure hydrogen from methane steam reforming has been built (Figure 5) and experimentally validated in a solar salt loop [14] built in ENEA Casaccia research center in cooperation with an Italian engineering firm (NextChem SpA).

Experimental results successfully confirmed the potential of the molten salt heated membrane reforming technology up to 550°C [14]: the membrane reformer following a pre-reformer allowed to achieve methane conversions in excess of 60%, despite the low operating temperatures; this value is twice as high as the maximum conversion that can be attained with a conventional reformer operating under the same conditions, with the production of a pure (> 99%) hydrogen permeate stream with < 100 ppm CO content. The WGS reaction approached completion, which results in an outlet retentate stream with <2%vol CO concentration and a relatively high CO_2 concentration (>30%vol) [14].

Projects and perspectives

The developments described in the previous sections have been obtained by ENEA in cooperation with National and International partners, in the framework of different projects, including:

- **National project METISOL** (methane/hydrogen mixtures: production by thermochemical processes powered by solar energy and on-board storage, 2011-2013) co-funded by the Italian Ministry for the Environment;
- **European project CoMETHy** (Compact Multifuel-Energy To Hydrogen converter, 2011-2015) co-funded through the Fuel Cells and Hydrogen Joint Undertaking (FCH JU).

The above projects allowed to advance the technology from basic concepts (TRL = 2) to the proof of concept at laboratory and pilot scales (TRL = 3-5). The obtained results show the potential for the deployment of the technology in different scenarios in the short, medium and long term, considering different aspects. First, beside the avoidance of CO_2 emissions with flue gases, it is noteworthy that the high CO_2 concentration (> 30%vol) in the outlet retentate stream simplifies downstream CO_2 capture processes. Therefore, membrane reforming leads to the pre-combustion decarbonisation of fossil fuels in a carbon capture, utilization and storage (CCUS) scenario, thus turning grey hydrogen into blue.

Second, when biogas or biomethane are used as feedstock, 100% green hydrogen will be produced from a combination of renewable sources and at competitive costs compared to traditional fossil-based systems. As a matter of fact, from techno-economic analysis the solar reforming process lead to hydrogen production at costs relatively close to the conventional process as far as the higher investment costs for the installation of the CST unit are balanced by the lower operative costs due to methane savings and CO_2 emission fees.

In general, solar-reforming can play a complementary role as back-up source of hydrogen where/when the demand for green hydrogen exceeds the direct offer from renewable-powered electrolysis.

Fig.5 The molten salt heated pilot membrane reformer built in ENEA Casaccia research center (project CoMETHy)

Today, R&D activities on this topic in ENEA are mainly focused on the optimization of the reactor design in the framework of the Electric System Research Programme funded by the Italian Ministry of Economic Development (Implementation plan 2019-2021).
In order to complete the R&D pathway it is necessary to verify performances and stability of the membrane reactor over longer periods (>5,000 hours) for final technology validation on pilot scale, and demonstrate the solar SMR in a real industrial environment, e.g. ammonia synthesis or hydrotreatment units for synfuel production.

Conclusions

Solar reforming of methane or renewable carbonaceous feedstocks like biogas is an alternative and potentially carbon-neutral hydrogen production route, which combines different renewable sources in a flexible way, while keeping competitive costs compared to traditional fossil-based systems. Thanks to these characteristics and without requiring radical technological changes in the current hydrogen production system, solar reforming can be readily taken up by the industry and play a key role in the short-term, by providing a more sustainable approach for the energy transition than conventional SMR combined with CCS/CCU. Furthermore hydrogen produced by solar reforming of renewable feedstocks is 100% green; this technology can play a role also in a fully decarbonized energy system, contributing to the hydrogen offer where/when the demand exceeds the green hydrogen availability from electrolysis driven by electric renewables, such as PV and wind.

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Splitting water with renewable heat: green hydrogen beyond electrolysis

In view of a diversification of energy sources and technologies for green hydrogen production, ENEA, since 2005, has been working on the development of water splitting thermochemical cycles powered by concentrated solar energy, participating in several research projects within National and European programs. Particularly ENEA has developed a unique expertise on materials and components with the aim of identifying critical aspects and defining innovative solutions to bring this challenging technology to an industrial maturity. To this end, within the Electric System Research programme, ENEA is currently investigating a "modified Sulphur – Iodine" thermochemical cycle, to increase both the thermal efficiency of the hydrogen production route and the technical feasibility of its integration with the solar technology. Innovative materials are under study and the preliminary results show that the use of intermediate solid reactants can be the key to reduce the maximum operating temperatures and the energy consumption of the separation steps.

In un'ottica di diversificazione delle fonti energetiche e delle tecnologie per la produzione di idrogeno verde, l'ENEA, dal 2005, si occupa dello sviluppo di cicli termochimici di scissione dell'acqua alimentati da energia solare concentrata, partecipando a diversi progetti di ricerca nell'ambito di programmi nazionali ed europei. In particolare ENEA ha sviluppato una competenza unica su materiali e componenti con l'obiettivo di identificare gli aspetti critici e definire soluzioni innovative per portare questa sfidante tecnologia ad una maturità industriale. A tal fine, all'interno del programma di Ricerca sul Sistema Elettrico, l'ENEA sta attualmente studiando un ciclo termochimico "Zolfo - Iodio modificato", per aumentare sia l'efficienza termica del percorso di produzione dell'idrogeno, sia la fattibilità tecnica della sua integrazione con la tecnologia solare. Sono allo studio materiali innovativi e i risultati preliminari mostrano che l'uso di reagenti solidi intermedi può essere la chiave per ridurre le temperature massime di esercizio e il consumo energetico delle fasi di separazione.

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The decomposition of water molecules by using renewable energy can be considered as the most straightforward pathway to green hydrogen production. In this perspective, water electrolysis powered by renewable electricity is currently the most technologically mature process; however, water splitting can also be achieved through alternative processes powered by high-temperature renewable heat, thus complementing electrolysis in a future flexible and resilient energy system based on multiple renewable energy sources and technologies.

The direct thermal decomposition of the H_2O molecule can be achieved at temperatures higher than 2500°C; however, the implementation of this process is hindered by several technological challenges related to the very high operating temperature and to the handling of hydrogen-oxygen mixtures, which pose material and safety issues, and require complex gas separation operations [1]. To overcome

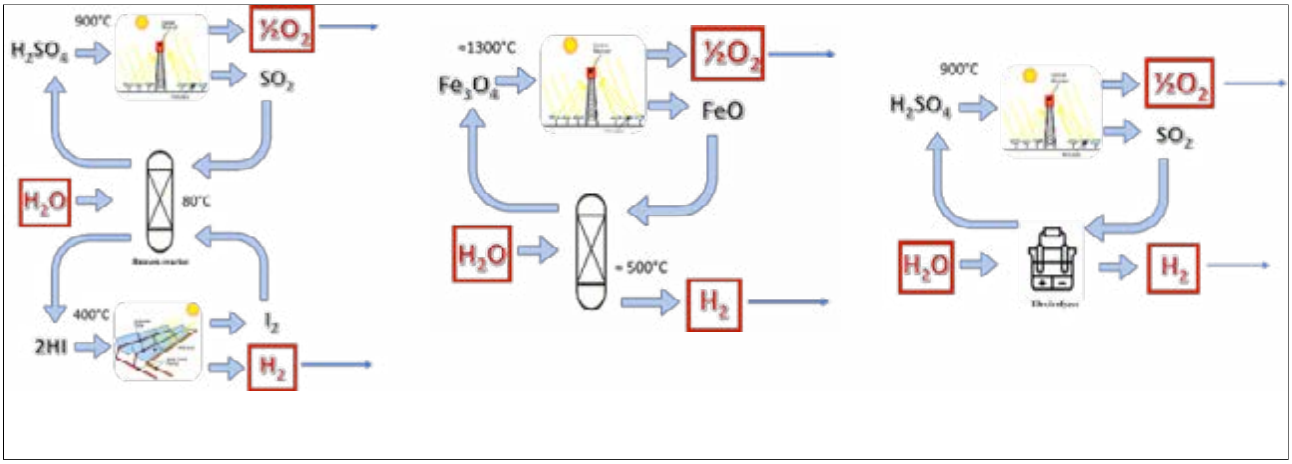

Fig.1 Three widely studied TWSCs: a) "Sulphur Iodine" b) "Iron Oxide" and c) "hybrid sulphur" cycles

these problems, the splitting process can be divided in multiple steps, where hydrogen and oxygen are produced separately and the maximum operating temperature is significantly reduced [2]. This is the approach followed by the so-called *Thermochemical Water Splitting Cycles* (TWSC), which are based on cyclic sets of chemical reactions involving different species, whose net result is water splitting. TWSCs typically require heat below 1500°C, which can be conveniently supplied by concentrating solar thermal plants, resulting in green hydrogen production.
Several TWSCs have been proposed since the 80's [3]. Figure 1 shows three of the most significant examples: in the "Sulphur Iodine" cycle (a), water is incorporated into two chemical species, typically acids, which are eventually decomposed [4]; in another widely investigated alternative (b), steam reacts with a reducing agent (Iron (II) in the example reported [5]) producing hydrogen and, subsequently, the resulting oxide is thermally split to obtain oxygen; a third option (c) includes an electrochemical step for hydrogen production, as in the "*hybrid sulphur*" process [6].

Overall, TWSCs can be classified according to the number and types of reactions involved, as summarized in Table 1.
Today, TWSCs have reached an inter-

TWSC	Examples	Advantages	Drawbacks
Sulphur based cycles	S-I cycle, basic [4] or S-I with metal oxides intermediates [7]	-The intermediates are low cost, commonly available chemicals. -Maximum temperature is below 850°C	-Concentrated strong acids and iodine are present (costly construction materials required)
Hybrid cycles with one electrochemical step	"Hybrid sulphur" process [6]	-Iodine and halides are not present	-Membrane and electrodes are to be optimized for the electrochemical step
Two-steps involving two oxidation numbers of a metal (red/ox)	Cerium oxide [5]	-No acids, only two steps	-Thermal decomposition of metal oxides requires >1300°C
Mixed Oxides	Ferrites [8]	-Non corrosive materials; -Maximum temperature is below 1000 °C	-Synthesis of ferrites can be complex -Hydrogen separation from excess water in the hydrogen production step is energy consuming

Table 1 Types of TWSCs according to types and number of reaction steps

mediate technology readiness level, with only few pilot-scale plants available worldwide. **Three main challenges need to be addressed for the further development of this technology: 1) improvement of structural and functional materials (reactants, catalysts) in terms of chemical and thermal properties; 2) design of solar reactors with higher thermal efficiency and higher single-pass conversion; 3) definition of effective integration strategies between the chemical process and the solar plant, also including thermal energy storage solutions in order to cope with the fluctuations of the solar resource.**

Fig.2 On the left, supported catalyst for SO_3 decomposition developed by ENEA within the SOL2Hy2 European Project; in the center, catalyst sample placed inside the quartz lab reactor; on the right, catalyst in the quartz tube in operation during SO_3 splitting tests in the HycycleS European Project.

Research and development activities in ENEA

ENEA has been active in the field of TWSCs since 2005 by participating in several research projects within National and European programs. In this 16 years period, **ENEA has developed significant expertise on the most critical aspects of this technology, by carrying out activities such as the investigation of reaction steps (catalysts, materials, reactors, etc.), the development of lab-scale and pilot-scale on-sun prototypes (in collaboration with other organizations), process design optimization and techno-economic analyses.**

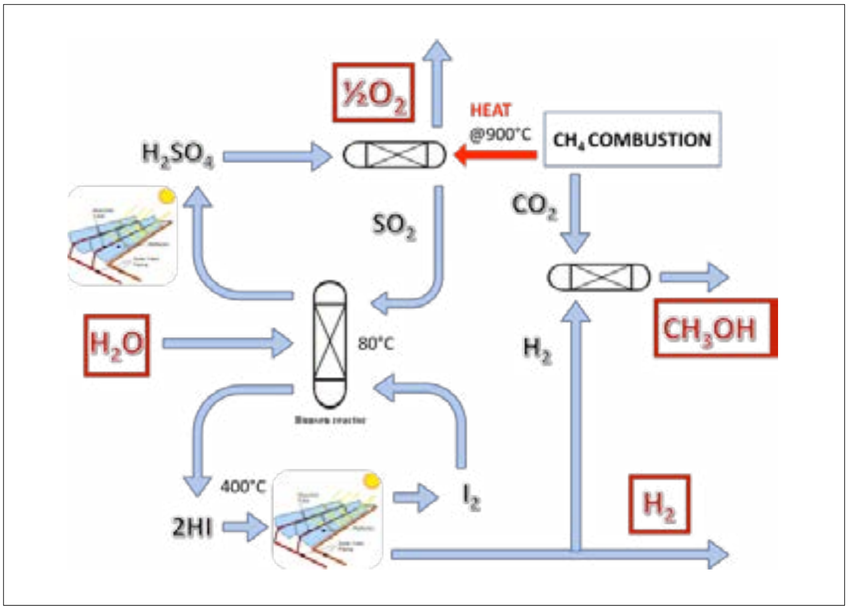

Fig.3 Alternative of the "Sulphur Iodine" scheme where H_2SO_4 cracking is driven by methane combustion. The obtained CO_2 is reacted with part of the produced H_2 in order to synthetize methanol.

Overall, ENEA's activities have been mainly aimed at improving the reacting materials in terms of reaction yield, chemical stability and thermal coupling with the concentrating solar technology. Particularly, with regards to the latter point, research activities have been focused on the reduction of the maximum operating temperatures of the TWSCs in order to adopt conventional structural materials for solar receivers, increasing their thermal efficiency.

ENEA's activities on this topic started within a FISR National project (TEPSI, 2005-2009), focusing on the "Mixed Ferrites" and the "Sulphur Iodine" cycles (Figure 1a). The former is an original process developed by ENEA, which is conceptually similar to the two-steps metal oxides cycles represented in Figure 2b; in this process, a manganese ferrite ($MnFe_2O_4$), appropriately syn-

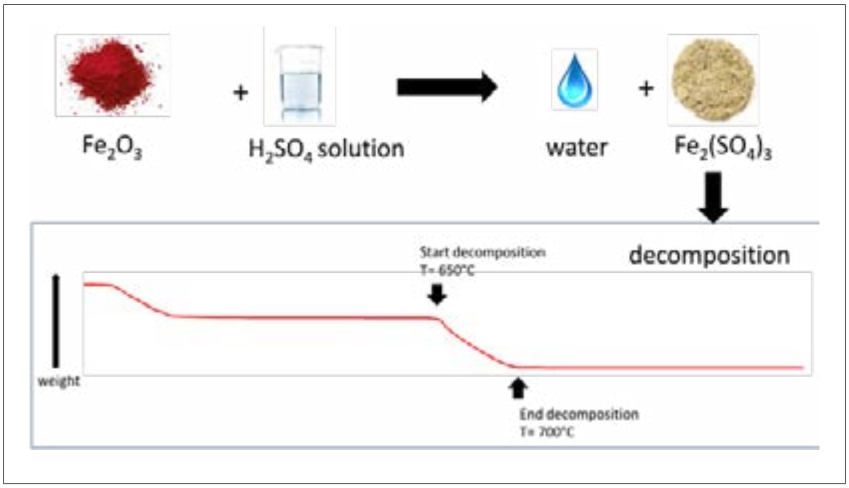

Fig.4 Alternative decomposition of sulfuric acid: the acid concentrated solution is reacted with Iron(III) oxide obtaining Iron(III) sulphate. The latter, as illustrated in the thermogravimetric pattern on the bottom, decomposes into Iron(III) oxide, sulphur oxides and oxygen at a lower temperature level than H_2SO_4 itself (between 650°C and 700°C).

thetized by ENEA, is reacted with sodium carbonate and steam to produce hydrogen, while the obtained material is reacted with CO_2 to release oxygen [8]. This method is very appealing for the relatively moderate operating temperatures (750-800°C) of both reactions, in particular the oxygen releasing step, which is considered the limiting step for the practical exploitation of most metal-oxide TWSCs. The "Sulphur Iodine" cycle, which is based on the adoption of commonly available acids and has a maximum operating temperature of 850°C, was thoroughly investigated by ENEA, from the extensive characterization of the involved chemical reactions and separation phases [9,10,11,12], to theoretical modelling and flowsheeting of the whole process [13]. As a result, the technical feasibility of the process and its economical sustainability were evaluated [14], and a bench-scale plant (with nominal capacity of 10 NL/h of hydrogen), was built and tested at ENEA laboratories [15], representing the first European demo for this technology.

On these topics, ENEA has collaborated with the main European research institutions (DLR, CEA, APTL; JRC, ETH) and materials providers (e. g. Outotec, Erbicol), developing innovative solutions for the Sulphur-based cycles, in particular in the framework of the European funded Projects HycycleS and SOL2HY2. Besides contributing to integration and techno-economic analysis [16], ENEA studied the sulphuric acid decomposition step, characterizing methods for large scale preparation of supported low-cost catalysts (Fig. 2) [17, 18] eventually supplied for on-sun tests in a pilot-scale solar reactor located at the Jülich solar tower facility of DLR (German Aerospace Center) [19].

The "Sulphur Iodine" process

The experience gained within the aforementioned projects allowed ENEA to identify the main solutions required to enhance manageability and efficiency of the "Sulphur Iodine" process, and particularly of the challenging steps sulfuric and hydriodic acids splitting, characterized by safety/material compatibility and limited conversion issues.

Indeed, the catalytic decomposition of H_2SO_4 requires severe operating conditions (acid environment at high operating temperatures, around 850°C [17]), while hydriodic acid (HI) splitting, which occurs at lower temperatures (<500°C), is thermodynamically limited [4]. In order to cope with these limitations, **ENEA has investigated several process alternatives, developing several patents [20,21,22]**. As an example, an alternative process configuration, powered by a combined solar/fossil energy source, with hydrogen and methanol co-production, was proposed to increase the efficiency and the technological sustainability of the high temperature reaction [23]; this alternative process exploits methane/biogas combustion to feed the high-temperature cycle step, while most heat required at medium temperatures (< 500°C) is supplied by linear focusing CSP technology. Therefore, methane combustion is proposed not only to supply thermal energy to the sulphuric acid decomposer, but also to convert the hydrogen generated by the cycle into methanol through the reaction with CO_2 contained in the flue gases [20], in a neutral CO_2 balance (Fig. 3).

Other patents focus on the use of oxides and metals as intermediates, leading to the formation of the related sulphates and iodides that are split in place of the corresponding acids [21,22,24]. The significant advantage of this methodology is that pure hydrogen production can proceed at nearly room temperature without thermodynamic limitations; furthermore, oxygen formation can be carried out without catalysts and at temperatures below 900°C [7]. Moreover, depending on the metal used as intermediate, the formation of low-solubility species allows for easier separation processes and storage of products [7, 25], thus de-coupling the solar energy step from hydrogen production.

Projects and perspectives

Currently, TWSCs are among the research topics included in the Electric

Cycle	Reaction involved	T max (°C)	Efficiency (LHV H2 /heat duty)	Cost (€/kg H2)
Sulphur-Iodine	$I_2 + SO_2 + 2H_2O \rightarrow 2\,HI + H_2SO_4$ $H_2SO_4 \rightarrow H_2O + SO_2 + ½\,O_2$ $2HI \rightarrow H_2 + I_2$	850	52	5.5 [26]
Westinghouse	$SO_2 + 2H_2O \rightarrow H_2SO_4$ $H_2SO_4 \rightarrow H_2O + SO_2 + 0{,}5O_2$	850	51	4.75 [26]
Zinc Oxide	$ZnO \rightarrow Zn + O_2$ $ZnO + H_2O \rightarrow ZnO + H_2$	≈2000	20.8	6.4 [27,28]
UT-3	$CaBr_2 + H_2O \rightarrow CaO + HBr$ $FeBr_2 + H_2O \rightarrow Fe_3O_4 + HBr + H_2$ $Fe_3O_4 + HBr \rightarrow 3FeBr_2 + 2H_2O + Br_2$ $CaO + Br_2 \rightarrow CaBr_2 + O_2$	760	49.5	4.0 [26,29]
Hybrid Copper chloride	$2Cu_2 + 2HCl \rightarrow 2CuCl + H_2$ $4CuCl \rightarrow 2Cu + 2CuCl_2$ $2CuCl_2 + H_2O \rightarrow Cu_2OCl_2 + 2HCl$ $Cu_2OCl_2 \rightarrow 2CuCl + 0.5\,O_2$	550	49	4.7 [26]
Mixed ferrites [30]	$2MnFe_2O_4 + 3Na_2CO_3 + H_2O \rightarrow 6Na(Mn_{1/3}Fe_{2/3})O2 + 3CO_2 + H_2$ $6Na(Mn1/3Fe2/3)O_2 + 3CO_2 \rightarrow 2MnFe_2O_4 + 3Na_2CO_3 + 0.5O_2$	800	/	7
Sulphur-Iodine modified [31]	$I_2 + SO_2 + 2H_2O \rightarrow 2\,HI + H_2SO_4$ $H_2SO_4 + Ni \rightarrow NiSO_4 + H_2$ $NiSO_4 \rightarrow NiO + SO_2 + 0.5\,O_2$ $NiO + 2HI \rightarrow H_2O + NiI_2$ $NiI_2 \rightarrow Ni + I_2$	900	20	/

Table 2 Main data of significant examples of TWSCs

System Research Programme funded by the Italian Ministry of Economic Development (Implementation plan 2019-2021). In this context, **ENEA is continuing to investigate a "modified Sulphur Iodine" scheme, based on the patents developed in the last years and described in the previous sections. In fact, these alternative approaches have the potential to improve the thermal efficiency of the process, which is 20% without any heat recovery [7]. The target of the activity is to bring the TRL of this alternative "Sulphur Iodine" cycle from the actual 2 to 3.**
Innovative materials are currently investigated, with the focus to optimize the composition of the intermediate solid reactants (metals, oxides and sulphates) employed in the cycle (Fig. 4). In particular, the selected chemicals should be featured by low toxicity and low environmentally impact, along with low cost and favourable chemical-physical properties. Regarding the latter point, the investigation is being dedicated to select and validate products that are insoluble or low-soluble in the liquid reaction mixtures in order to reduce the heat demand of the separation processes (i.e. further increasing the cycle efficiency) and to facilitate handling and storage of the same intermediates. Activities in progress are specifically dedicated to the experimental characterization of each step of the water-splitting process, with the aim to select the most promising configuration; a flowsheet analysis is also being performed in order to assess the investment and operative cost of the complete process loop.

TWSCs are also part of the strategic research and innovation agenda developed by Hydrogen Europe in the foreseen public-private partnership **Clean Hydrogen for Europe**. In this context, water splitting powered by solar heat is considered among the environmentally neutral processes that, in addition to water electrolysis, can be used in the future for green hydrogen production. A roadmap to significantly advance the technology readiness level of these processes in the next 10 years is also traced. The development of solutions to achieve an overall efficiency of 20%, and the deployment of demonstration projects on the MW scale, are identified as key actions to achieve the development and operation of the first 10 MW demonstration project and decrease the hydrogen production costs from the current 4-7 €/kg (Table 2) to nearly 2 €/kg by 2030, thus bringing the technology closer to the market.

Conclusions

Even if water electrolysis is considered s the most mature approach for green hydrogen production, the development of thermochemical water splitting cycles powered by concentrated solar energy can represent a complementary strategy to fully exploit different energy sources available in different geographical contexts and to favour large scale hydrogen productions thanks to the intrinsic scale-up capability of thermochemical processes.

In accordance with the strategic research and innovation agenda developed by Hydrogen Europe, and within the Electric System Research Programme, **ENEA is currently developing a "modified Sulphur Iodine" thermochemical cycle, based on the patents developed in the last years, to increase both the thermal efficiency of the hydrogen production route and the technical feasibility of the integration of the solar technology with the chemical process. The target of the activity is to bring the technology readiness level (TRL) of this alternative "Sulphur Iodine" cycle from 2 to 3, identifying suitable intermediate solid reactants to reduce the maximum operating temperatures** and the energy consumption of the separation steps.

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Biological processes in the Green Hydrogen value chain

Biological processes can be integrated in the green hydrogen value chain acting with the dual role of producers and consumers. Green hydrogen is produced biologically from organic wastes through Dark Fermentation, a biological process which has some advantages compared to other renewable H_2 producing technologies. It is a carbon neutral process which can produce continuously green H_2 with low energy requirement, combined with sustainable waste management. Moreover, together with H_2, it produces a number of valuable by-products. The use of H_2 to convert CO_2 to methane is the key bio-reaction of the biomethanation process which allows the enhancement of the conventional Anaerobic Digestion process. Moreover, the consume of H_2 as a source of reducing power by microorganisms has the potential of producing a large spectrum of bio-based products of industrial interest. Biological processes play a fundamental role in the development of future waste-based, H_2-oriented, bio-refineries.

I processi biologici possono essere integrati nella catena del valore dell'idrogeno verde agendo con il duplice ruolo di produttori e consumatori. L'idrogeno verde viene prodotto biologicamente da rifiuti organici attraverso la fermentazione scura, un processo biologico che presenta alcuni vantaggi rispetto ad altre tecnologie di produzione di H_2 rinnovabile. È un processo carbon neutral in grado di produrre H_2 verde continuamente con un basso fabbisogno energetico, combinato con una gestione sostenibile dei rifiuti. Inoltre, insieme a H_2, produce una serie di preziosi sottoprodotti. L'uso di H_2 per convertire la CO_2 in metano è la bio-reazione chiave del processo di biometanazione che consente il potenziamento del processo convenzionale di digestione anaerobica. Inoltre, il consumo di H_2 come fonte di potere riducente da parte di microrganismi ha il potenziale di produrre un ampio spettro di bioprodotti di interesse industriale. I processi biologici giocano un ruolo fondamentale nello sviluppo di future bioraffinerie basate sui rifiuti, orientate all'H_2.

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by **Antonella Marone, Giulia Massini, Vito Pignatelli, Silvia Rosa, Antonella Signorini (*)**

Biological processes will play a relevant role in the green hydrogen value chain: they participate with the dual role of producers and users of green H_2, providing sustainable and renewable technologies for energy and added value products. Green H_2 is produced biologically from the valorisation of organic wastes through the Dark Fermentation (DF). As part of the Anaerobic Digestion (AD) process, H_2 is a by-product of the first acidogenic conversion of organic matter into volatile organic acids and alchols [1].

H_2 can be used to convert CO_2 into methane (CH_4) through biological means, the so-called biomethanation process [3], a "Power to Gas" (P2G) technology. The biomethanation, as the DF, consists in a "reinterpretation" of the conventional AD process since the microorganisms involved both in the H_2 production and in the conversion of CO_2 and H_2 into CH_4, are already present within the community realizing the AD process (Fig. 1).

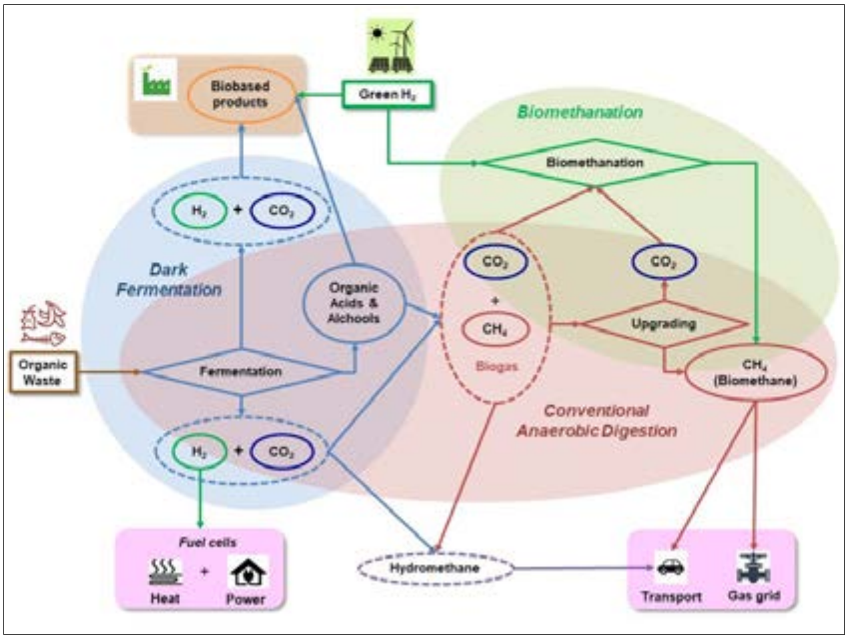

Fig.1 Biological processes integrated in the green H2 value chain: Background coloured areas enclose the main step of each process; Rectangles represent process; feeding Diamond shapes represent technological stages; Round shapes represent products; Dotted lines enclose gas mixtures; Background coloured rectangles represent the end uses.

Moreover, microorganisms consume of H_2 as a source of reducing power producing a large spectrum of bio-based products of industrial interest. These abilities can be exploited for the development of biotechnological processes.
ENEA research tackles to overcome the actual bottlenecks to make these biotechnologies truly viable. The main technical limits of DF are both the low yield and the low energy efficiency [2]: due to thermodynamic limitations, only a maximum of 33% of the energy contained in the organic substrates can be theoretically recovered in the form of H_2, while yields of 21% are obtained experimentally and most of the energy remains in the form of value-added soluble compounds. Concerning the H_2 consuming bioprocesses, the major challenges are related to the low H2 solubility in the media where the microorganisms operate and to the related increase of H_2 partial pressure in the headspace of reactors.

Research and development activities in ENEA

The research carried out at ENEA aims at improving the conversion efficiency of poor biomass, such as agro-industrial wastes and by-products, into bio-H_2 both by optimising the processes and by developing the concept of environmental bio-refinery. An eco-biotechnological approach based on natural selection rather than on genetic or metabolic engineering [4], is the characteristic of the Working Group on Advanced Anaerobic Digestion Processes [5–7].
Tailored acclimatization strategies are developed to obtain enriched microbial communities and strains from original mixed communities collected from natural or anthropogenic ecosystems and to design artificial consortia exhibiting target functions. For instance, during the **project IDROBIO (Integrated Special Fund for Research)**, a very efficient H_2 producing consortium was enriched from costal lake sediments during a continuous process [8]. It showed high substrate versatility being effective both on simple sugar [5] and complex substrates in co-digestion (cheese whey, crude glycerol, buffalo slurry) [9] (**METISOL project** co-funded by the Italian Ministry for the Environment). In the context of the Italy/China Exec-

Fig.2 GRAIL project: 3L biofermenter collected to the gas-stripping apparatus for ethanol collection

utive Programme, a stable functional consortium able to efficiently convert crude glycerol, a by-products of biodiesel industry, into H_2 and ethanol (patent n° RM2011A000480) was enriched from activated sludge after several months of adaptation on crude glycerol [10,11]. The further optimization of the process conditions, developed during the **EU-FP7 project GRAIL,** allowed to simultaneously reach very high productions of H_2 (21±2 L/L) and ethanol (39±1 g/L), by a non-sterile fed-batch fermentation mode using crude glycerol as the unique carbon substrate. Very high yields, both close to the theoretical maximum yield of glycerol = 1 mol/mol, were obtained (Fig. 2).

The research group also develops bioaugmentation strategies to increase the proportion of key functional microbial species in real substrates, already containing a high indigenous microbial diversity. **In the context of the IDROBIO project and the Electric System Research Programme (funded by the Italian Ministry of Economic Development) bioaugmentation was successfully applied to improve the H_2 production (4 times both the yield and the rate)** from vegetable wastes by re-inoculating, both individually and in a constructed consortium, three H_2 producing strains [12], previously isolated and enriched from the same types of vegetable wastes [13]. To boost both the hydrolytic and the H_2 producing steps, during fermentation of recalcitrant (lignocellulosic and chitinous) wastes, bioaugmentation with hydrolytic anaerobic fungi strains combined with a H_2 producing consortium was successfully designed, leading to 75% increase of the H_2 yield, during a two stage configuration of anaerobic digestion process [14]. Experiments aimed at scaling up (10x and 100x) the obtained results were also performed and used to set up a simplified mathematical model to simulate the kinetics of the process [15].

Indeed, the ENEA team also carry out the validation of laboratory results to the industrial stage by setting trials at the pilot scale. This was the case of the two-stage pilot plant (ENEA/CREA Patent n° 0001416926), which consists of a fermentation reactor coupled with an anaerobic digester, functioning with cheese whey and animal manure (Fig. 3). It was built in the context of the **project MAREA** (co-funded by the Italian Ministry for the Agriculture), for the simultaneous production of H_2 and CH_4 in a cascade process for the complete exploitation of waste streams, within a bio-refinery framework. Beside the added value of producing also H_2 instead of CH_4 alone, the two-stage process presents several advantages compared to the conventional one-stage AD process: higher stability, higher energy yield and higher organic loading rates, all factors contributing to subsequently increase the CH_4 productivity [16]. This was demonstrated in a 50 L pilot plant treating dairy wastewater in the context of the project METISOL. The separation of H_2 and CH_4 phases allowed an increase of more than 26% the CH_4 production rate, together with 30% increase of the yield of and 20% increase of CH_4 content in the biogas.

Fig.3 Two-stage, hydrogen and methane, pilot plant ENEA/CREA Patent.

Since 2018, the research team is also studying the biomethanation process, with the aim of developing innovative technologies for "in situ" biogas upgrading to bio-CH_4, to improve the conventional AD plants, significantly reducing the costs associated with the gas cleaning process (Electric System Research Programme). For this purpose a novel hybrid gas-stirred tank reactor (Fig. 4) was developed with a partial immobilization of the microbial community [17]. The new system allowed the enrichment of CH_4 in biogas from 50% to 80% with a CO_2 residue of approximately 7%, during the treatment of cheese whey.

Currently, studies are conducted (AZERO project, Electric System Research Programme), in collaboration with players of the industrial sector, to evaluate the effectiveness of DF and AD treatments in degrading specific organic micro- [18] and macro-pollutants [19]. Moreover, experimentations on H_2 fer-

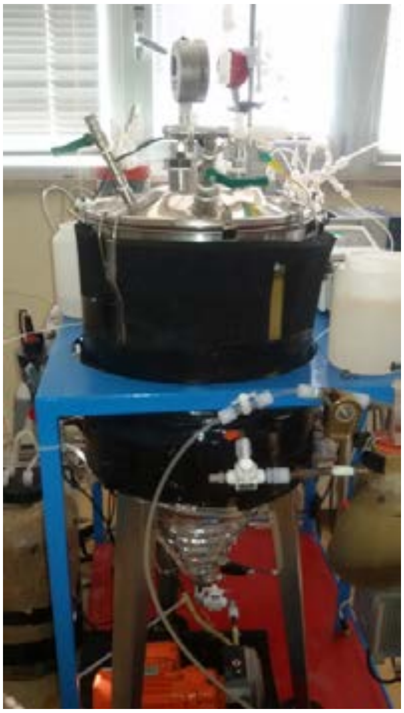

Fig.4 A novel hybrid gas-stirred tank reactor (50L) treating dairy wastewater, implemented with a partial immobilization of the microbial community for in situ biomethanation research.

mentation by acetogenic bacteria for the production of bio-based building blocks (acetic acid and alcohols), are also carried out (COMETA project) in the framework of the Syngas bio-refinery.

Projects and perspectives

Compared to other renewable H_2 producing technologies, DF of organic wastes has some advantages because it is a carbon neutral process which can produce continuously green H_2 with low energy requirement, while allowing sustainable waste management with pollution control. Moreover, it could become an important opportunity for future bio-refineries because potentially able to produce, together with H_2, a number of valuable by-products. Waste biomass potentially represents an abundant resource, locally available, for the decentralised production of renewable and clean H_2 [19], which can be directly used in fuel cells for producing green electricity at a local level or, alternatively, to boost the decarbonisation of the gas grid. A mixture of bio-H_2($\leq$ 10%) and bio-CH_4, produced by a new generation of advanced AD plants, can be injected into the natural gas network with the additional benefits of reducing the import of fossil CH_4 and improving the gas fuel combustion process in terms of flame velocity, stability and reduction of CO and NOx emissions [1]. In the near future, bio-H_2 or H_2 produced by the excess of renewable electricity from non-programmable sources will serve to improve the existing AD plants, which are widely distributed (more than 2100 DA plants distributed throughout in Italy) transforming electrical energy into easily stored chemical energy (P2G). Compared to other methanation processes, biological processes (biomethanation) are particularly interesting because they can be used in plants with medium-small size like most of current biogas plants in Italy [3]. **ENEA developed a technological know-how starting from the activities on specific projects (IDROBIO, MAREA, METISOL, Electric System Research Programme, GRAIL, COMETA, AZeRO antibiotics, VERITAS) and today collaborates with other research institutions (CNR, CREA, INRAE) and Universities (Sapienza, Tuscia, Federico II of Naples) for the development and optimisation of advanced AD processes and waste-based bio-refineries.** Research on microbiological aspects is carried out relying on the Microbial Resource Research Infrastructure called MIRRI, a pan-European high-performance platform aiming to exploit microbial biodiversity for bioeconomy and bioscience. The group also participates to IEAH_2 renewable hydrogen task as expert in bio-H_2. **ENEA's activities range from the study and understanding of the basic mechanisms of microbiological systems for the control of bioprocesses, to the design and development of pilot scale prototypes in relevant environment, in order to satisfy the market requirements. Consequently, ENEA's researchers are closely cooperating with the CIB (Italian Biogas Consortium) and with players of the industrial sector and boast partnerships with industries supplying different kind of organic waste. Research efforts at ENEA are now aiming at improving the conversion yields of complex biomass.** Researchers' objective is to develop a marketable process, based on freeze-dried microorganisms, to increase the production of bio-H_2 and bio-CH_4 from biomass with a high content of lignocellulosic component. Regarding the "in situ" biomethanation, the research activity is currently devoted to further reduce the CO_2 content to a maximum of 3%, in order to obtain a final mixture of H_2 and CH_4 with characteristics that make it suitable to be introduced into the gas network or used as biofuel for transportation, without requiring an expensive upgrading stage. Experimental trials on a 1 m^3 pilot plant (Figure 5) will start within the current year by using, in addition to the dairy wastewaters, other substrates of potential interest (municipal waste and biomass from agro-industry). In order to create a flexible system for testing, in the short term, the innovative technological solutions in existing biogas plants, H_2 will be produced locally by means of an electrolyser powered by photovoltaic. Finally, to overcome the limitation of H_2 solubility in the fermenting mixture, ENEA researchers are planning to test solutions based on "in situ" H_2 production by new electrochemical or bio-electrochemical means.

Conclusions

Although bio-hydrogen is not developed at the market level, yet, its production seems to be particularly suitable for decentralised small-scale systems, integrated with waste from agriculture and food industries

or from waste-processing facilities. The best short term opportunity is to convert the fermentation by-products to CH_4 by anaerobic digestion. Thus, in a near future, the most realistic scenario is that DF and biomethanation will both contribute to the establishing of "second generation" AD plants (newly built or from the revamping of existing plants, which in Italy can be well over a thousand) aimed to the production of "green gas" rather than renewable electricity.
The future of DF as a core technology for hydrogen generation lies within the concept of the environmental bio-refinery. In this perspective, a strong policy, regulatory framework and finance (hydrogen-based) associated to improve the efficiency of DF systems (optimization of reactors design and operation and, most important, hydrogen productivities and yields) will guarantee the economic feasibility of waste valorisation by DF [1].

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Green hydrogen through biomass gasification

In a future that aims at using hydrogen as an energy carrier to achieve a climate-neutral global economy, its production through biomass gasification can be considered as one of the green options available. However, the exploitation of biomass gasification is not yet ready for large-scale deployment. In this context, ENEA is actively involved in the development and implementation of innovative solutions aimed at achieving the full technological readiness, while ensuring the possibility of producing hydrogen at relatively low-costs. ENEA has been working in the field of biomass gasification for a long time and has acquired substantial expertise in process chemistry and reactor design, with the development of relevant know-how and patents. At ENEA-Trisaia Research Center a technological park has been established with biomass gasification plants based on different reactor setups and sections for gas cleaning and conditioning. Ongoing R&D activities aim at overcoming techno-economic barriers to make biomass gasification reliable and competitive with traditional route, by broadening the flexibility to low-cost, low-value feedstock and introducing innovative and cost-effective methods for gas cleaning and conditioning.

In un futuro che ambisce a utilizzare l'idrogeno come vettore energetico per conseguire l'obiettivo di un'economia globale climaticamente neutra, la sua produzione attraverso la gassificazione della biomassa può essere considerata una delle opzioni green disponibili. Tuttavia, la maturità tecnologica raggiunta non è ancora tale da consentire una sua diffusione su larga scala. In questo contesto, l'ENEA è attivamente impegnata nello sviluppo e nell'implementazione di soluzioni innovative volte al raggiungimento della piena maturità di processo e tecnologica, tale da aprire alla possibilità di produrre idrogeno a costi relativamente contenuti. ENEA opera da tempo nel campo della gassificazione delle biomasse e ha acquisito una notevole esperienza nella chimica di processo e nella progettazione di reattori, con lo sviluppo di proprio know-how e relativi brevetti. Presso il Centro Ricerche ENEA-Trisaia è stato allestito un parco tecnologico con impianti di gassificazione di biomasse basati su reattori di differenti configurazioni e sezioni per la purificazione e il condizionamento del syngas prodotto. Le attività di ricerca e sviluppo in corso puntano a superare le barriere tecnico-economiche per rendere la gassificazione della biomassa affidabile e competitiva con modalità più convenzionali, ampliando la flessibilità a materie prime residuali, di basso costo e di basso valore, e introducendo metodi innovativi ed economici per il trattamento e la conversione del syngas.

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In December 2019 the European Union kicked off the Green Deal initiative, the roadmap to a sustainable EU [1]. To achieve such ambitious goals, hydrogen can play an important role and a specific implementation program has been outlined in the communication "A hydrogen strategy for a climate-neutral Europe" [2]. In fact, the use of hydrogen in itself does not emit CO_2 and net CO_2 emissions can be avoided even in the production phase. **Hydrogen from biomass through gasification is one of the options to meet such requirements; biomass is in fact a CO_2-neutral energy source being the result of the conversion of solar energy into chemical energy through photosynthesis. At national level this feature has been included in the Italian Strategy for Hydrogen Research [3].** Hydrogen through gasification is included in the roadmap to 2030, with R&D programs at different technology readiness level (TRL) (i.e. *Basic research* (TRL 2-3), Industrial R&D (TRL 3-5), *Demonstration* (TRL 5-7)).

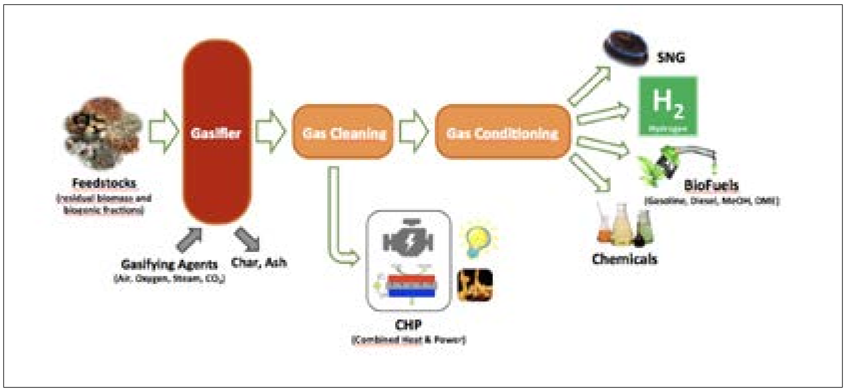

Fig.1 General process steps in gasification and related producer gas applications

The thermochemical gasification of biomass

Gasification is the thermochemical process by which a solid fuel can be converted into a gaseous one of higher value. Following the increased awareness and concerns for global warming, since the 1970s gasification received increasing interest as a process to replace fossil fuels with woody biomass and some categories of biowastes. Such feedstocks are typically residues, locally available, so that gasification enables turning them into a resource with both energy and environmental value. From a chemical viewpoint, gasification can be seen as an incomplete combustion promoted by an oxidizing agent (e.g. air, pure oxygen, H_2O, CO_2 and mixtures). Unlike combustion, where heat and an exhaust gas consisting of CO_2 and steam are obtained, in gasification the produced gas also contains H_2, CO_2 and a low amount of CH_4. Often called producer gas or syngas, this gas

Gasifying agent	%-v (dry basis)					Gasification Technology	Reference
	H_2	CO	CO_2	CH_4	N_2		
Air	12-20	17-22	9-15	2-3	50-54	downdraft	[6]
Air	7-9	13-17	18-21	3	50-59	Bubbling fluidized bed	[7]
Oxygen	23	36	28	5	7	Entrained flow	[8]
Steam/Oxygen	30-33	22-27	28-32	9-11	<2	ICBFB ENEA	[9]
Steam/Oxygen	30-31	17-19	34-35	7	8-10	Circulating fluidized bed	[10]
Steam	36-42	19-24	20-25	9-12	-	DFB	[11]

Table 1 Illustrative overview of producer gas compositions from biomass.

has a calorific value that depends on the adopted gasification agent: low (4-6 MJ/Nm$^3_{dry}$) if produced using air, medium (10-15 MJ/Nm$^3_{dry}$) if produced with oxygen and/or steam [4]. Low calorific syngas is generally suitable for direct uses aimed for combined heat and power (CHP) production, even on a small-medium scale. Medium calorific syngas is considered of higher value, suitable not only for direct use but also for more innovative process chains, aimed at the production of gas or liquid fuels such as SNG and H_2, MeOH, diesel, gasoline, DME, as well as green chemicals (e.g. acetic acid, alcohols, aldehydes) [5]. A general process and applications scheme is shown in Figure 1.

Table 1 shows examples of syngas compositions depending on the gasifying agent and gasification reactor technology.

State of the art

The technology readiness level (TRL) of a gasification process is linked to the final use of the produced syngas. To date, gasification has reached the cogeneration (CHP) market of on small scale (i.e. tens to hundreds kWe). Industrial level can be recognized for CHP application even at medium size level (i.e. few MWe) [12], but there is a small number of plants of this capacity [13]. Lower TRL is obtained in the case of advanced applications, such as high efficiency CHP via SOFC, and the production of liquid and gaseous secondary energy carriers, including hydrogen, where the demonstration or pre-commercial level has been reached so far. **The difference in TRL between small-medium scale CHP and other advanced applications is mainly due to two linked features: economic sustainability and technological solutions for gas purification and conditioning [14].** The first issue is dealing with materials suitable for gasification: in general, the impact of feedstock supply costs is in the range of 20-35% of the operating costs. In order to reduce the impact of this factor, the use of low-cost feedstocks is considered, widening the spectrum to different types, including the renewable fraction of wastes (biowastes) that may eventually provide revenues for their disposal. **To achieve these goals, R&D activities on feedstock pre-treatment and on the design of gasification reactors are crucial.** Concerning the second TRL topic, gas cleaning and conditioning can impact investment costs by more than 40% [15,16]. In many relevant applications, the related equipment is shifted from conventional sectors, such as oil industry. These solutions, although effective, achieve economic sustainability on large scales, from several hundred to thousands of MWth at the gasifier input [17-19]. However, achieving full maturity for biomass gasification requires cost-effective operation on smaller scales compared to fossil-based processes. There is a strong need for development of solutions specifically adapted for biomass-derived syngas.
The above constraints indicate a strong need for R&D activities aimed at improving gasification flexibility to feedstocks and achieving significant process intensification to reach economic sustainability even at relatively small scales. Overcoming the above barriers will positively impact on the cost effectiveness of biomass-based conversion processes, making them more consistent with a decentralized production model based on short supply chains, which will likely foster their diffusion. **On these topics, ENEA is among the major players actively engaged in the development and implementation of innovative solutions, with R&D initiatives described in the following sections.**

Hydrogen production: conventional vs. gasification methods

H_2 from Natural Gas
Of the more than 70 Mton per year of hydrogen produced worldwide, about 75% comes from natural gas (NG) through methane steam reforming (SMR) [20]:

$$CH_4 + 2\,H_2O \rightarrow CO_2 + 4\,H_2 \qquad \text{(R1)}$$

The SMR reaction is endothermic; the energy required to sustain the process is produced by additional NG. Overall, it is estimated that for every kg of H_2 produced via SMR, more than 7 kg of CO_2 are emitted [20], corresponding to a molecular ratio of 1 to 1/3, instead of the stoichiometric 1 to 1/4.
To date, the production of H_2 from NG is the most economical, with costs ranging from 0.94 US$/kgH2 to 1.78 US$/kgH2. Fuel costs are the largest

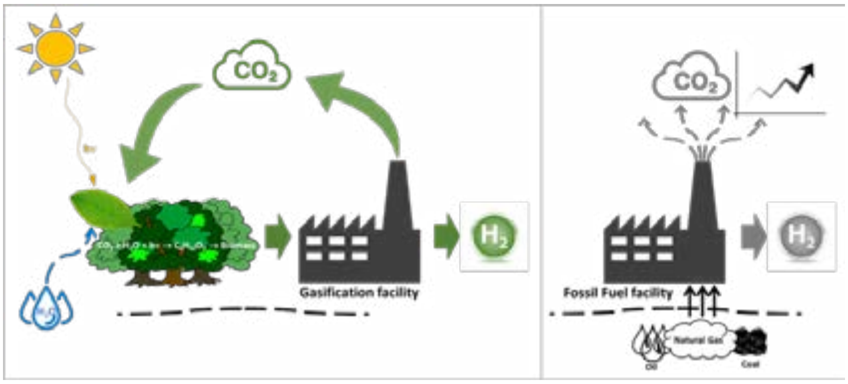

Fig.2 General production concepts: a) Green hydrogen from biomass versus b) hydrogen from fossil fuels

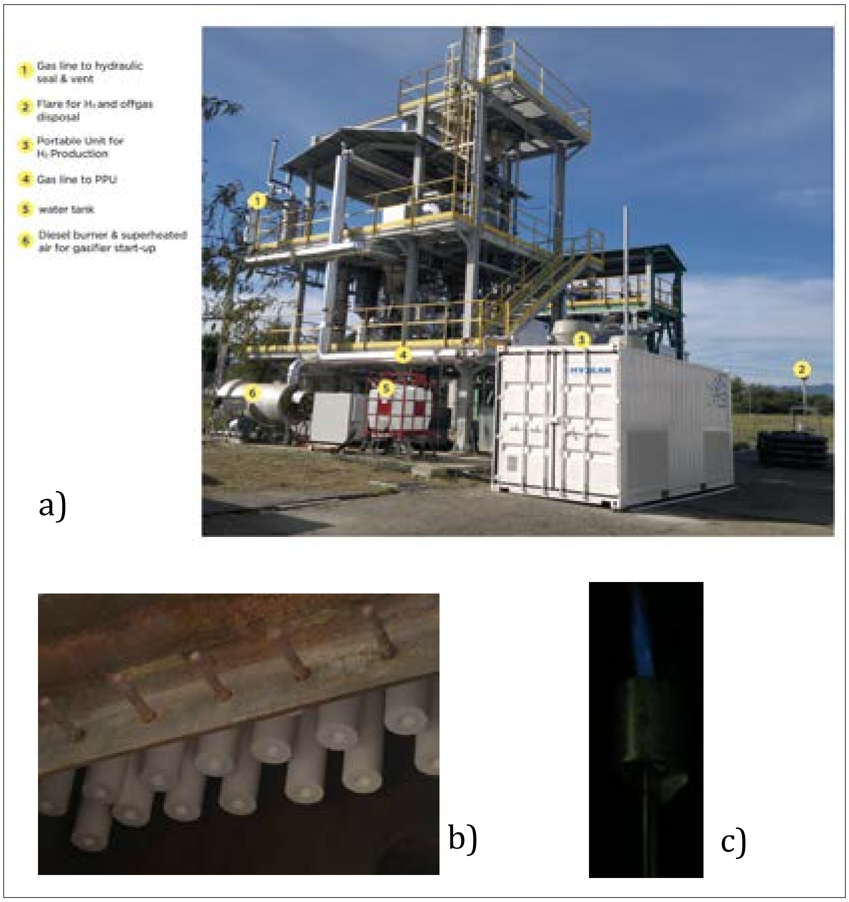

Fig3 UNIfHY integrated plant at the ENEA-Trisaia Research Centre: a) facility coupled to the portable purification unit (PPU) for gas conditioning and H_2 separation; b) view detail of the in-situ HT filtration system; c) gas disposal flare, fed by the produced H2 and the off-gas streams from the PPU

item, accounting for between 45% and 75% of production costs [21]. These costs are only apparently low because environment impact costs are not included. Higher costs are obtained when solutions to contain the environmental impact of CO_2 emissions are also included: in Europe production costs range from 1.73 US$/kg$H_2$ without CO_2 capture to 2.32 US$/kg$H_2$ with CCUS (Carbon capture, utilisation and storage), while in China the rates move from 1.78 US$/kg$H_2$ to 2.38 US$/kg$H_2$, respectively [21].

H_2 from biomass gasification

Useful feedstocks for green H_2 through gasification are both residual lignocellulosic biomass and biogenic fraction of wastes. Residual biomass is derived from forestry, agriculture (e.g. cereal straw, corn stover, pruning), agro-industry (e.g. dried fruit shells, olive pomace, citrus pulp), wood processing, as well as waste streams from other processes that can be valorised for energy purposes rather than be disposed of. Examples are the black liquor from paper mills, or the digestate from Anaerobic Digestion, now facing a problem of overproduction. The biogenic fractions of Municipal Solid Waste can be included too. Referring to the average elemental compositions, for biomass the empirical formula $C_4H_6O_3$ can be considered. To have an estimation of the maximum potential amount of H_2 from biomass, and thus make a comparison with the production from NG, a reaction pathway similar to SMR can be considered:

$$C_4H_6O_3 + 5\,H_2O \rightarrow 4\,CO_2 + 8\,H_2 \quad \text{(R2)}$$

R2 points out that the yield of H_2 per carbon in the feedstock is, on average, about half of that from NG (R1). However, the lower yield of H_2 is balanced by the different nature of CO_2 emissions. As known, being biomass the product of photosynthesis, the CO_2 from biomass returns to the atmosphere at the end of the process with virtually null overall environment and global warming effects. In the case of SMR, a net increase in CO_2 concentration is instead observed. A schematic comparison of the CO_2 flow in the two processes is shown in Figure 2.

Research and development activities in ENEA

ENEA has been working in the field of biomass gasification for a long time and has acquired substantial expertise in process chemistry and reactor design, with the development of relevant know-how and patents [22]. At ENEA-Trisaia Research Center a technological park has been established with biomass gasification plants based on different reactor setups (e.g. fixed bed, fluidized bed, rotary kiln, three staged, SCWG) and sections for gas cleaning and conditioning. These plants, available at pilot and laboratory scales, allow to study and to characterize process performances in different applications such as CHP *with Internal Combustion Engine* and SOFC, or the production of SNG and H_2 as secondary energy carriers. Among these, the production of H_2 has been studied both within national and EU projects. In the national context, it is worth mentioning the R&D activity carried out within the Electric System Research Programme funded by the Italian Ministry of Economic Development, sub-programme "Bioenergia" [23]. In collaboration with University of L'Aquila, ENEA has studied a process for endogenous H_2-enrichment of syngas using SEWGS (sorption-enhanced water-gas shift) sorbents. Thanks to the simultaneous establishment of the WGS reaction and CO_2 capture, syngas with high H_2 contents were obtained. Since some amount of CH_4 was also present in the producer gas, the obtained H_2/CH_4 mixture turned out to be of interest as a fuel or to produce high purity H_2 for more dedicated and advanced applications, after further refining. Produced hydrogen can be mixed with NG or biomethane to produce hydromethane (30% H_2 and 70% CH_4, by volume) for transport sector or for injection into the national gas distribution grid. In Italy the interest on this approach is led by Snam SpA, which first in Europe, in April 2019 [24] and then in early 2020 [25], injected in its NG distribution grid, at the municipality of Contursi Terme, a mix of H_2 and natural gas (H_2NG) with an hydrogen content up to 10%v.

In the international context, H_2 production from biomass was in particular the goal of the EU project UNIfHY [26]. Coordinated by Guglielmo Marconi University, the project involved the collaboration of nine partners with international excellence on the key features of the proposed approach. The overall performance evaluations were achieved through the integration of the developed components at the Trisaia 1000 kWth pilot plant (Figure 3) and its operation in experimental gasification campaigns coordinated by ENEA. The gasification plant setup is based on an innovative reactor design, developed for process intensification to achieve reductions in investment and operating costs. Such goals were achieved firstly through a bubbling fluidized bed (BFB) gasifier designed to allow internal recirculation of the bed inventory [27], thus increasing the feedstock residence time in the reaction environment and facilitating its conversion into gas. Secondly, by a bundle of ceramic candles for HT gas filtration directly integrated in the reactor freeboard.

Overall, the UNIfHY project enabled to demonstrate the feasibility of FCV-grade H_2 (> 99.99%) through biomass gasification and to provide an estimation of the production costs. The techno-economic assessment indicated production costs of 3-6 €/kgH_2 for plants of 10 MWth size [28], thus comparable with that from fossil source (SMR) coupled with CCUS [21, 29].

At present, ENEA is involved in two new EU projects dealing with biomass gasification, i.e. BLAZE [30] and GICO [31]. BLAZE aims at producing a low-contaminant syngas, to feed a 25 kWe SOFC unit. Using syngas in SOFC systems implies the availability of stream with high purity, i.e. concentration levels in the ppm range for most contaminants. To this goal, both primary and secondary methods for gas cleaning and conditioning are included. **ENEA is involved in the study of primary methods, investigating low-value active materials, added to the bed inventory, to counteract the contaminants evolvement directly during their formation. Although the main application in BLAZE is different from H_2 production, gas purification is a general issue to be faced in biomass gasification for H_2 production, as well.**

Started only a few months ago, **GICO is a multi-purpose project** as it provides for different outputs in the context of circular use of resources and sustainability. The reference process is gasification in the presence of calcium-based sorbents for CO_2-capture, and its regeneration (calcium looping). This method of feedstock processing will enhance the production of a stream with high H_2 concentration from which pure H_2 will be more easily obtain later. Moreover, thanks to the action of the sorbent, the process avoids CO_2 emissions. On this aspect, ENEA is leading activities on performance evaluation of both natural and innovative materials in fluidized bed and rotary kiln reactors. In order to broaden the spectrum of usable feedstocks, GICO includes the study of the effectiveness of Hydro-Thermal Carbonization (HTC) pre-treatment on gasification performance. Via HTC, the project aims to reduce the impact on production costs by exploiting also low grade feedstocks.

Conclusions

Biomass gasification is a carbon-neutral hydrogen production route that, besides other direct renewable pathways, can contribute to the future green hydrogen production mix. With the establishment of demo plants with different reactor setups, R&D activities at ENEA aim at overcoming techno-economic barriers to make biomass gasification reliable and competitive with conventional route, by broadening the flexibility in terms of feedstock supply (thus accepting low-cost feedstock) and introducing innovative and cost-effective methods for gas cleaning and conditioning.

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Membrane technologies for hydrogen separation

Separation technologies based on membranes can be applied in continuous processes and are characterized by system design flexibility (easy scaling-up and hybridization with conventional processes), capability to produce high-quality products and saving energy. Membranes consisting of thin-walled Pd-Ag tubes have been developed by ENEA for recovering hydrogen isotopes in the fusion fuel cycle (hydrogen and tritium separation from He, water detritiation) and for producing ultra pure hydrogen via reforming and other dehydrogenation reactions in green chemistry applications.

Le tecnologie di separazione a membrana possono essere applicate con successo a processi continui per ottenere prodotti di alta qualità e risparmiare energia, grazie alla loro flessibilità, alla facilità di accrescerne le dimensioni e di abbinarli a processi convenzionali. L'ENEA ha sviluppato tubi in lega di palladio a parete sottile che possono essere utilizzati per recuperare e/o separare gli isotopi dell'idrogeno nell'ambito del ciclo del combustibile dei reattori a fusione. In particolare, questi dispositivi consentono la separazione di idrogeno e trizio dall'elio e la detriziazione dell'acqua e trovano anche applicazione nella produzione di idrogeno ultrapuro attraverso il reforming e altri processi di de-idrogenazione nel campo della chimica verde.

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by **Silvano Tosti, Alfonso Pozio, Alessia Santucci (*)**

Separation technologies based on membranes can be applied in continuous processes and are characterized by system design flexibility (easy scaling-up and hybridization with conventional processes), capability to produce high-quality products and saving energy. In this vein, the features of the membrane technologies result to be fully sound with the requirements of the green chemistry processes. Membranes consisting of thin-walled Pd-Ag tubes **have been developed by the ENEA Frascati** laboratories for recovering hydrogen isotopes in the fusion fuel cycle (hydrogen and tritium separation from He, water detritiation).

Pd-membrane reactors resulting from the combination of membrane tubes with a catalyst bed can exhibit high reaction conversions thanks to the continuous removal of the hydrogen, one of the reaction products. Based on their capability to separate hydrogen from gas mixtures with an infinite selectivity, these Pd-based tubes, developed in the framework of the fusion fuel cycle activities, have then been applied for producing at lab-scale ultra-pure hydrogen (e.g. suitable for feeding polymeric fuel cell) through dehydrogenation reactions.

The Department for Fusion and Technologies for the Nuclear Safety conducts at Frascati laboratories the R&D activities on fusion energy, mainly supported by the European program (European Fusion Development Agreement, 1999-2013, and Consortium EUROfusion, 2014-present).

One of the main activity carried out at ENEA Frascati laboratories has concerned the development of separation units dedicated to the extraction and purification of the hydrogen isotopes. Such processes are a part of the fusion fuel cycle aimed at providing the deuterium and tritium needed to sustain the fusion reaction

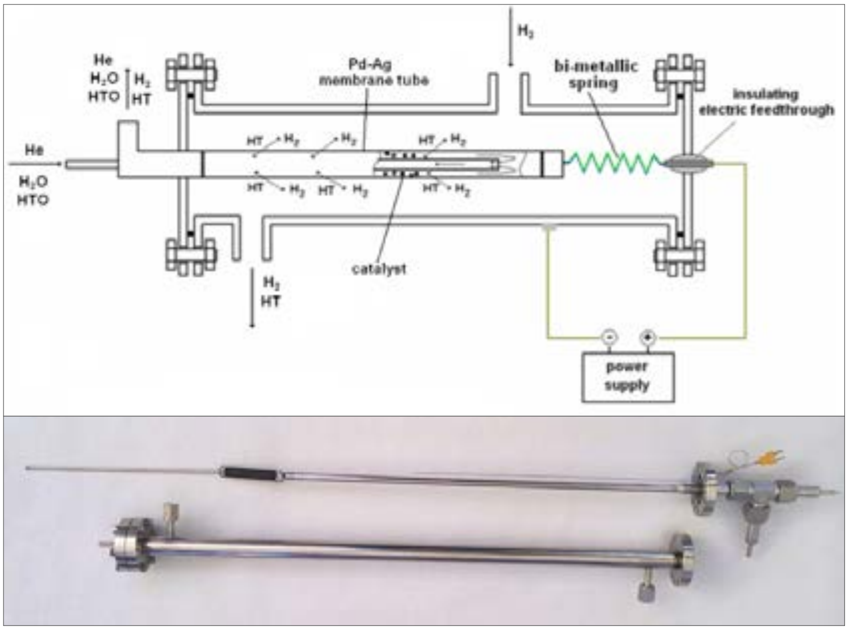

Fig.1 Scheme (top) and picture (botton) of a Pd-membrane reactor for the recovering of tritium from tritiated water via isotopic exchange. Fig. 1 (top) reprinted from [5], with permission from Elsevier.

[1, 2]. The research activities were focused on the design, construction and characterization of thin-walled Pd-tubes that exhibit the capability of separating with infinite selectivity hydrogen and its isotopes from gas mixtures [3, 4]. The Pd-tubes were used both as permeators and as membrane reactors for recovering tritium via gas permeation, water gas shift and isotopic exchange reactions [5, 6]. As an example, Fig. 1 shows a Pd-membrane reactor studied for the recovering of tritium from tritiated water via isotopic exchange.

An innovative Pd-membrane reactor and a process have been developed with the CEA (Commissariat a l'energie atomique et aux énergies alternatives) for the recovery of tritium from tritiated waste of the JET (Joint European Torus in operation at Culham, UK) [7-9]. Following this collaboration, Pd-membrane reactors designed for detritiation processes have been produced by ENEA laboratories and delivered to CEA in the frame of commercial agreements: Fig. 2 reports the internal view of a membrane reactor consisting of 8 Pd-tubes. In a recent study, an innovative application of porous membranes (acting as a membrane gas-liquid contactor) was proposed for the extraction of tritium from liquid breeder of fusion reactors [10, 11].

Ultra-pure hydrogen

Further studies carried out in strict collaboration between Frascati and Casaccia research centers demonstrated that the Pd-membranes developed for the fusion fuel cycle exhibit the capability to produce ultra-pure hydrogen via dehydrogenation of hydrocarbons, alcohols and biomass. In principle, a Pd-membrane reactor, a combination of a Pd-membrane with a catalyst, is capable to perform dehydrogenation reactions with very high conversions [4]. In fact, the continuous removal of one of the products (i.e. the hydrogen) promotes the reaction conversion according to the well-known "shift effect" of the membrane. **Main applications have concerned the production of hydrogen via reforming of methane, ethanol and biomass**. Fig.3 shows the scheme and the picture of a membrane reactor made of thin-walled Pd-tubes for producing pure hydrogen via ethanol reforming. In particular, from the reforming of olive mill wastewater (OMW), a by-product of the olive oil industry with significant pollution effect in the Countries of the Mediterranean regions, it is possible to produce hydrogen and syngas [11-13]. OMW reacts over a catalyst bed inside Pd-tubes while the hydrogen produced is extracted through the membrane: some kg of hydrogen can be produced per ton of OMW while the content of organic compounds in the retentate of the membrane reactor is reduced by more than 90%.

Fig.2 Scheme Internal view of a multi-tube membrane reactor for detriation processes.

The reforming of methane with OMW has been studied through a reforming unit consisting of multi-tube membrane reactors and capable to produce up to 1 m^3/h of hydrogen [13]. In the frame of the project Microgen30 (call Industria2015), the high-grade hydrogen produced by these membrane units has been thought to feed polymeric fuel cells of cogeneration systems where electricity and heat were produced from methane with high efficiency.

Hydrogasification of biomass

Another application shows the use of Pd-based tubes, that exhibit com-

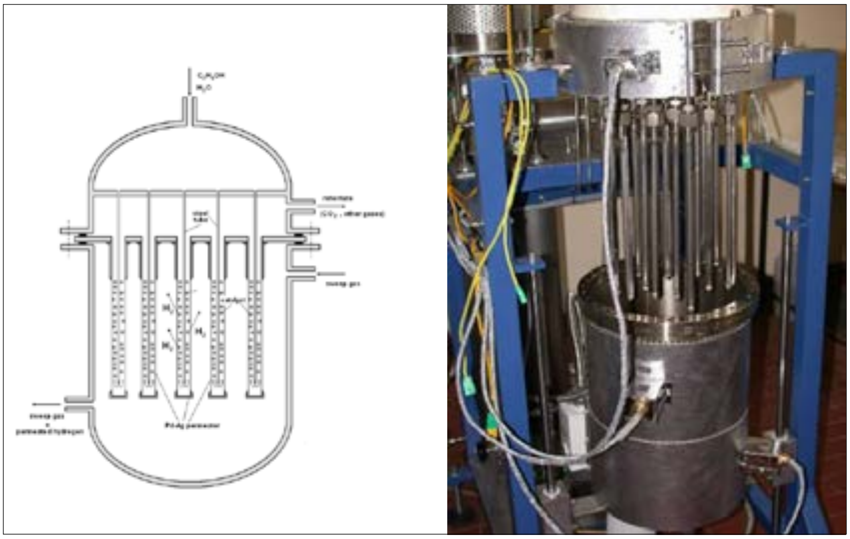

Fig.3 Scheme (top) and picture (botton) of a multi-tube membrane reactor for the production of hydrogen via ethanol steam reforming. Fig. 3 (bottom) reprinted from [4], with permission from Elsevier.

plete selectivity to hydrogen, in small scale applications for purifying the hydrogen produced by the alkaline electrolysers. **A study dedicated to these applications has developed an alkaline electrolyser where the cathode consisted of a Pd-membrane tube as shown in Fig.4 [14, 15].** In this device, about 50% of the hydrogen produced by electrolysis is directly extracted through the membrane tube as ultra-pure hydrogen without any need of further purification.

Other studies considered the hydrogasification of biomass to produce methane enriched streams [16]. The hydrogasification of refuse derived fuel (RDF) is a waste-to-fuel process characterized by negligible toxic emissions (e.g. dioxins and furans) typical of the other thermal processes used for the treatment of this biomass (e.g. incineration, gasification, etc.) [17, 18]. The operation with excess of hydrogen allows to achieve high methane yields and practically zero emissions of dioxins as reported in Fig. 5 related to the case of a hydrogasification reactor fed with 1000 kg h^{-1} of dry RDF and a hydrogen excess of about 40 kg h^{-1}.

A recent analysis was addressed to the use of an innovative reactor for the direct thermal splitting of water. This membrane reactor consists of two distinct membranes for the extraction of the hydrogen and the oxygen respectively as schematically reported in Fig.6 [19, 20]. This study has shown that the presence of a couple of membranes amplifies the “shift effect” typical of a membrane reactor thus allowing the reduction of the process temperature. In a case study considering a membrane reactor made of Ta membrane tubes of wall thickness 0.15 mm and a chamber perm-selective to oxygen made of hafnia of thickness 0.1 mm, reaction conversions of 20% are obtained by this membrane unit at around 2000 °C, much below the temperature of 2700 °C needed to a traditional reactor for attaining the same performances. At 2000 °C, about 200 and 100 Nm^3/h of pure hydrogen and pure oxygen are respectively produced by feeding 1000 kg h^{-1} of water and assuming a membrane permeation efficiency of 0.9. The reaction conversion of about 10% is achieved by this membrane reactor at 1800 °C, a temperature that could make feasible the exploitation of solar energy for the direct production of hydrogen and oxygen from water.

Projects and perspectives

Presently, the high cost of the precious metal used for manufacturing the thin-walled Pd-tubes is consistent with their applications in the fusion fuel cycle. Outside fusion technologies, these Pd-membrane units have found only niche applications where high hydrogen purity is required. Typical examples are laboratory alkaline electrolysers where the hydrogen purification can be efficiently performed by Pd-membranes. The perspective of using these metal membranes on large scale devices is based on the development of less expensive metal alloys instead of the Pd-based ones [21]. In this vein, the studies on binary and ternary alloys based on refractory metals are expected to demonstrate the viable and economic applicability of dense metal membranes for producing pure hydrogen

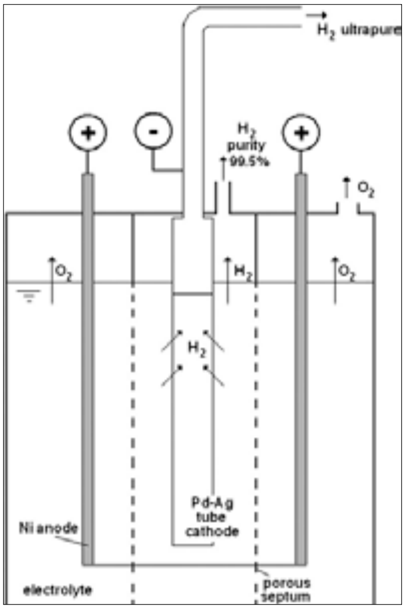

Fig.4 Alkaline electrolyser with Pd-Ag thin-wall tube acting as cathode. Reprinted from [15], with permission from Elsevier

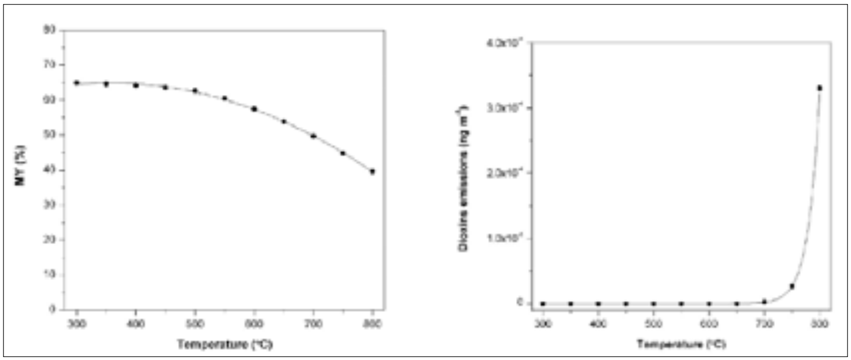

Fig.5 Methane yield (left) and dioxins emission (right) of a hydrogasification reactor fed with 1000 kg $^{h-1}$ of dry RDF and a hydrogen excess of about 40 kg h^{-1}. Reprinted from [18], with permission of Elsevier.

via reforming of biomass. In fact, as verified with the Pd-membranes, this kind of membrane reactors could operate in continuous processes by exhibiting high reaction conversions as required by the future processes of the "hydrogen chain".

Main technological transfer actions are expected within the sectors of the treatment of the OMW and the RDF hydrogasification. ENEA is discussing collaborations with Italian enterprises of these sectors with the aim to complete the industrialization of the processes studied through the realization and optimization of prototypical installations.

The R&D activities on the Pd-membranes in the fusion fuel cycle are mostly carried out in the frame of the EUROfusion program that is funding the European research on fusion energy. The Frascati laboratories plays a prominent role for the realization of membrane processes to extract hydrogen isotopes from He (used both as coolant and purge gas in breeding blankets) and from tritiated water. Main collaborations are with the partners of the EUROfusion Consortium, in particular the laboratories of the Karlsruhe Institute of Technology (DE) and the CEA-Cadarache Center (FR). The use of Pd-membranes for recovering tritium from gaseous streams are currently proposed also inside the project TRANSAT aimed to select cross-cutting technologies for tritium processing in fusion and fission reactors.

Conclusions

The collaboration between the departments FSN and TERIN has allowed the development of a sound know-how around Pd-based membranes and membrane processes for the separation of hydrogen and its isotopes. Several characteristics of the membrane processes (continuous operation, modularity, reduction of sizes, capability to work with high reaction conversion and then high energy efficiency) are the pivotal requirements for the fusion fuel cycle applications since they have to operate safely and with low tritium inventory. **The challenge is to develop metal alloys cheaper than those Pd-based, with the aim to candidate the separation technologies based on metal membranes for supporting the penetration of the hydrogen as an efficient and safe energy vector in the future sustainable energy scenarios.** Processes for producing hydrogen from renewable sources (e.g. reforming of biomass, solar-assisted water splitting) or exploiting the renewable hydrogen to produce green fuels (e.g. hydrogasification of RDF) could be applications where to demonstrate the results of R&D activities on metal membranes.

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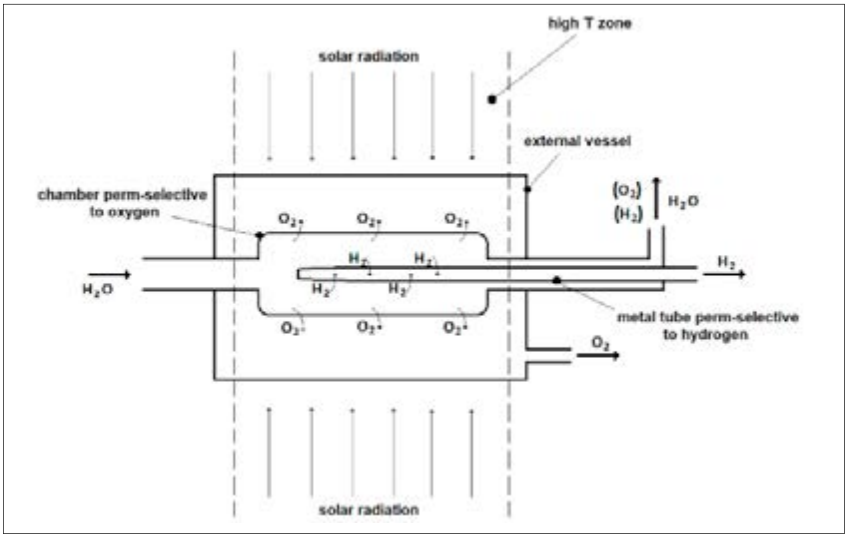

Fig.6 Schematic configuration a solar-powered membrane reactor. Reprinted from [20].

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The potential of E-fuels as future fuels

E-fuels are renewable, climate-friendly and can be used as energy carriers and feedstock; they are the most sustainable solution to meet the energy demand of a growing global economy and will play an important role in an optimized future energy system. Technologies for production of this kind of fuels are proven and tested in many installations worldwide, but processes have not yet been scaled up to industrial scale and like any emerging technology, production costs for e-fuels are currently high. In order to reduce costs in an effort to penetrate the market, it is strategic, together with the development of technological aspects, also the creation of industrial synergies. Currently ENEA there is a multidisciplinary technological know-how with skills that cover the complete e-fuels value chain; future development projects may involve activities on laboratory scale and on prototype and pilot plant scale covering different TRL value. Process and predictive analyses, technical economic and environmental feasibility studies will also be carried out. ENEA, as proposals´ leader within funding programs, develops various applied research projects by integrating lines of activity that aggregate industrial partners with various core business, but which can find interest in the common development of technology.

Gli e-fuel sono rinnovabili, rispettosi del clima e possono essere utilizzati come vettori energetici e materie prime; sono la soluzione più sostenibile per soddisfare la domanda energetica di un'economia globale in crescita e giocheranno un ruolo importante in un futuro sistema energetico ottimizzato. Le tecnologie per la produzione di questo tipo di combustibili sono provate e testate in molte installazioni in tutto il mondo, ma i processi non sono ancora stati portati su scala industriale e, come ogni tecnologia emergente, i costi di produzione degli e-fuel sono attualmente elevati. Per ridurre i costi nel tentativo di penetrare nel mercato, è strategico, insieme allo sviluppo degli aspetti tecnologici, anche la creazione di sinergie industriali. Attualmente ENEA dispone di un know-how tecnologico multidisciplinare con competenze che coprono l'intera catena del valore degli e-fuel; i futuri progetti di sviluppo possono comprendere attività su scala di laboratorio e su scala di prototipi e impianti pilota che coprono diversi valori di TRL. Verranno inoltre svolte analisi di processo e predittive, studi di fattibilità tecnica economica e ambientale. L'ENEA, in qualità di capofila delle proposte all'interno dei programmi di finanziamento, sviluppa diversi progetti di ricerca applicata integrando linee di attività che aggregano partner industriali con diversi core business, ma che possono trovare interesse nello sviluppo comune della tecnologia.

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by **Rosanna Viscardi, Claudia Bassano, Giuseppe Nigliaccio, Paolo Deiana (*)**

E-Fuels, or electrofuels, or Powerfuels, refers to any technology which converts (renewable) electrical power to a gaseous or liquid energy carrier. There are different taxonomies that refer to e-fuels: in the REDII the Commission uses the terminology 'Renewable liquid and gaseous transport Fuels of Non-Biological Origin' (RFNBO) and in the "A hydrogen strategy for a climate-neutral Europe" the Hydrogen-derived renewable synthetic fuels refer to a variety of gaseous and liquid fuels on the basis of hydrogen and carbon where the hydrogen should be renewable. Renewable fuels can be promoted most effectively if they can be easily distinguished from more polluting energy sources. Therefore, the Commission will work to introduce a comprehensive terminology and a European certification system covering all fuels renewable. **As regards to e-fuel production pathways, several conversion routes are identified.** Using the electrolysis process electrical power is converted to hydrogen thus allowing decoupling the energy from the electricity sector for use in other sectors. Hydrogen can then be used directly as a fuel, or alternatively reacted with either CO_2 or nitrogen to produce a range of different gaseous or liquid fuels. We can distinguish: power-to-liquids (Fischer-Tropsch, methanol, DME, ammonia and other synthesis liquid) and power-to-gas (hydrogen, methane,). In all pathways the outcome is carbon neutral, provided that the electricity used comes from renewable sources.

E-fuels offer many advantages: being currently able to bring carbon emission reduction, being carbon neutral, making use of the existing infrastructure and even more importantly of the existing vehicle fleet [1]. They feature a significant energy content per mass, and can be moved, stored in liquid or gaseous form, in the long term, without energy losses. They provide energy security and reliability to energy system. The storability and portability of these fuels allow to stock necessary volumes to be used in case of black out or any other supply issue with other energy carriers. Their production and deployment must be stepped up to deliver their full potential to fight against climate change.

The overall energy efficiency of various e-fuels production pathways is about 50%, because of the energy used in the course of the synthesis process. The production costs of liquid e-fuels (based on the Fischer-Tropsch production pathway) is estimated at 2050 between a cost of approximately 5.2 to 9.6 €ct/kWh (0.5 and 0.9 $€_{2018}/l_{liquid}$). According to Irena (2019) ammonia production cost is in the range of 0.5 -0.6 $\$_{2018}/kg_{NH3}$. Methanol and DME production costs may lie in the order of 100-210 $€_{2030}$/

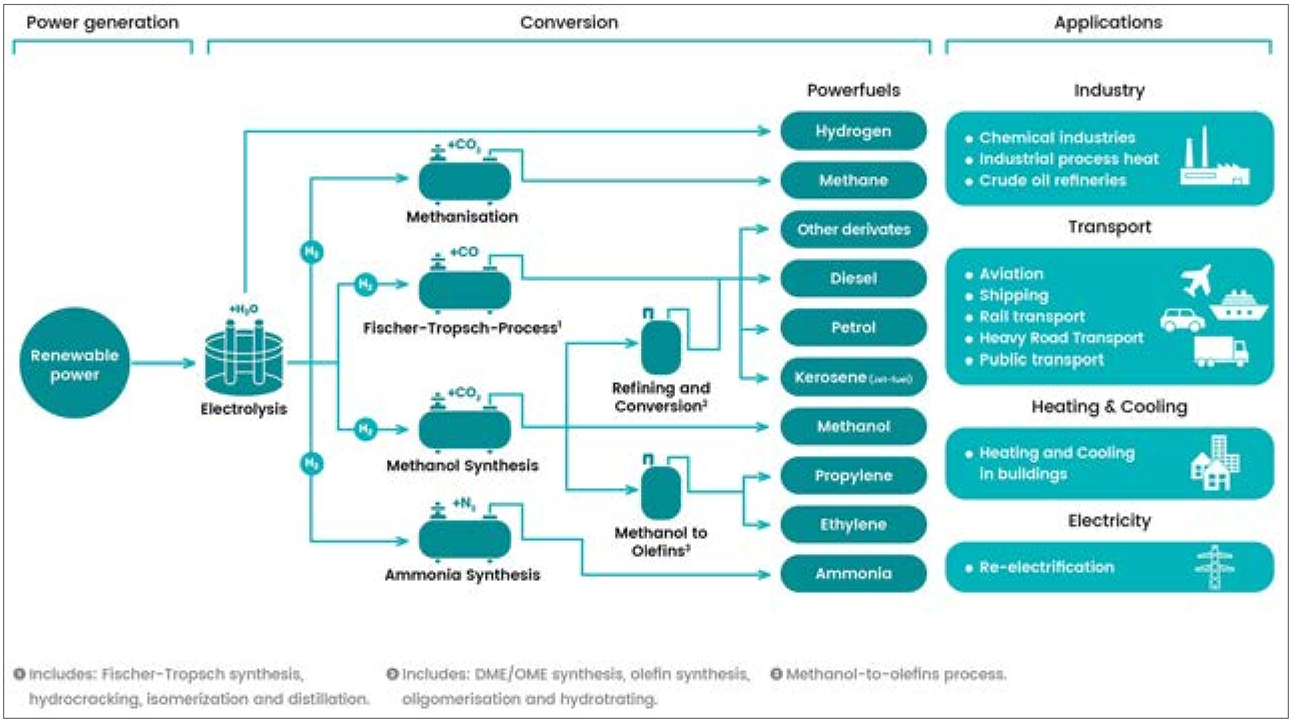

Fig.1 e-fuel production pathways [4]

MWh$_{methanol}$ and 100-310 €$_{2030}$/MWh$_{DME}$ in the future [2]. Finally, Synthetic natural gas production cost are in the range of 8-60 €$_{2017}$/MWh$_{SNG}$ [3]

Like any emerging technology, production costs for e-fuels are currently high. Economies of scale are expected with the development and deployment of these solution.

With regard to R&D challenge in the synthesis step, major challenges are the direct utilisation of CO_2, with research concerning catalyst step, catalyst behaviour under flexible and dynamic operation. Additional research concerning the influence of reactor and process design choices on the dynamics and the determination of the dynamic plant behaviour should be given more attention, as well as techno-economic guidance to improve design choices. These challenges could be different depends on the PtL product.

Research and development activities in ENEA

The major obstacle in the transformation of CO_2 to e-fuels consists in the inertness of the CO_2 molecule and the associated substantial energy required for the carbon reduction. Additionally, checking the selectivity of the desired product is not trivial due to the multiple competing reactions involved, like reverse water–gas shift (RWGS) or FT. Therefore, the research of efficient and highly selective catalysts is crucial to improve process sustainability [5]. This last point is very important since the above mentioned inertness of CO_2 requires the utilization of expensive hydrogen as a co-reagent to activate CO_2. Therefore, any loss of selectivity implies the consumption of avoidable H_2 that hinders the final economic process viability. Since 2014 by the National Program on Electric System Research funded by the Italian Ministry of Economic Development, at the ENEA lab experimental tests have been carried out in order to optimize the CO_2 hydrogenation to methanol/DME. Our laboratory was involved in the research of an appropriate catalyst with suitable acid strength, pore size, morphology, active temperature range, toxicity and coking resistance that provided a useful tool to lead DME direct synthesis by CO_2 hydrogenation. In addition, it was necessary to find a material having good resistance to the water produced from CO_2 hydrogenation or CO_2 rich syngas because water is believed to block the active sites for methanol consumption during one-step synthesis of DME [6]. For these reasons, in collaboration with University of Parma, we have successfully developed and tested a new class of SO_3H-functionalized materials that has been proposed for the first time as efficient catalysts to perform the methanol dehydration process to DME [7].

These materials were very active, selective and stable catalysts for methanol to DME transformation. Moreover, their catalytic activity and water resistance were better than that of reference commercial catalyst for this process. These materials will be tested as acid part of the bifunctional catalyst for DME direct synthesis in the experimental facility that we are developing in the next months. The purpose of this highly versatile experimental apparatus will be to find the most economical route towards the synthesis of these fuels from CO_2 and green hydrogen.

To reach this objective, (i) fundamental mechanistic understanding, (ii) the development of efficient multifunctional catalysts, (iii) rigorous testing and characterization of the obtained fuels, and (iv) the design of the most adequate process layout have to go hand in hand.

We strongly believe that the lack of ex situ characterization of the spent catalyst component needs to be addressed by the scientific community to achieve a fundamental mechanistic understanding, an essential requisite for catalyst development.

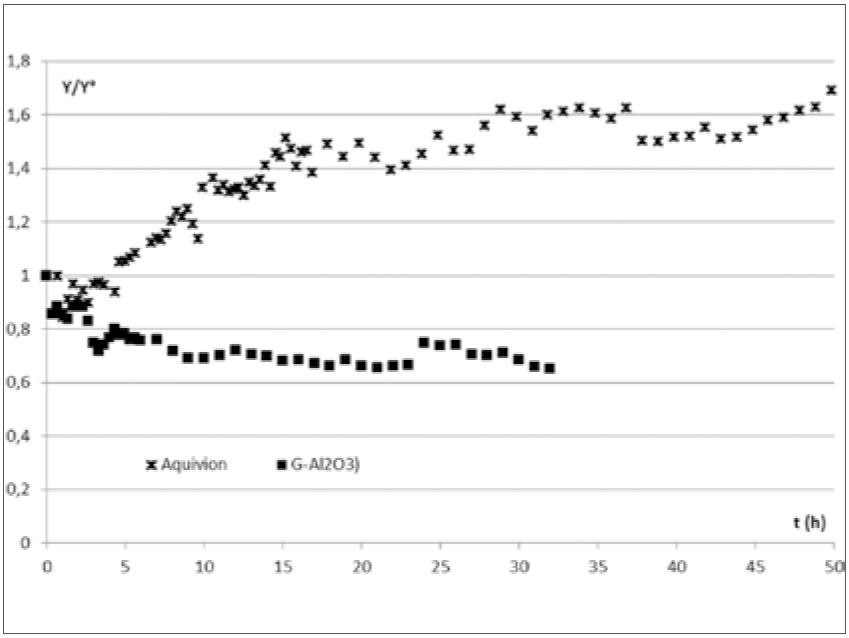

Fig.2 Experimental results of methanol dehydration to DME reaction

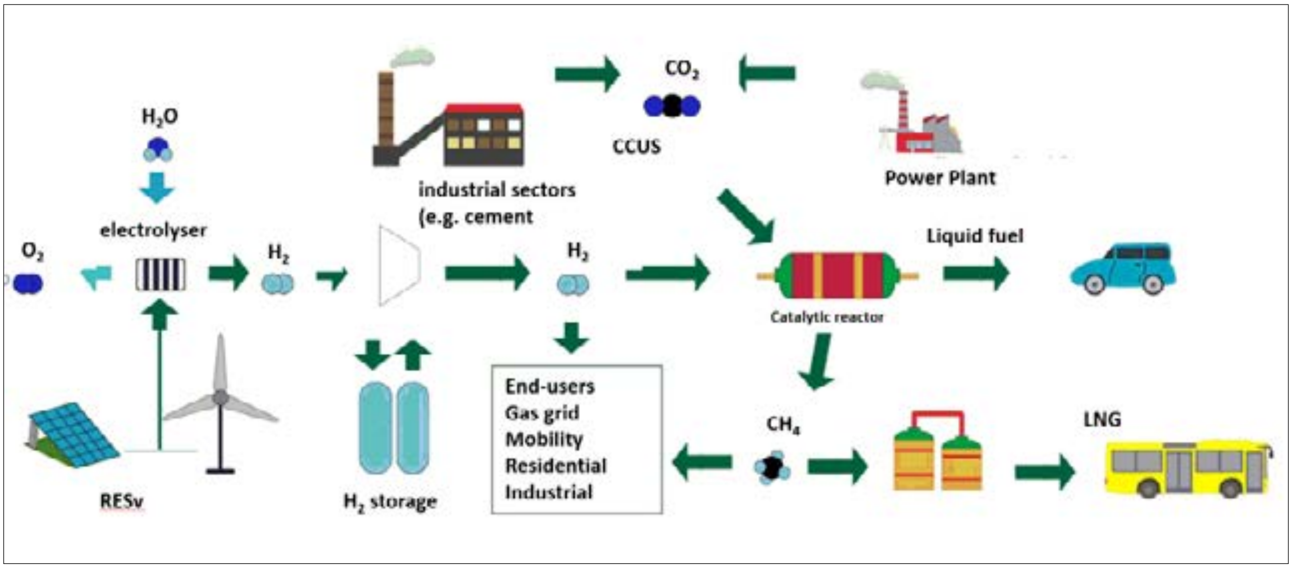

Fig.3 E-CO_2 project scheme [8]

Projects and perspectives

Gaseous and liquid fuels and feedstocks will still play an important role in an optimized future energy system. From today's perspective, energy carriers with high energy density as well as specific raw materials have great difficulties being replaced. This can be seen especially in both the chemical and transport sectors. **E-fuels are the most sustainable solution to meet the energy demand of a growing global economy, even in the future**. Technological progress and cost reductions in wind and solar power, as well as electrolysers, have been significant in recent years. Therefore, even from a cost perspective, there has been an increasing amount of interest in creating a market for those fuels. Combining these factors will mean that **E-fuels can offer new opportunities. These can be shortly summarized in few points:**

- **Complement to direct electrification in all sectors:** E-fuels provide an opportunity to use renewable fuels in all sectors and in nearly all available applications. They complement the direct use of renewable energies, specially where direct electrification is not possible or economical.
- **Use of existing infrastructure:** E-fuels can be integrated completely or partly into the existing gaseous and liquid fuel infrastructure.
- **Energy security and diversification:** E-fuels contribute to energy security and energy stability.
- **Sustainability and costs:** E-fuels can be more efficient and less resource-intensive than biomass products, but are currently more expensive
- **Global commodity and new markets:** E-fuels could become a tradeable global commodity. Countries with low natural resources but good solar and wind conditions, will get the chance to improve their own energy supply and become a new player in the global energy market.
- **Technological innovation progress and local benefits** such as new employment in industry and in research and development.
- **Storage:** e-fuels can also be considered a valid system for the seasonal storage of the surplus of production from RES. Compared to batteries, therefore, they have a different usage target in terms of the amount of energy that can be stored and times of usage.

Currently in ENEA there is a multidisciplinary technological know-how with skills that cover the complete e-fuels value chain. Future development projects may involve activities on laboratory scale (catalyst synthesis and test) and on prototype and pilot plant scale covering different TRL value. In this contest, process and predictive analyses, technical economic and environmental feasibility studies will be carried out.

In order to reduce costs in an effort to penetrate the market, it is strategic, together with the development of technological aspects, also the creation of industrial synergies.

ENEA, as proposals´ leader within funding programs, develops various applied research projects by integrating lines of activity that aggregate industrial partners with various core business, but which can find interest in the common development of technology.

A good example is the aggregation of

industries characterized by high local CO_2 emissions, with others that develop technologies for the production of energy and hydrogen from renewable sources and, to close the supply chain, with the potential end users interested in e-fuels (such as the transport sector) [8][9].

Conclusions

Worldwide, private and industrial consumers are accustomed to energy prices that exclude external costs and often include subsidies. Under such conditions, renewable fuels – especially E-fuels – are unable to reach competitiveness with their non-climate-friendly competitors. Currently, one of the main challenges are relatively high production costs for E-fuels due to the lack of industrial scaling of technology, which means high investment costs. In addition, state-induced price elements can substantially increase operational costs. E-fuels are a missing link for a future low emission energy system. But although being necessary for achieving climate mitigation goals, E-fuels are facing competitive disadvantages at present. **Therefore, political support is necessary for their entry into the global market. Synthetic fuels are currently inefficient in terms of energy required for production and are confronted with high production costs**. Support to progress the development of this conversion technology, including demonstration and upscaling of the full production process, is relevant with a view to having substitutes for fossil fuels in particular in the most difficult to decarbonise sectors.

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Hydrogen turns Europe green. And more

What are the strategies that have already been adopted internationally for the development of hydrogen? Which countries are at the forefront of investments and policies aimed at making this vector more widespread? Some of the most interesting cases are illustrated in this article, which also offers a current snapshot of what is being done in Italy.

Quali sono le strategie già adottate a livello internazionale ed europeo per lo sviluppo dell'idrogeno? Quali sono i Paesi all'avanguardia per investimenti e politiche volte alla diffusione di questo vettore? Alcuni dei casi di maggiore interesse sono illustrati in questo articolo che scatta anche una fotografia aggiornata di quanto si sta facendo nel nostro Paese.

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by **Laura Moretti,** *Unità Relazioni e Comunicazioni ENEA*

Lightweight, energy-intensive, efficient and able to produce "clean" energy on a large scale. Hydrogen, one of the cornerstones of the energy transition, is a necessary step towards carbon neutrality by 2050, the topic that today dominates the agendas and recovery and development plans of the European Union and its Member States.

In July 2020 the European Hydrogen Strategy was launched, crowning a journey that began years earlier with initiatives such as Fuel Cells and Hydrogen Joint Undertaking (FCH JU), the Clean Hydrogen Alliance, the EU Roadmap and the European Parliament Report. It is an ambitious plan that has taken shape in initiatives for an increasingly interconnected, decarbonised and efficient energy sector, for a transition that can create competitive development and relaunch the economy in line with the Next Generation EU package and the European Green Deal. For the Member States the watchwords are investment, research&development&innovation, regulation and the creation of a hydrogen market in sectors such as industry, transport, electricity production and construction. Last but not least, the integration of energy systems and consumer sectors through designated carriers and infrastructure. The Clean Hydrogen Alliance was created with this specific objective in mind, bringing together representatives of industry, civil society, national and European institutions, the European Investment Bank and research bodies – including ENEA – to develop the hydrogen value chain and facilitate the implementation of the new European strategy and the 2030 investment agenda. Objectives that are also shared by the International Energy Agency, which aims to hasten the decarbonisation of hydrogen by 20 years (from 2070 to 2050) through four areas of intervention: the use of industrial hubs, the exploitation of infrastructure assets, the involvement of the transport sector and the opening of new global commercial routes. But what are the strategies that have already been adopted internationally for the development of hydrogen?

Japan has certainly been a pioneer, with a long history of developing hydrogen technologies, including fuel cells. Its first research dates back to the 1970s. To maintain its leading role, Japan was among the first countries to adopt a "hydrogen strategy", as early as 2017. Today, the Japanese government has identified hydrogen as the game changer of climate change, so much so that it is looking to create the world's first supply chain with a production of 3 million tonnes in 2030 and 20 million tonnes in 2050, and a reduction in costs estimated at €0.24 per m^3 within 10 years and €0.16 per m^3 by the middle of the century for transport and electricity generation. According to a study con-

ducted in 2019 by Fuji Keizai, by 2030 the hydrogen market in Japan is expected to grow 56 times, reaching 408.5 billion yen (about €3.2 billion). Examples of some cutting-edge projects include SeaEra, for the production of green hydrogen on a "floating" infrastructure, to be used as a fuel for maritime transport; a high-purity hydrogen and oxygen generator; a network of hydrogen refuelling stations; and the development of an innovative technology for the production of hydrogen from ammonia for use in fuel cell vehicles.
But Europe has not sat idly by. Indeed, some countries like France and Germany have put the pedal to the metal, seeking to consolidate a Franco-German energy axis: after joint projects launched in the field of batteries, the two nations are now looking for a point of contact on the new energy vector by allocating important investments to the new green gold.

In fact, **France**, while being one of the 13 States that according to the European Environment Agency (2019 data) has not yet reached the target of a 23% share of renewable sources in gross final consumption by 2020 (currently below 17%), when it comes to hydrogen it has adopted a national strategy that allocates investments for over €7 billion divided as follows: 54% to accelerate the production of hydrogen, 27% to decarbonise the heavy transport sector and 19% for research, innovation and development. **Hydrogen is part of the €100 billion "France Relance" plan, which consists of some 70 measures linked to the European Recovery Fund. The French strategy is focused in particular on the development of "green" – low-carbon – hydrogen with a target of around 6.5 megawatts by 2030 to avoid six million tonnes of CO_2 and to create up to 150,000 new jobs at full capacity.** Furthermore, in April 2021 Sncf Voyageurs, the French rail operator, ordered the first 12 dual-mode electric-hydrogen trains (plus two optional trainsets) of the Coradia Polyvalent range for a regional line, for a value of almost €190 million. On the horizon there are also maxi-projects such as "Masshylia", an investment of over €100 million, the largest ever in France, which brings together the energy giants Total and Engie within the biorefinery of La Mède in Provence for the production of green hydrogen from water powered by electricity from a 100 megawatt photovoltaic system.

For **Germany**, integration and cooperation are the mantra for pursuing the objective of being the main supplier of green technologies for hydrogen in the global market. The national strategy launched in July 2020 aims to strengthen cooperation with the other States of the European Union, in particular in the North Sea, Baltic and Southern Europe areas. An agreement with Canada to produce green hydrogen using Canadian hydropower was also recently signed.
Hydrogen will receive €9 billion of the €130 billion appropriated by the 2020-2021 Relaunch Plan, of which €2 billion for partnerships with other countries. The top priority of Angela Merkel's government is to support the creation of a green hydrogen market along the entire value chain, developing the needed infrastructure, which also includes the conversion of part of the unused gas infrastructure, for a total production of 5 GW by 2030 and 10 GW by 2040, making it a world leader. With regard to key technologies, the German strategy focuses in particular on electrolysis, bio-based processes, methane pyrolysis, artificial photosynthesis and fuel cells. A 25-member National Hydrogen Council has also been set up with representatives of industry, the scientific world and civil society to advise the government.
And then there are the countries of the North Sea that have the possibility of

producing green hydrogen from electrolysis that exploits wind energy, largely with offshore wind farms. Great Britain and the Netherlands are the prime movers in this region.

Great Britain, a pioneer in the study of hydrogen, is now a leader in the Old Continent both in terms of research and funding for the development of a dedicated supply chain. **In the 10-point plan of the "Green Industrial Revolution" launched on 18 November 2020, which provides for public investments of £12 billion by 2030, Boris Johnson's government focuses on "low-carbon" hydrogen (not necessarily green) and 5 GW of production capacity.** Through projects funded by the Department for Business, Energy and Industrial Strategy, the path towards the promotion and diffusion of hydrogen includes several stages starting from verification of the feasibility of introducing mixtures into networks that are increasingly rich in hydrogen, up to 100%, to the analysis of the impacts along the value chain, to the construction of the first "hydrogen city" by the end of 2030, with hydrogen-heated homes and residential districts that distribute hydrogen produced by electrolysis powered by wind energy. The Tees Valley area in the north-east part of the country, on the other hand, saw the launch of a project that brings together research, industry and public institutions to create a **"pioneering hydrogen hub"** that will be an template for the development of projects promoting the widespread use of hydrogen as an alternative fuel.

The Netherlands, one of the first countries in Europe to approve a hydrogen strategy, is more determined than ever to become Europe's Hydrogen Valley, among other things building 4 GW of electrolysers by 2030. To meet the target, a group of 31 companies and local authorities – including Gasunie, Shell, Rwe, Engie, Equinor, Eneco and Vattenfall – launched a €9 billion plan for the production of 100 million gigajoules of hydrogen (75% green and 25% blue) per year by 2030, capable of satisfying a quarter of north-west Europe's needs. With its unique location, the presence of industrial nodes and a dense network of gas transport and storage infrastructure connected to ports, the country would thus host the world's largest green hydrogen plant, which will exploit the electricity produced by an offshore wind farm in the North Sea. The facility is expected to start operating in 2030 with an annual production of 800,000 tonnes of hydrogen. The roadmap for the development of the hydrogen supply chain is based on four pillars: legislation and regulation, reduction of green hydrogen costs (through a research and development plan and incentives of up to €300/tonne) and supporting policies. For the transport of hydrogen, the objective is to promote the use of the existing gas network and to identify possible opportunities for maritime transport to also create and promote the development of a market in this sector.
The countries of the Mediterranean area have responded with their own strategies that aim to create a Mediterranean hydrogen hub, representing an infrastructure bridge connecting northern Europe. Among these countries, Spain and Italy are ready to invest in hydrogen. Indeed, Italy could become the infrastructure bridge between Europe and the aAfrican continent (Italy could in fact import hydrogen produced in North Africa through solar energy at a cost that is 10-15% lower than domestic production, exploiting the greater availability of land for the installation of renewable energy, a high level of irradiation and at the same time decreasing seasonal variability).

Spain intends to invest almost €9 billion in green hydrogen over the next 10 years and to become a major player in production and export. In October 2020, the Sanchez government presented its Hoja de Ruta del Hidrógeno, with 60 measures, three macro-targets and a roadmap for the development of the sector. The plan outlined by the Ministry for the Ecological Transition sets a 2030 target of 4 GW of electrolysers, equal to 10% of the power proposed by the European Commission for the entire EU. The 2030 timetable calls for 25% of industrial hydrogen consumption from renewable origins and a fleet of at least 150 fuel-cell buses, 5,000 light and heavy vehicles and two commercial train lines. Hydrogen networks will also be developed at ports and airports. Overall, the government estimates that achieving the 2030 targets should enable Spain to reduce greenhouse gas emissions equivalent to 4.6 million tonnes of CO_2. The package of 60 measures envisaged by the Ministry includes the promotion of R&D, the design of financial instruments to support industry, the creation of Hydrogen Valleys and the development and mass production of high-power electrolysers (100 MW).

In **Italy,** last November the Ministry of Economic Development published and opened the "National Hydrogen Strategy - Preliminary Guidelines" for consultation to promote the development of a hydrogen supply chain in our country. It is an objective that is also considered a priority by the Minister of Ecological Transition Stefano Cingolani, for whom it is critical to create the conditions to make it the main carrier at a reasonable price, in line with international trends. To date, with over 160 projects and 120 beneficiaries, alliances between top Italian manufacturers and international research institutions and a strategic geographical position, Italy is among the sector's leaders in Europe, making it a prime candidate to become a European and Mediterranean hub. H2it, the Italian Hydrogen and Fuel Cell Association, has more than 70 members, and many companies – Enel, Eni, Snam and even Rete Ferroviaria Italiana, to name just a few – have undertaken an array of projects in this field. This is also confirmed by participation in global initiatives such as Mission Innovation with investments of €18 million, and the commitment laid out in the **National Recovery and Resilience Plan (NRRP) with €3.6 billion in investments as part of the M2C2 "Energy Transition and Sustainable Mobility" mission**. Key points of the Italian roadmap include: the exploitation of abandoned industrial areas for the creation of hydrogen valleys, the use of hydrogen in energy-intensive sectors such as the chemical, steel and oil refining industries, the conversion to hydrogen of at least six railway lines among those with considerable use of diesel trains in regions with high passenger traffic, and the creation of a network of 40 hydrogen refuelling stations. Finally, the strengthening of R&D resources for the production of green hydrogen, the development of technologies for the storage and transport of hydrogen, the transformation into other derivatives and green fuels and fuel cells as a technology of choice for an efficient and clean use of hydrogen.

ENEA plays a leading role in this area: after the launch of the Hydrogen Valley in the Casaccia Research Centre and the coordination of European projects including Prometeo for the production of green hydrogen through innovative high-temperature systems, it signed an agreement with Confindustria to identify the development potential of industrial chains and is providing technical and scientific support to the Ministry of Economic Development for the establishment of the first hydrogen IPCEI (Important Project of Common European Interest).

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Hydrogen and "green transport"

Transportation sector, which represents the source of one third of total CO_2 emissions in the EU, could benefit from the renewed attention on green hydrogen, since, as energy vector it could help to replace fossil fuels and reach EU climate change targets. Hydrogen could be a lead actor for transport decarbonisation especially in those sectors, such as aeronautics, long-haul road, maritime transport, and railways, where batteries are an impracticable solution to substitute fossil fuels, due either to the large amount of energy required or the long distance that needs to be covered. At the same time, a great interest has been shown to replace ICE Diesel technology in heavy-duty transport with hydrogen technology. Hydrogen will be able to contribute to the efforts for transport decarbonisation, working together with electrification and not in competition with it, filling that gap that could not be technically or cost-effectively covered by batteries.

Il settore dei trasporti, causa di un terzo delle emissioni di CO_2 in Europa, potrebbe trarre giovamento nell'impiego di idrogeno verde quale sostituto dei combustibili fossili per conseguire gli obiettivi di neutralità climatica individuati dalla UE. L'idrogeno ha potenzialità per assumere un importante ruolo in quelle aree ove le batterie mostrano limiti applicativi per via delle maggiori distanze da percorrere o per il maggior contenuto di energia da porre a bordo dei veicoli, come nel trasporto marittimo, ferroviario, stradale di lunga percorrenza, aeronautico. Allo stesso tempo, è stato mostrato un grande interesse nel sostituire la tecnologia dei motori a combustione interna Diesel con la tecnologia dell'idrogeno nel trasporto pesante. L'idrogeno avrà modo di contribuire agli sforzi di decarbonizzazione del trasporto, lavorando in cooperazione e non in competizione con l'elettrificazione, colmando l'ambito applicativo ove le batterie non trovano convenienza tecnica-economica.

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by **Antonino Genovese, Fernando Ortenzi, Francesco Vellucci (*)**

Nowadays we are witnessing a revival of interest for hydrogen as energy carrier in several application fields. Paraphrasing the homonymous movie of the mid '80s we can say that hydrogen "comes back to the future". The renewed focus presents hydrogen as a key pillar to decarbonise energy sectors characterized by high carbon footprint that might find hard or expensive to deploy other solutions. However, this statement will be successfully verified only if hydrogen will be produced from renewable energy, giving rise to the so-called "green hydrogen", or from other colored pathways which will be able to offer a safe, cost-effective and CO_2 emissions free hydrogen source.

Transportation sector represents the source of one third of total CO_2 emissions [1] in Europe (EU) and it could benefit from the renewed attention on hydrogen to replace fossil fuels and meet the EU decarbonisation targets. The ongoing revolution in road transport is oriented to substitute petrol and Diesel-powered vehicles with less CO_2 emitting vehicles preferring electrification as the main solution. Cars and motorcycles powered by batteries have good chance to reduce CO_2 and pollutants emission having zero "on road" emissions while overall emissions depend on the energy mix used to generate electric energy. Battery electric vehicles (BEVs) range and recharging time are now more responsive to user needs and make BEVs more attractive to meet mobility requirements on short-medium range daily trips. Current batteries for cars have energy capacity up to 100 kWh, offering real range of 300 km and over. Heavy duty vehicles engaged in long range transport and public transport buses, usually powered with Diesel internal combustion engine (ICE), are less suitable to be substituted by battery powered vehicles because they would need a larger battery capacity in order to run appropriate distances. Battery packs would be result bulky and heavy and, moreover, charging power should be rather high to limit the charging time.

Hydrogen in transport could be a lead actor in sectors where batteries are an impracticable solution to substitute fossil fuels as well as for maritime transport (ferries, coasting trade or inland waterway) and in rail application. At the same time, a great interest has been shown to replace ICE Diesel technology for heavy duty transport with hydrogen technology. First prototypes of H_2 trucks have recently been unveiled by Toyota, Nikola and Hyunday while other manufacturers have just started to undertake this promising challenge.

H_2 as fuel in internal combustion engines

Hydrogen is an energy carrier capable to power road vehicles in two ways: as fuel to be injected in the ICE or as fuel to supply the Fuel Cell (FC) system. ICEs can be modified or redesigned to run on 100% H_2, exploiting hydrogen properties as fuel: wide range of flammability, high flame speed, low ignition energy, high diffusivity. **ICE is a mature technology and could be converted to run on hydrogen, given the benefits from already existing manufacturing facilities.** H_2 ICEs can result cheaper, less dependent on rare and expensive materials and more tolerant to hydrogen impurities compared with FC technology. Although the H_2 ICE emission is water vapor, traces of carbon-based emissions (CO, HC) could be present in the exhaust gas due to oil lubricants and NOx resulting from oxidation of nitrogen (N_2) in the air by high combustion temperature. Feeding H_2 to ICEs in a lean condition with exhaust gas recirculation (EGR) minimizes the NOx emissions. Alternatively, a stoichiometric combustion can be combined with a three-way catalytic converter in order to reduce NOx. Fuel injection in the intake manifold is the solution employed in many demonstration prototypes but this technology is affected from a reduced power density since a large volume of H_2 leads to a displacement of air in cylinders (Figure 1). This drawback can be solved using direct injection, a solution able to increase the volumetric efficiency with an injection pressure higher than 100 bar which overcomes the high in-cylinder pressure. In 2009, BMW equipped an H_2 ICE with a high pressure direct injection system (300 bar) and reached a 42% of maximum efficiency similar to a Diesel engine [2]. In Hyfleet:CUTE (2006-09) and CHIC projects (2010-16) H_2 ICE buses based on naturally aspirated injection were put in regular service showing a service availability larger than 89% [3]. In H_2 ICEs attention must be drawn to the embrittlement coming from hydrogen diffusion inside crystalline lattice of materials that could lead weakening and cracking phenomena.

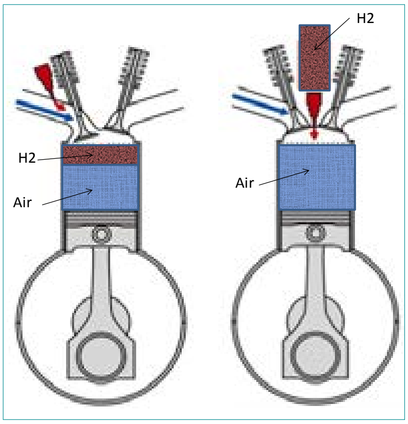

Fig.1 intake fuel injection and direct injection of H_2 in ICE

A soft application of H_2 in ICE is possible fueling engine with a blend of natural gas/hydrogen (NG/H_2). In this case H_2 operates as "additive" to natural gas giving advantages which make it possible to operate lean combustion thanks to the improved performance in combustion kinetics and flame propagation. The use of hydrogen blends is supported by other aspects such as the possibility to use the exiting NG pipeline for mixture supply to refueling stations. The NG/H_2 blend leads to a CO_2 reduction due to the hydrocarbon molecules substitution with hydrogen molecules and a possible additional reduction for a major efficiency resulting from the higher combustion speed. Obviously NG/H_2 blends are not a carbon-free fuel but can be a solution to support the transition toward a 100% carbon-free transport.

FC for road transport

A Fuel Cell is an electrochemical device where hydrogen and oxygen react, converting chemical energy to electric energy and giving water as reaction product. Reactants are introduced individually in two electrodes separated by an electrolyte which avoids direct mixing of the reactants but allow the transfer of ions. The most common technologies adopted in transport are based on the use of a Polymeric Electrolyte Membrane (PEM) as electrolyte. This kind of electrolyte makes this FC technology interesting thanks to the low operating temperature (70-90 °C), compactness and power density. Usually, a platinum catalyst is used to facilitate reduction and oxidation reactions. The performance of PEM FCs depend on the different components but also on operating parameters such as humidity and temperature. The high efficiency that characterizes PEM FCs makes them competitive in energy term while durability is another important requirement in order to meet transport needs yet. In transport applications reference lifespan (defined as the maximum lifetime of a FC with no more than 10% loss in efficiency) are 6,000 hours for cars and 20,000 hours for buses respectively. Higher FC lifespan are required for a long haul application where a high mileage is expected: 50,000 hours and over is the target. **At present, FC vehicles are expensive, although mass-production could reduce costs, bringing them closer to other powertrains.** Platinum catalyst is a rare material having a yearly production of 170 tons in 2020 with two third of world production in South Africa. This resource could be subject to market variability, a potential risk factor for future supply. To avoid this uncertainty, manufacturers are engaged to decrease platinum content in order to reduce FC cost and to push the volume scale up. **Another critical point to large mass market diffusion is hydrogen storage:** pressure vessel up to 350 or 700 bar is the option adopted for passengers cars, but other solutions as liquid cryogenic hydrogen are under investigation in order to increase the storage energy density. FC vehicles present a longer driving range in comparison with BEV and a refueling time comparable with ICE vehicles. Market of FC cars presents a small number of models (i.e. Hyunday Nexo, Honda Clarity ,Toyota Mirai) powered by FC and currently available for sale.

H_2 in rail transport

Hydrogen mobility is proving to be a valid alternative to Diesel fueled trains on non-electrified lines in Europe. Hydrogen trains are considered competitive for those railway sections not electrified, with low frequency of service and operating on long distances. These conditions are frequent in rail transport, making hydrogen rail mobility interesting from an economic point of view and an excellent opportunity to further decarbonise public transport. The fuel cell technology, unlike other "clean" technologies such as batteries, is able to offer high range in terms of mileage and high nominal driving power.

Fig.2 The "Coradia iLint" train (Image courtesy of Alstom)

The "Coradia iLint" train (Figure 2) by Alstom [4], for example, has H_2 tanks which ensure an autonomy varying from 600 to 800 km depending on the conditions of the route and the service offered; it is also capable of reaching a maximum speed of 140 km/h having a total available power of 850 kW and passenger capacity of 327 seats.

The National Hydrogen Mobility Development Plan for Italy [5] released by H_2IT consortium underlines that in Italy there are favorable conditions for consistent introduction of H_2 trains. The refuelling of H_2 trains is programmable, so the refuelling station can be also used for other users such as buses or private cars. The H2iseO project [6] developed by the railway company FNM, involves the purchase of 6 hydrogen trains produced by Alstom, with the option for the supply of additional 8 trains, which from 2023 will serve the non-electrified Brescia-Iseo-Edolo line in replacement of the current 14 Diesel trains; this project envisages the construction of hydrogen production plants, initially intended for new clean energy trains and, by 2025, also for local public transport and freight logistics.

H_2 in maritime sector

The maritime sector is a major consumer of oil products, accounting for about 5% of the World's demand [5]. As it uses heavy oils as fuel, it has detrimental effects on air quality, particularly around ports. In 2018, the International Maritime Organization introduced and adopted a real strategy in order to reduce total annual greenhouse gas emissions from international shipping by at least 50% by 2050 compared to 2008 [7]. In this context, **hydrogen takes advantage of the opportunity to reduce not only emissions during sea navigation, but also those deriving from port operations.** In this perspective, the use of energy carriers and alternative fuels with a reduced environmental impact is the key to reach the objectives of reducing greenhouse gas emissions. The current role of the maritime sector in H_2 deployment is limited to demonstration projects involving ships for river waterway, coastal crafts and ferries powered by hydrogen produced from renewable sources. **The first experience of a hydrogen-powered boat in Italy was made in 2009, in Venice, with the construction of the "Accadue" water bus**, a prototype powered by fuel cells [8]. Later, an evolution of the aforementioned prototype, the ferry called HEPIC (Figure 3) was also built in the Venice lagoon [9]. As far as large ships are concerned (on board installed power capacity of a few tens of MW) it seems currently difficult that propulsion would be driven by hydrogen fuel cells, especially considering the large volumes that would be necessary for storage. It therefore appears more likely that, for systems that require

Fig.3 The HEPIC (Image courtesy of Alilaguna)

high power, hydrogen could be used more for power supply of some auxiliary services rather than for propulsion. Therefore, hydrogen offers an interesting potential for passenger ferries operating on short distances (for example those for city use) generally having a limited power and autonomy request so that the space necessary for the storage of hydrogen on board would not be excessive, silence and the reduction of emissions are factors of great importance. **Hydrogen-based technologies for maritime transport have big potentials in Italy, considering the number of ports and their volumes.** Making industrial ports strategic hubs for hydrogen use for different types of activities would strongly boost the hydrogen market in activities closely related to it including, for example, goods mobility such as material handling and heavy transport. Ports are an ideal logistic ecosystem for creating synergies that can lead to a reduction in operating costs and several projects are active on this matter.

Projects and perspectives

Differently from a few years ago, the exploitation of hydrogen as energy carrier is now supported by increasing availability of renewable energy that makes hydrogen a "green fuel". Storing energy as hydrogen is a valid option to balance the power grid, making large volumes of green hydrogen available when produced in electrolyzer plant. To make hydrogen attractive the production cost would decrease in a way that supports the hydrogen economy in the transport sector. **Research and technologic progress in FC in the next years should offer higher lifespan, lower sensitivity to hydrogen impurity, deployment of cheaper catalyst materials in order to make hydrogen a real democratic fuel for environment preservation.**

The current revival of interest for hydrogen as energy carrier has the potential to provide a significant positive impact on the decarbonization of the transport sector, especially where the limitations of electric solutions (batteries) represent relevant economic and/or the technical burdens, as it is the case of long range heavy vehicles. Therefore, hydrogen will be able to contribute to transport decarbonisation working together with electrification and not in competition with it, filling that gap that could not be technically or cost-effectively covered by batteries.

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Hydrogen and the fuel-flexibility dilemma in gas turbines

The objective of this article is to clarify the state-of-the-art of gas turbines in terms of their fuel-flexibility, today intended as their capability to operate with hydrogen blends safely and reliably even with unplanned temporal composition fluctuations. From OEMs's catalogues, DLE (Dry Low Emission) gas turbines can operate with natural gas/hydrogen mixtures up to 30% by volume of H_2, on average: although this level corresponds just to 5% by mass with negligible reduction of CO_2 (near 75% by volume of H2 is required to achieve a 50% CO_2 reduction), it has to be considered as a challenging level in case of quick and unplanned hydrogen content fluctuations. Progress in fuel-flexibility is occurring fast but the journey towards fully-flexible "H_2-turbines" (0-100% of H_2) will still take some years and require some low TRL (2-3) activities too. The article reports the main problems to solve to reach the goal by 2030 in Europe and briefly describes ENEA's activities on the topic. For example, ENEA's IPSE Lab is developing and promoting activities on hydrogen gas turbines in some projects (Electric System Research, NextMGT), industrial collaborations (SNAM, BAKER HUGHES, ANSALDO ENERGIA) and international associations (European Turbine Network, Hydrogen Europe): focus is on the effects of adding H2 to natural gas in terms of flame topology (wrinkles, length), burning rate, thermo-acoustic instabilities, gas turbine operation.

L'obiettivo di questo articolo è di chiarire lo stato dell'arte delle turbine a gas in termini della loro "fuel-flexibility", oggi intesa come capacità di operare con miscele idrogenate in modo sicuro ed affidabile anche in presenza di inaspettate fluttuazioni temporali di composizione. Dalle informazioni deducibili dai cataloghi dei produttori, le attuali turbine a gas di tipo DLE (Dry Low Emission) sono in grado di operare con miscele gas naturale/idrogeno con un tenore di H_2 fino al 30% in volume, in media: nonostante questo corrisponda al solo 5% in massa, con abbattimenti di CO_2 irrilevanti (circa il 75% in vol. di idrogeno è richiesto per ottenere una riduzione di CO_2 del 50%), tale livello è già considerevole in caso di rapide ed inaspettate variazioni temporali del contenuto di H_2. I progressi nel campo della fuel-flexibility sono rapidi ma occorrono ancora alcuni anni ed attività di basso TRL (2-3) per ottenere turbine a gas in grado di operare con miscele con contenuto di idrogeno dallo 0 al 100%. L'articolo riporta i principali problemi da risolvere per raggiungere tale obiettivo in Europa entro il 2030 e sintetizza le attività ENEA sull'argomento. Per esempio, il Laboratorio IPSE di ENEA sta sviluppando e promuovendo attività sulle turbine a idrogeno in progetti (Ricerca di Sistema Elettrico, NextMGT), collaborazioni industriali (SNAM, BAKER HUGHES, ANSALDO ENERGIA) ed associazioni internazionali (European Turbine Network, Hydrogen Europe): l'attenzione è focalizzata sugli effetti dell'aggiunta di H_2 al gas naturale in termini di topologia del fronte di fiamma (corrugamenti, lunghezza), velocità di combustione, instabilità termo-acustiche, operabilità delle turbine a gas.

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by **Eugenio Giacomazzi e Giuseppe Messina (*)**

Nowadays, the term fuel-flexibility refers to gas turbine capability to operate with hydrogen blends as fuel in a stable, safe and reliable way when the H_2 content unpredictably varies in time due to intermittent production from renewables. Such blends range from hydrogen-enriched natural gas (HENG) to ammonia (a promising H_2-carrier).

Both producers and users already have a huge experience in feeding their gas turbines with syngas containing hydrogen from 30 to 60% by volume, a solid base to burn mixtures with higher H_2 concentrations. Looking at OEMs' catalogues, the stat-of-the-art exhibits, on average, DLE (Dry Low Emission) gas turbines able to burn H_2 up to 30% by volume with low NOx emissions (<25 ppmv at 15% O_2). Due to the higher flame temperatures with respect to naural gas, in some cases NOx emissions are controlled only by derating the machine, i.e., reducing its power [1]; besides, it must be said that the strongest NOx limitations for natural gas (<15 ppmv at 15% O_2) are not always reached today[1]. Higher hydrogen content can be burnt by adopting the WLE (Wet Low Emission) technology, but with penalties in NOx emissions, reduced efficiency and life cycle, higher costs. Hence, most of investments are on DLE technology, i.e., lean premixed combustion without dilution (steam, nitrogen, water), also for retrofit solutions. New combustion concepts are also explored, such as the sequential combustion at constant pressure (implemented in the GT36) and that based on micro-mixing and exhaust gases recirculation (EGR).

An important aspect, easy to understand but very often neglected is that large hydrogen mass fractions are required in fuel mixtures to significantly affect CO_2 emissions. Talking in terms of volume fractions is a common practice, but in a methane/hydrogen mixture the H_2 volume percentage largely differs from its mass counterpart, as shown in Fig. 1; for example, 30 and 50% vol. correspond just to 5 and 11% mass, while 80% vol. is required to reduce CO_2 emissions by 55%. However, even the low 30% vol. becomes really challenging if significative temporal fluctuations of composition are considered.

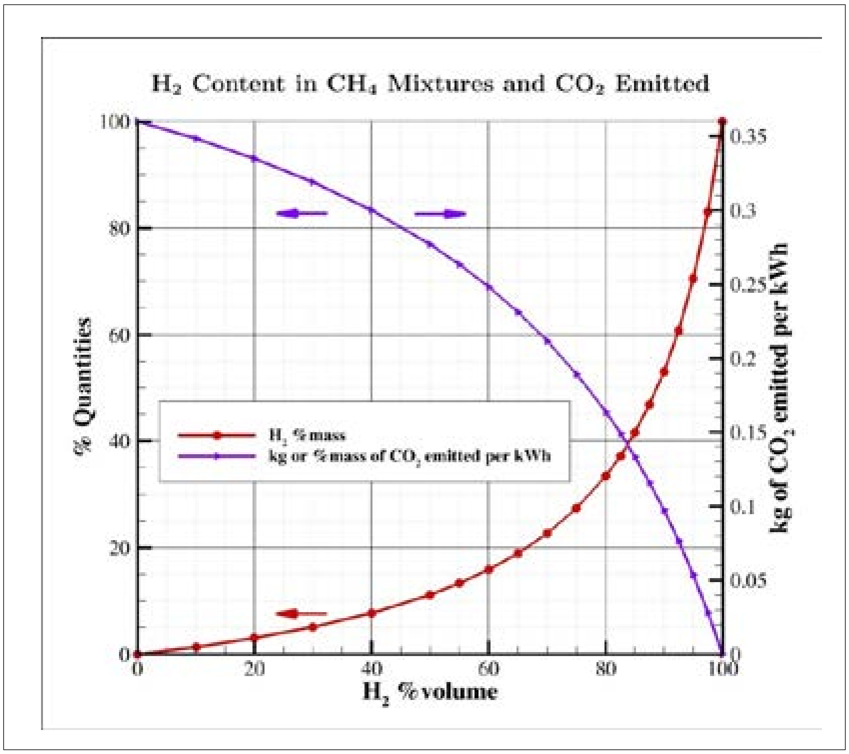

Fig.1 Relation between volume and mass percentages in methane/hydrogen mixtures, and impact in terms of CO_2 emitted (assuming an electrical efficiency of 55%). The percentage quantities on the left are with respect to pure methane.

Main issues

Hydrogen strongly alters combustion characteristics of a reacting mixture with respect to natural gas: the laminar flame speed increases, the ignition delay time decreases, the flammability limits enlarge, the adiabatic flame temperature increases, the turbulent flame speed becomes pressure dependent [2,3]. Such changes can dramatically affect combustion dynamics producing dangerous flashbacks [4] and/or thermos-acoustic instabilities [5,6] that may drive to unplanned overhauls thus reducing system reliability. Although **both research and industrial sectors have been investigating the combustion instability topic for many years, it is still a not fully solved problem:** strategies commonly adopted to avoid or limit the dangerous effects of such instabilities in modern gas turbines are based on empirical methods. Besides, the effects of hydrogen content on combustion dynamics make the Wobbe index unreliable for its applicability as fuel interchangeability index [7]. Special attention has to be given to control temperature peaks to limit NOx emission; maintaining them below 25 ppmv appears challenging for gas turbines operating in the range 0-100% H2 up to 2030: this is a difficult task due to the easily reached higher temperatures; there is an open discussion since the current limits for natural gas are lower, i.e., 15 ppmv. Another important effect of burning fuel mixtures with high H2 content is the higher steam content in

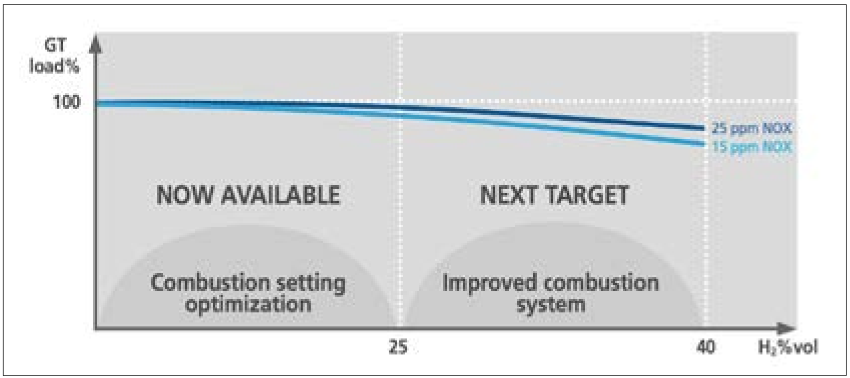

Fig.2 Engine derating to fulfill NOx emission limitations, taken from ANSALDO ENERGIA [9].

the exhausts. This increases the heat exchange in the hot path of the gas turbine, thus requiring more cooling [8] and reducing component life cycle due to increased risk of hot corrosion. As a consequence, reducing the turbine inlet temperature, and consequently reducing the machine power with penalty losses of 2% points in efficiency (another challenging limit to maintain up to 2030), is a commonly adopted solution (see Fig. 2).

Adding H_2 to natural gas also affects other operations of gas turbines, as at start-up and shut-down. Start-up procedures are commonly based on natural gas or liquid fuels, combining diffusive and premixed combustion at least up to FSNL[2] state. At present, an average of 5% H_2 by volume is tolerated at start-up.

Another term often used is "load-flexibility" or "operational flexibility". This refers to gas turbine capability to change its power in small time to quickly stabilize the electric grid. Different solutions were proposed and implemented in the recent years, reaching today a power rate of 10% of nominal power per minute. Such a value seems to be fine for gas turbine users today and should be maintained in the future moving to hydrogen gas turbines.

With reference to micro-gas turbines, despite the efforts of some OEMs, they do not follow the learning curve of the heavy-duty ones at the same pace, having a very tiny hydrogen tolerance. However, being the micro-gas turbines users of the same gas grid of larger ones, more efforts on R&D are mandatory to reach the same hydrogen compliance. Looking at the gas turbine hydrogen tolerance on a broader perspective, nowadays and presumably at least up to 2030, the major issues will not be on the technology but on the hydrogen availability and cost. The current global production of hydrogen is around 70 Mt per year, 99% of them coming from coal and natural gas. If all current hydrogen production would be produced from water electrolysis, the amount of electrical energy required would be around 3600 TWh per year, more than the annual production of the whole European Union [10]. The availability issues will be much more challenging if the electricity for water electrolysis should come from the excess of VRES production: the amount of curtailed wind power generation in Germany on 2016 was 4722 GWh, while the energy requirement to produce hydrogen by electrolysis to run just one 9HA.02 gas turbine for 8000 hours at nominal power is 19600 GWh [11]. Even not introducing the costs issue, just from this perspective, in the authors' opinion the use of blue hydrogen will be mandatory to build a realistic hydrogen value chain, as a precursor of a wide exploitation of green hydrogen when available in

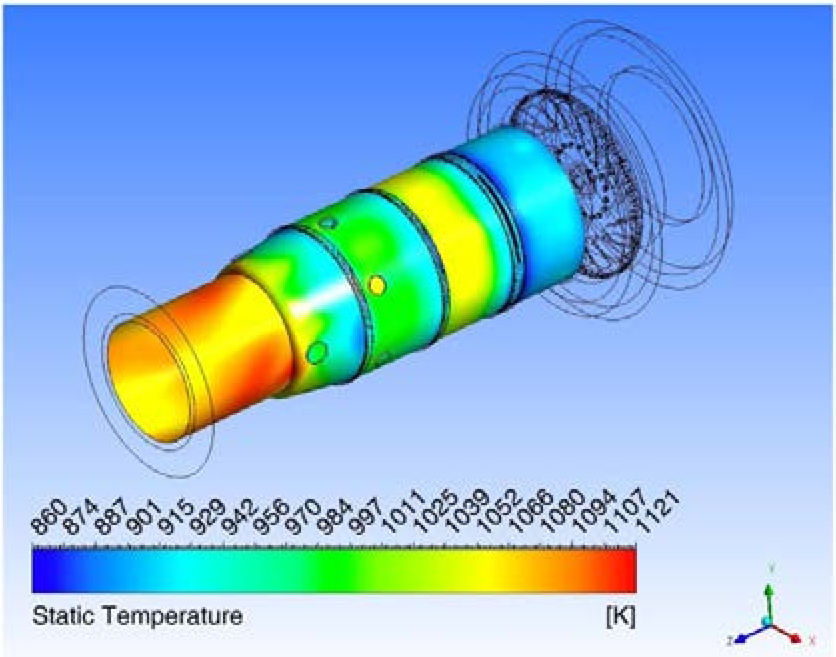

Fig.3 Temperature distribution on the liner inner walls of a micro-gas turbine combustor fed with methane and syngas [14].

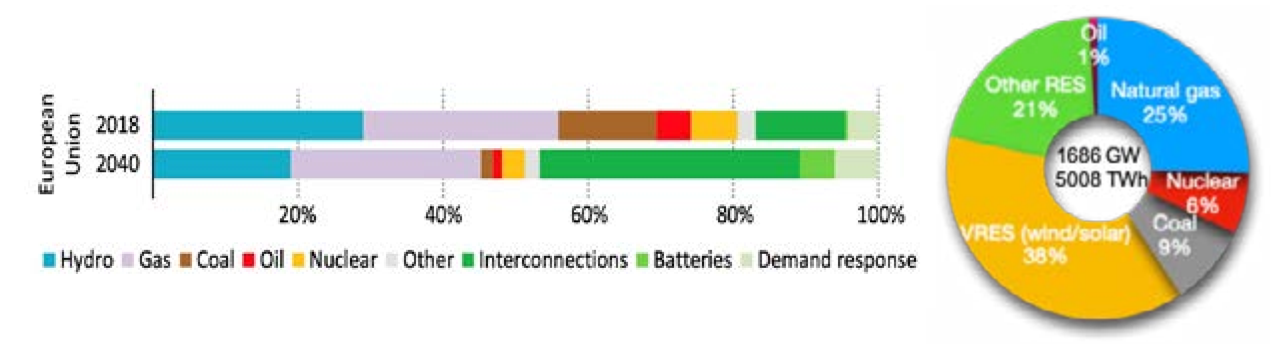

Fig.4 European electric system capacity (Current Policies Scenario) and flexibility sources (Stated Policies Scenario) in the 2040 vision [17].

practical quantities for an effective CO_2 emission abatement.

Research and development activities in ENEA

ENEA (IPSE Lab) is developing and also promoting activities on hydrogen gas turbines in some projects (Electric System Research, Next-MGT), industrial collaborations (SNAM, BAKER HUGHES, ANSALDO ENERGIA) and international associations (European Turbine Network, Hydrogen Europe): focus is on the effects of adding H_2 to natural gas in terms of flame topology (wrinkles, length), burning rate, thermo-acoustic instabilities, gas turbine operation. Numerical simulations with the in-house code HeaRT run on the HPC platform CRESCO6 are aimed at flame topology analysis [12]: simple configuration injections are investigated also in EGR conditions, i.e., including mixing of fresh reactants with some hot exhaust gases. Fundamental studies are also performed experimentally in simple combustion devices suitably designed for a better coupling with numerical investigations [13]; in particular, the attention is focused on thermo-acoustics by using laser diagnostics and specific real-time sensors developed by ENEA (ODC, to identify instability precursors and DOES, to measure composition).
More complex geometries, like the combustor (including injection plate, liner, dilution holes) of the micro-gas turbine of the AGATUR plant in ENEA, are simulated by using the ANSYS code to obtain helpful information for the operation of the related gas turbine. An example of the effects of hydrogen in this combustor is in [14]. Work is in progress to feed the micro-gas turbine TURBEC T100 of the AGATUR plant with hydrogen [15,16]: here, the aim is to understand how to operate the machine and explore its behaviour under different steady and fluctuating H_2 contents.

Perspectives

Hydrogen is going to play a central role in decarbonizing different sectors. In the power sector, gas turbines are asked to operate as a back-up service (seasonal and peak) to sustain variable renewable energy sources and stabilize the electric grid (both in voltage and frequency): their contribution to the electric system flexibility is expected to be important even in a 2040 projection (see Fig. 4), with an estimate of annual operating hours less than 3000. In this scenario, post-combustion carbon capture technologies are not applicable both from the technical and economic point of view: the potential annual CO_2 reduction due to 100% hydrogen gas turbines is larger than 450 Mt.
To complete the picture and specialize it to Italy, it is reminded that natural gas is the major source contributing to limit the greenhouse gases emission, with very quick positive effects at local level. Besides, in Italy the gas network is very spread and reliable, while gas turbines are critical to ensure the adequacy of the electric system in view of the coal phase-out in 2025.
The recent European roadmap on gas turbines, developed within the Clean Hydrogen Energy association to be transferred into the "Strategic Research and Innovation Agenda" (SRIA 2020), has identified some goals that require also low TRL activities:

- development of fuel-flexible retrofit solution for existing power plants;
- research on combustion physics and dynamics for pure hydrogen and hydrogen blends (ammonia included) at gas turbine relevant conditions (TRL 2-3);
- development and demonstration of highly flexible combustion systems (0-100% H_2);
- development and demonstration of innovative and advanced solutions up to their commercialization.

Conclusions

Although the long history of gas turbines and their application in different sectors, the article stressed that some research and developments are required for their reliable and safe operation with increasing hydrogen content, to reach at least 80% by volume for a significant CO_2 reduction. **However,**

behind the technological effort required, the widespread diffusion and availability of H_2 is the real barrier, mainly linked to its production cost. Once accepted hydrogen as part of the solution to the climate change, transition to the "hydrogen society" can only happen starting to build the whole infrastructure and, in the authors' opinion, by using the cheap "blue hydrogen" in the short term, and the still expensive "green hydrogen" in the long term.

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2. Full Speed No Load.

Industry green transition: a catalyst for hydrogen economy

The use of hydrogen is one of the possible ways to decarbonise industry, and such a process may act as catalyst for the development of a “hydrogen economy”, exploiting the economic leverage of already existing industrial clusters. Potentially, hydrogen can be used for industrial heating, especially in hard-to-abate sectors that require high temperatures (such as the industry of steel, concrete, glass, ceramic, paper), and where direct electrification may not be the most effective or feasible alternative, as well as in the production of chemicals, petroleum refining and in the primary steel industry. In ENEA, research and development activities are mainly focussed on the process of Sorption Enhanced Reforming, while other numerous projects on hydrogen production technologies, such as biomass gasification, are being implemented.

L’utilizzo dell’idrogeno è una delle possibili vie per decarbonizzare il settore industriale e può agire da catalizzatore per lo sviluppo di un’ “economia dell’idrogeno”, sfruttando la leva economica di cluster già presenti. Oltre che per la produzione di prodotti chimici, la raffinazione del petrolio e l'industria siderurgica primaria, l'idrogeno può essere potenzialmente utilizzato anche per il riscaldamento industriale, soprattutto nei comparti “difficili da abbattere” che richiedono di fornire alte temperature (ad esempio i settori della siderurgia, del cemento, del vetro, della ceramica e della carta) e dove l'elettrificazione diretta potrebbe non essere l'alternativa più efficace o fattibile. Le attività di ricerca e sviluppo in ENEA si concentrano sul processo di Sorption Enhanced Reforming e sono in corso altri numerosi progetti sulle tecnologie di produzione di idrogeno come ad esempio la gassificazione della biomassa.

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by **Claudia Bassano, Stefano Stendardo, Giuseppina Vanga, Paolo Deiana (*)**

Implementation of hydrogen offers a solution to decarbonise industrial processes where reducing carbon emissions is both urgent and hard to achieve. A large share of the CO_2 emissions in Italy comes from the industry [1]. At 2017 45 % of the Italian greenhouse gas emission was allocated in hard to abate sector. **Switching to alternative energy and feedstock entails a high GHG abatement potential. Many of the industrial processes where natural gas or other fossil sources are used as feedstock would be replaced with renewable (green hydrogen), low-carbon hydrogen (blue hydrogen) and other green process.**
An immediate application in industry is to reduce and replace the use of carbon-intensive hydrogen in refineries, in the production of ammonia, of other chemical products and new forms of methanol, or to partially replace fossil fuels in iron and steel making processes. Currently in most industrial applications, hydrogen is provided by grey hydrogen production from conventional energy source that takes place on-site using natural gas reformers or coal/biomass gasifiers and feeds directly into chemical and industrial processes.
An immediate application in industry is to reduce and replace the use of carbon-intensive hydrogen in refineries, in the production of ammonia, of oth-

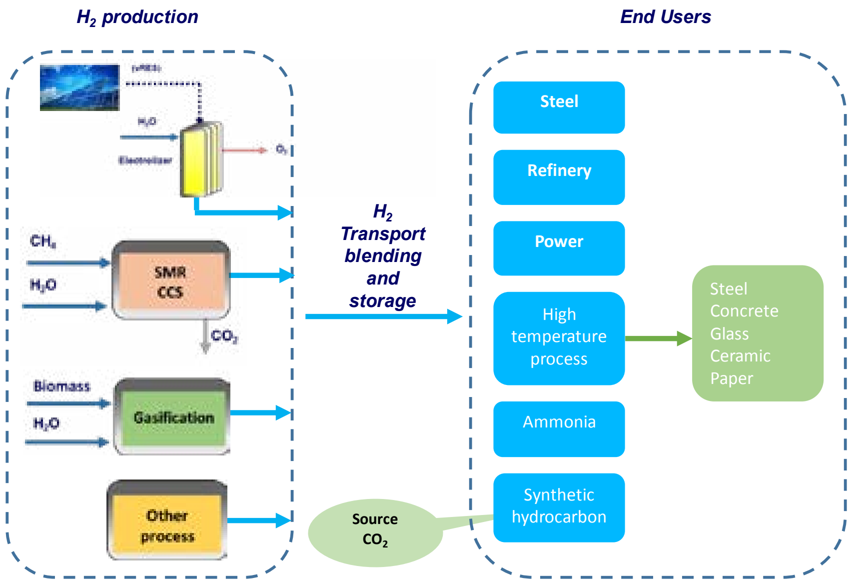

Fig.1 simplified scheme of hydrogen implementation in different industry sector

er chemical products and new forms of methanol, or to partially replace fossil fuels in iron and steel making processes. Currently in most industrial applications, hydrogen is provided by grey hydrogen production from conventional energy source that takes place on-site using natural gas reformers or coal/biomass gasifiers and feeds directly into chemical and industrial processes.
In industrial sector, in addition to the production of chemicals, petroleum refining and to the primary steel industry, hydrogen can potentially also be used for the industrial heating, especially for processes "hard to abate" that require to provide high temperature (for example industry of steel, concrete, glass, ceramic, paper) and where direct electrification may not be the most effective or feasible alternative, as reported in the European SPIRE 2050 Roadmap.
Development of hydrogen production and use in industry includes R&D projects, research infrastructures, pilot plants, first industrial deployment and integration of new technologies in existing industrial processes. Industrially relevant examples for the use of hydrogen replacing fossil feedstock are the production of low carbon steel by replacing coke coal with hydrogen and the use of renewable hydrogen or blue hydrogen in refineries.

Key technical challenges and R&D

Key technical challenges and R&D can be summarized as follow [2] :

- **Integrating variable electrolyser operation with continuous industrial processes, testing large scale electrolyzers.**
- **implementation of carbon capture and storage processes into steam methane reforming process.**
- **R&D of direct reduction iron process.**
- **H_2 burner components integrated into gas turbines**
- **Development of fuel flexible and 100 % H_2 burners and combustion chamber with low or zero NOx emission.**
- **Production of synthetic hydrocarbon and ammonia.**
- **Research in using hydrogen as energy carrier and feedstock within the industry**

In the short term in the transition phase, blue hydrogen, using CCS to make SMR-based hydrogen processes carbon neutral, could help significantly reduce industrial emissions in a timely and cost-efficient way and can prepare the ground for a wider hydrogen economy.
A revision of ETS market could create positive business cases. Cost development and competitiveness in case of use hydrogen to provide heat and power for industry and the grid is driven mainly from the CO_2 cost (e.g. ETS market) and by low hydrogen production costs.
Growing hydrogen demand in major industries offers the opportunity to create hubs that bring down the cost of low-carbon hydrogen pathways and kick-start new sources of demand. **Consequently, it's essential make industrial clusters the nerve centres for scaling up the use of hydrogen. It will be therefore necessary to fund large scale demonstration projects.**

Research and development activities in ENEA

In industrial hydrogen production processes such as coal gasification, methane steam reforming, water gas shift (WGS) reaction and biomass gasification, the emissions of CO_2 can be reduced by CO_2 capture. The goal of our research activity is to develop combined sorbent-catalyst materials (CSCM) for Sorption Enhanced Reforming (SE-SR) process. By combining processes (1)–(3) it is seen that the strongly endothermic steam reforming is thermally neutralized by carbonation reaction obtaining Eq.(4), therefore SE-SMR will be considered an energy efficient process. The CO_2 produced in SR(steam reforming) and WGS (water gas shift) is chemically fixed on site upon a high temperature sorbent, so that CO_2 emission is suppressed and thermodynamic equilibrium reactions are potentially brought to completion according to the Le Chatelier's principle producing high-purity H_2.

Steam reforming of methane
$CH_4+H_2O = 3H_2 + CO$
$\Delta H°_{298} = +206$ kJ mol^{-1} (1)

Water gas shift
$CO+H_2O = H_2 + CO_2$
$\Delta H°_{298} = -41.1$ kJ mol^{-1} (2)

CO_2 sorption
$CaO + CO_2 = CaCO_3$
$\Delta H°_{298} = -178$ kJ mol^{-1} (3)

Global reaction
$CH_4 + 2H_2O + CaO = CaCO_3 + 4H_2$
$\Delta H°_{298} = -13.1$ kJ mol^{-1} (4)

The best-known sorbent suitable for SE-SR process is CaO coming from naturally occurring minerals (limestone, dolomite) due to its low-cost, abundance, and non-toxicity. However, when the sorbent is subjected to repeated thermal cycles a sharply decline of reactivity of CaO lime versus CO_2 arises as a result of sintering of CaO particles that engenders severe damaging of pore structure. For this reason, in the last decade intense research activities have been devoted on to development of synthetic CaO-based sorbents owing to their high reactivity versus CO_2, fast carbonation/decarbonation kinetics, good cyclic stability, and relatively low cost of production [4]. Currently, the $CaO\text{-}Ca_{12}Al_{14}O_{33}$ system is the most studied among different synthetic sorbent materials that can be applied in various CO_2 sorption capture technologies.
The integration of both sorbent and catalyst in a single particle offers some advantages such as the lowering of the mass transfer resistance, the reduction of reactor volume, and the simplification of the system. In this context, the development of bifunctional materials with core/shell structure where a hollow shell is made of catalyst with sorbent nanoparticles in the interior is becoming a central topic in the field of reforming intensification process. In our work a combined $CaO\text{-}Ca_{12}Al_{14}O_{33}\text{-}Ni$ sorbent-catalyst material with improved CO_2 capture stability and catalytic activity to be used in SE-SR of methane process has been successfully prepared by a novel synthesis method based on a multi-step approach. According to this method a mixed calcium-aluminium oxide ceramic was at first prepared by wet mixing/sintering method and subsequently used both as spacer for CaO sorbent and as support for Ni catalyst. Finally, the synthesized $CaO\text{-}Ca_{12}Al_{14}O_{33}\text{-}Ni$ has been tested over ten consecutive reforming (600°C)/regeneration (750°C) cycles. The good performance of SE-SR of methane over ten consecutive reforming (600°C)/regeneration (750°C) cycles at $H_2O:CH_4=3:1M$ ratio using CSCM pellet has allowed to produce a H_2-rich (> 90%) gaseous stream with low concentrations of CO_2 and CO.
This work has been supported by the European Union within the 7th Framework Program under ASCENT(Advanced Solid Cycles for Efficient Novel Technologies www.ascentproject.eu)grant agreement no.608512 coordinated by ENEA. The ASCENT Work Package 4 (WP4) included ENEA, IFE(Institut for Energy, Norway), CSIC (Consejo Superior de Investigaciones Científicas, Spain), Marion Technologies(industrial partner, France),INERIS (Institut national de l'environnement et des risques, France),and University of L'Aquila (Italy) in cooperation with University of Strasbourg (France).

Projects and perspectives

Presently in ENEA there is a multidisciplinary technological know-how with skills that cover aspect of R&D on hydrogen utilization in industry. **ENEA is in charge of a 0.5 MWth pilot plant ZECOMIX (Zero Emissions of Carbon with MIXed technologies) whose key objective is the production of H2 water-gas shift or steam methane reforming process with simultaneous CO_2 capture.** A syngas can be produced in the ZECOMIX plant which is similar in composition to the off-gas leaving a blast furnace for iron and steel making process. This feature of ZECOMIX permits to demonstrate at TRL 7 the decarbonisation of off-gases produced in iron and steel mill via an environmental-friendly calcium based solid sorbent.
From 2018, this plant has been selected as a European Carbon Dioxide Capture and Storage Laboratory Infrastructure (ECCSEL). Being a member of ECCSEL consortium is a label of quality: it has been evaluated through a European process based on commonly agreed criteria and recognised as being of the highest standards and relevance to research and industry in Europe. **By means of the ECCSEL consortium, ZECOMIX is connected to a wider user group composed of the research and industrial communities as well as public services.**

ENEA is a member of the H2020 GICO (Gasification Integrated with Carbon capture and cOnversion) project coordinating by the University Gugliemo Marconi. In this project ENEA is the work-package leader of an innovative process for H_2 production from biomass gasification with simultaneous CO_2 uptake by CaO sorbent. The exhausted solid sorbents can be reused in several industrial processes (e.g. cement and bricks production, agglomerates) reducing the industrial wastes and making the H_2 production from biomass a more profitable option.
ENEA is coordinating also project on Systems for Flexible Energy via reuse of carbon (SFERO) within the Research Line "1.6 Efficienza energetica dei prodotti e dei processi industriali" of the Italian research programme

2019-2021: "Ricerca di Sistema" funded by the Italian Ministry of Sustainable Economic Development. The main objective of SFERO is the development of an efficient process for H_2 production from reforming of methane integrated with CO_2 chemisorption. The captured CO_2 will be reused in plasma reactor for renewable fuels production.

ENEA is participating as facility owner in the H2020 ECCSELRATE project coordinating by NTNU. The main target of this project is to develop marketing, access and services models for industry and SMEs in the field of carbon ca pture. ENEA will share the ZECOMIX plant for the demonstration of H_2 production from methane and syngas via carbon capture processes.

Future development projects may involve activities on laboratory scale and on prototype and pilot plant scale covering different TRL value (i.e. synthesis and test catalyst for SMR process, test on burners operated in hydrogen rich environments, improvements in catalytic reactions and chemical processes, use of renewable carbon feedstock, use of oxygen from electrolysis, dynamic operation capability etc.). In this contest, process and predictive analyses, technical economic and environmental feasibility studies will be carried out.

Conclusions

Industry implementation of hydrogen is one of the ways to decarbonise the industry sector especially "hard to abate" sector and can acts as catalyst for hydrogen economy deployment. Approximately 16 TWh/year of hydrogen is currently (2020) used in Italy in a wide range of industrial processes (mainly refining and chemical use) [3]. Moreover, hydrogen can replace fossil fuels as a feedstock in other industrial process (as a reducing agent in the steel manufacturing process) and can be used to produce liquid fuels, synthetic natural gas and important petrochemicals and also as an energy source for heat and power generation. **In order to achieve this transformation, large quantities of hydrogen at competitive conditions as well as appropriate conversion technologies and process adaptions are needed.** R&D actions can foresee demonstration projects proving hydrogen integration across key industrial processes and heat and power generation.

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The key role of PtG technologies in the Italian Energetic System

Power to Gas (PtG), namely the conversion of electric energy into gas, hydrogen or synthetic methane could allow European Countries to achieve the ambitious decarbonization targets foreseen in their energetic transition roadmaps. The paper underlines how those goals could be attained and the impacts over the Italian energetic system of the electric/gas network integration. The PtG technologies, their maturity, the challenges and the necessary habilitation actions are listed and analyzed. In this context, ENEA is developing several activities that cover different aspects of the value chain, starting from water electrolysis to methanation process. Currently in ENEA there is a multidisciplinary expertise on PtG that ranges from materials (membranes for electrolysers and fuel cells, catalysts for the chemical reaction of methane synthesis, microorganism for biological methane synthesis) to the study of processes at laboratory and pilot scale. Other activities are focused on modelling and simulation related to processes and plants and to the regulatory aspects of coupling electric and gas networks. The general approach involves experimental activities on different scales and TRLs as well.

Il Power to gas (PtG), ossia la conversione di energia elettrica in gas, idrogeno o metano sintetico, potrebbe consentire agli Stati Europei di raggiungere gli ambiziosi traguardi di decarbonizzazione previsti nelle loro roadmap verso la transizione energetica. L'articolo descrive come questi obiettivi possano essere conseguiti e gli impatti attesi sul sistema energetico italiano dell'integrazione delle reti elettrica e del gas. Le tecnologie alla base del PtG, la loro maturità, le sfide e le necessarie azioni abilitanti sono elencate ed analizzate. In questo contesto, l'ENEA sta sviluppando molteplici attività che coprono aspetti differenti della catena del valore, dall'elettrolisi dell'acqua al processo di metanazione. Attualmente l'ENEA possiede competenze multidisciplinari sul PtG che spaziano dai materiali (membrane per elettrolizzatori e celle a combustibile, catalizzatori per la reazione chimica di sintesi del metano, microrganismi per la sintesi biologica del metano) allo studio dei processi a scala di laboratorio o di pilota. Altre attività riguardano la modellistica e la simulazione in fase di progetto di processi e impianti e gli aspetti regolatori dell'accoppiamento delle reti elettrica e gas. L'approccio generale comprende attività sperimentali su scale e TRL differenti.

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by **Paolo Deiana, Paola Gislon, Claudia Bassano (*)**

European and national energetic roadmaps foresee a continuous growth of renewable power production [1,2]. The PNIEC [3] states to set the renewable target up to 30% of the gross final energy consumption. PtG, allowing the long-term, even seasonal, electric energy storage in 100% renewable vectors, its long distance transportation and distribution, favours renewable power penetration and exploitation. Other PtG impacts comprise the decarbonization of industrial and final energy user, especially of those hardly electrifiable, as some industrial and mobility sectors, and a larger sustainability, security and flexibility of the national energetic system.

The PtG technologies role is evidenced in "Documento di Descrizione degli Scenari Terna–Snam 2019" [4], the most ambitious scenario foresees a growing green gases demand, up to 6.5 Mm^3/year in 2040, shared between synthetic methane and hydrogen.

PtG refer to the conversion of energy from electrical to chemical, in the form of gaseous hydrogen (PtH – Power to Hydrogen) or other carbon compounds hydrogen-derived, such as methane (PtM – Power to Methane).

Figure 1 illustrates the large variety of PtH/PtM employment: the hydrogen from renewable power can be used locally in industrial processes, transported by a grid for mobility applications, converted into methane or again into power by feeding fuel cell systems, or can be stored.

Another benefit of PtG is the valorisation of the existing gas infrastructures, avoiding electricity grid implementations, through the electricity and gas networks integration, the sector coupling. Being the current gas grid and end-users immediately ready for synthetic methane use, **PtM can be considered an enabling technology toward the energy transition in the short term, particularly in Italy, where the gas grid is extended and capillary; moreover, it gives an opportunity to valorise unavoidable carbon dioxide emissions.**

PtG term refers to a set of different processes and technologies. The hydrogen production is attained by water electrolysis, at large energetic expenses. Currently three electrolytic processes can be considered market-ready: alkaline electrolysers (AEL), the most mature technology, polymeric membrane electrolysers (PEM), and the most re-

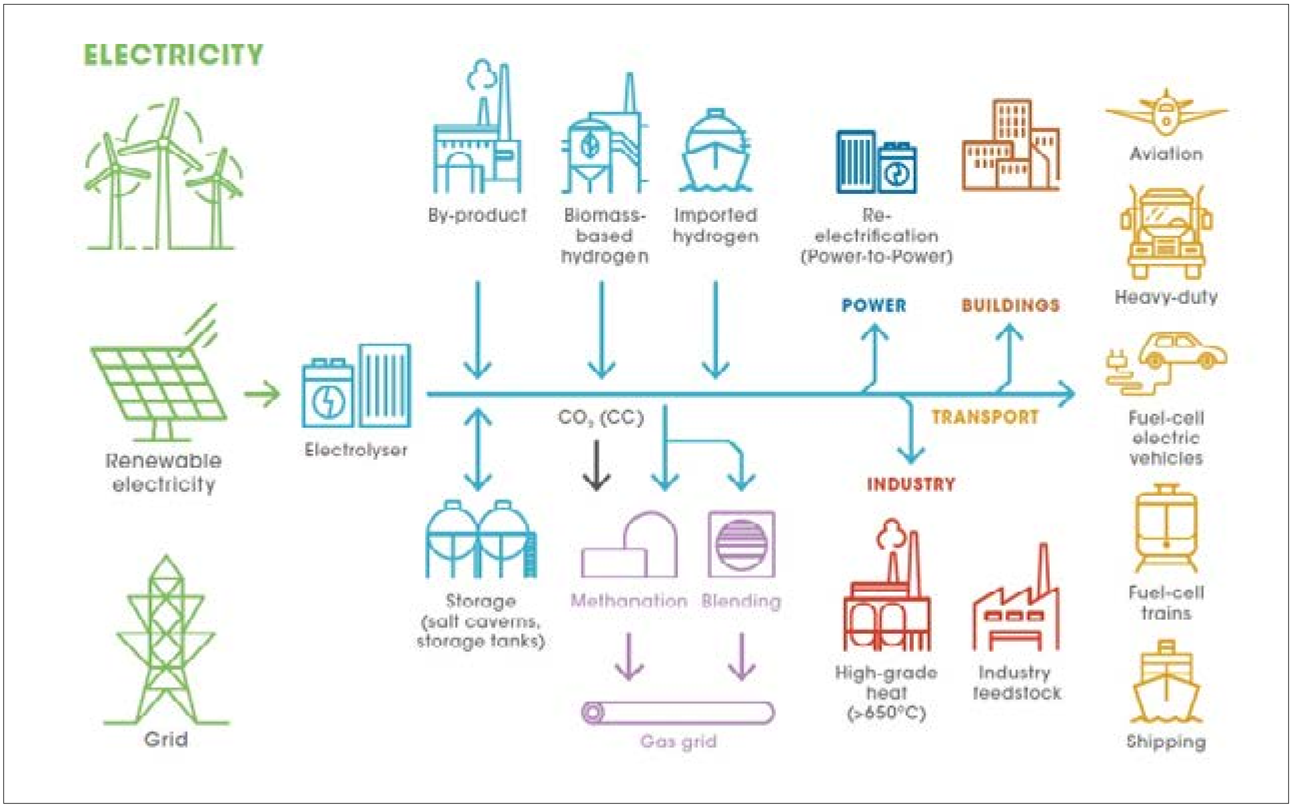

Fig.1 PtG technological value chain [Source: IRENA 2019]

Fig.2 MENHIR plant details and thermal imaging camera during a test

cent solid oxide electrolyzers (SOEC). AELs use an alkaline solution (KOH or NaOH) at atmospheric or slightly higher pressure; PEMs polymeric membranes for protonic exchange; SOECs work at 700-800°C, their strength is reversibility, they can return power to the grid if necessary.
The thermochemical methanation [5] is a catalytic (Sabatier) process: the reaction of H_2 with CO_2 to get synthetic natural gas at 250-550°C and elevated pressures; CO_2 can derived from biogas, syngas from gasification, industrial flues, or other. The reaction is highly exothermic, making temperature control the most challenging aspect. The valorisation of heat takes place for example in biogas upgrading plants, or industrial processes or district heating networks or greenhouses.
A second methanation process, the biological one, utilizes methanogen microorganisms, as Archaea, acting as biocatalysts at 20-70°C and pressure higher than atmospheric one.
PtG technological challenges include electrolyser development in dynamic regimes, heat valorisation for catalytic methanation, volume reduction for biological methanation, integration of the different technologies in an optimized PtG system.
Currently electrolysers efficiency is in the 65-85% range; the largest plants are decades of MWe, costs are about 650€/kWe for alkaline electrolysers and 950€/kWe for PEM. The declared goal of the next "European Green Deal" calls is to reach electrolysers plant sizes of 100MWe, consuming 49kWh/kg H_2 (67% efficiency) and 52kWh/kg H_2 (64%) for alkaline and PEM electrolysers respectively, and 480€/kW and 700€/kW CAPEX, respectively. The PtM process total efficiency is 5-8% lower than PtH; in a typical PtM plant, considering a 2500-3000€/kWe CAPEX, costs are generally split into 40% electrolyser, 20% methanation, 40% storage, engineering works and BOP.
The more expensive green hydrogen and methane costs with respects to fossil gases represent a definite drawback, to be overcame by government incentives, particularly in the assessment and technological development step.
Normative to get hydrogen utilization, transportation and storage feasible are under development. **A hydrogen and methane green origin certification and guarantee are welcome.**
Enabling actions should break technological, economic, financial and normative barriers: the role of governance, research and industrial stakeholders and their synergic involvement is crucial. Among the specific actions to be undertook to reduce the gap with respect to conventional technologies are the development and validation of demonstrative projects in small energy district and a dedicated research plan.

Research and development activities in ENEA

Power-to-Gas (both PtH e PtM) is a promising process ensemble that include different technologies with different TRL values, some of those are commercially available however their implementation in the power to gas chain is still being evaluated. Consequently, further R&I efforts are needed to reduce technology and non-technology costs, to improve performances and to promote technology deployment to market.
Currently in ENEA there is a multidisciplinary expertise on PtG that ranges from materials (membranes for electrolysers and fuel cells, catalysts for the chemical reaction of methane synthesis, biological process) to the study of processes at laboratory and pilot scale. Other activities are focused on modelling and simulation related to design of processes and plants and to the regulatory aspects of coupling electric and gas networks. The general approach involves experimental activities on different scales and TRLs as well.
Specifically, the activities focused on innovative electrolysis technologies (SOEC, MCEC and AEM) and on biological and catalytic methanation, processes are reported in other articles of this journal.
The MENHIR (MEthaNe and Hydrogen Infrastructure from Renewable)

facility dedicated to study the PtM process is under construction at Casaccia Research Center. It is an infrastructure aimed at optimizing different process features, such as catalysts, reactors type, heat management, temperature control and dynamic operation. Presently, even with commercially available methanation plants, research is considered still necessary to optimize different process features, such as catalysts, reactors type, heat management, temperature control and dynamic operation. The electrolyser dynamic operation remains a challenge, since variable loading and cycling operation can generate substantial performance losses and critical degradation of the constituent materials.
Moreover ENEA performs techno-economic evaluation of the whole PtG value chains for different feasible pathways and for the expected intermediate and final products. This analysis aims to evaluate replicability and scalability of PtG configuration considering the different value chain (different final use, sector coupling, geographic area, energetic scenario). In this way, business models aim to evaluate economic performance providing Levelized Costs of Hydrogen (LCoH), Energy (LCoE), methane LCoX. ENEA carry out assessment of the expected impacts of the project on end-users and the community by means of key performance indicators (KPI) as well.

The MENHIR plant

MENHIR plant is a modular, moveable and containerized facility. The facility is composed by an electrolyser and a methanation unit. The alkaline type electrolyser is able to produce hydrogen up to 4 Nm^3/h (24 kWe). The methanation section was designed to test catalysts, reactors type, able to work in cooled or adiabatic conditions, and process setups. The methanation section aims to produce a gas up to 1-2 Nm^3/h, ready to be injected in the gas grid. The experimental plant is equipped with several sensors and a data acquisition system suitable to monitor and control the main operating process parameters.
MENHIR is a plant suitable for: evaluating the dynamic behaviour of the singular components and of the integrated system (plant able to work at load between 20 % and 100%) testing different methanation catalysts and intensified reactor, testing different process methanation configuration (e.g. cooled or adiabatic reactor condition), testing methanation unit performance in different operating conditions of temperature, pressure, inlet flows, typical of the implementation in Power To Gas (start up, shut-down, stand-by e idle), testing upgrading methodologies (e.g. membranes).
The plant is also fully flexible in its modularity, so new hydrogen production systems, new reactors or processes, can be inserted into the infrastructure using the existing auxiliaries equipment. Finally, the plant is suitable to be implemented with other energy storage systems such as batteries to support the electrolyser or thermal storage for heat management of the methanation process.

Projects and perspectives

The reasons for the development of PtG in the Italian energetic system include strategic reasons as larger power network stability and a larger independence from foreign fossil energetic suppliers. In the Italian context, different stakeholders are already actively involved in PtG technologies, confirming the high level of interest and the possible positive industrial growing in the field. The PtG plants could carry benefits in the assessment of a new industrial chain. The different areas that could benefit are both the end-users and suppliers, as the energetic sector, particularly the energy from RES and gas producers the chemical, engineering industry and the heavy CO_2 emitters/producers.
Concrete actions to reduce the gap with conventional technologies can be found in the development of demonstrative plants, in a research plan aimed at overcoming the barriers, in a legislation that can accelerate the effective deployment and better define incentives to sustain creation of case studies. Over a longer period, it would be desirable to design and build infrastructures that involve the management and large-scale use of hydrogen and the storage of renewable energy in the form of gas.
Research Institutions can play a fundamental role in overcoming existing scientific and technological barriers and helping policy makers to take the necessary actions to encourage the use of technology on a large scale. The contribution of research should act synergically with the industrial world. In particular, ENEA, in its institutional capacity, is candidate to play an effective role in the development of the technologies involved in the PtG chain, contributing to the development of individual technologies, from the technological and regulatory aspect, acting as stakeholder aggregator.
In that field, ENEA has recently proposed the **Hydrogen demo Valley Project** aimed to create an infrastructural hub for testing and demonstration of hydrogen technologies. It will cover production, storage, distribution and utilisation of hydrogen (in blends with natural gas as well), for applications in the energy, industrial, residential and transport sectors.
The multifunctional infrastructure will be implemented in the Casaccia Research Centre of ENEA, north of Rome, to act as a breeding ground for hydrogen value chain technologies and services with the aim of accelerating their deployment in view of the energy transition and overall decarbonisation.
Beside this context, ENEA has signed two Collaboration Agreements with SNAM and SGI, among the most important TSOs in the gas sector in Italy. Moreover, ENEA and Confindustria

have signed a collaboration agreement that aims to develop industrial hydrogen value chains, innovative solutions and possible operational scenarios, through a strengthened collaboration between research and industry. **A working group of ENEA and MISE is running support activities for companies and defining a IPCEI hydrogen project.**

Conclusions

Power to Gas could allow European Countries to achieve the ambitious decarbonization targets foreseen in their energetic transition roadmaps. **The main features of a PtG introduction are the possibility to store electric overproduction from renewables and a complete fossil fuel replacement with green gases in every sector, from energy production to industry, from mobility to residential heating.** In this context, ENEA is developing several activities that cover different aspects of the value chain, starting from water electrolysis to methanation process. In a framework where PtG seems particularly attractive for Italy due to its already existing capillary national gas grid, ENEA has recently proposed the Hydrogen demo Valley Project and has in pipeline the realization of the MENHIR pilot plant.

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The role of hydrogen in European port ecosystems

Ports can play a pivotal role in the world's decarbonisation challenge as natural hubs for sector coupling and energy system integration. They could become the frontrunners of the energy transition, if port authorities and industry sectors join forces. Hydrogen technologies and fuel cell technologies can help ports to reduce pollution and increase operational efficiency in all the sectors involved. Consequently, these innovative technologies have generated considerable interest from ports around the world, even though the actual experiences carried out so far are very few but effectively increasing. ENEA is actively involved in H2Ports project (www.h2ports.eu) as linked third party of ATENA Scarl, facing with the first European application of hydrogen technologies in port handling equipment: the main activities are focused on the prototyping, piloting and deployment fuel cell equipment for non-road applications into real port operations. H2Ports aims to boost the transition of the European port industry towards an effective low- carbon/zero-emission and safe operative model, by piloting, evaluating and demonstrating new fuel cell technologies oriented to increase energy efficiency, decarbonisation and safety of port terminals.

I porti possono svolgere un ruolo fondamentale nella sfida mondiale della decarbonizzazione, essendo degli hub reali dove poter dimostrare con successo il concetto di sector coupling e dell'integrazione del sistema energetico. Le tecnologie dell'idrogeno e delle celle a combustibile possono dare un contributo fondamentale per ridurre l'inquinamento e aumentare l'efficienza di tutti i settori che operano in ambiente portuale. Questi sistemi innovativi hanno riscosso un notevole interesse da parte degli operatori del settore portuale di tutto il mondo, anche se ad oggi esistono poche esperienze concrete svolte. L'ENEA è attivamente coinvolta nel progetto H2Ports (www.h2ports.eu) come terza parte di ATENA Scarl; il progetto ha l'obiettivo di dimostrare la prima applicazione europea delle tecnologie dell'idrogeno nei mezzi utilizzati per la movimentazione delle merci in ambito portuale; le attività principali sono focalizzate sulla prototipazione, implementazione e testing di mezzi con celle a combustibile utilizzate per operazioni portuali. H2Ports mira a promuovere la transizione dell'industria portuale europea verso un modello operativo efficace ed a basse emissioni di carbonio, dimostrando la fattibilità di nuove tecnologie delle celle a combustibile orientate ad aumentare l'efficienza energetica, la decarbonizzazione e la sicurezza dei terminal portuali.

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by **Viviana Cigolotti,** ***Energy Storage, Batteries and Hydrogen Production and Utilisation Technologies Laboratory***

The European Union counts in total over 1400 ports (fig.1) and has many direct connections with about 850 ports in the Far East and almost 600 ports in South and Central America. In total, these **ports cover the handling of 3.6 billion tons of freight and 410 million passengers** (2018 data). The average CO_2 emissions in EU ports, both taking into account emissions under control of the Port Authority (such as buildings, lighting, OPS services, etc.) and those from external partners operating in the port (companies, ship owners and operators, port handling activities operators, etc.), count for about 150 kton per year, thus reaching a total emission by the 1400 EU ports of 210 Mton per year. This means that **about 4.7% of the total CO_2 emissions (4.500 Mton, fig.2) in Europe are directly linked to emissions in and by the ports.**

A real transition in the area of ports from fossil fuel based energy use towards energy vectors based on Renewable Energy Sources (RES) is needed and will have a relevant impact, given that waterborne transport is responsible for about 13% of all EU transport GHG emissions. In addition, **since waterborne transport accounts for about 90% of global trade, the importance to help this sector to initiate its transition towards zero emission waterborne transport will bring positive impacts on climate change.**

Fig.1 Location (blue dots) of the 1400 ports in the EU [1]

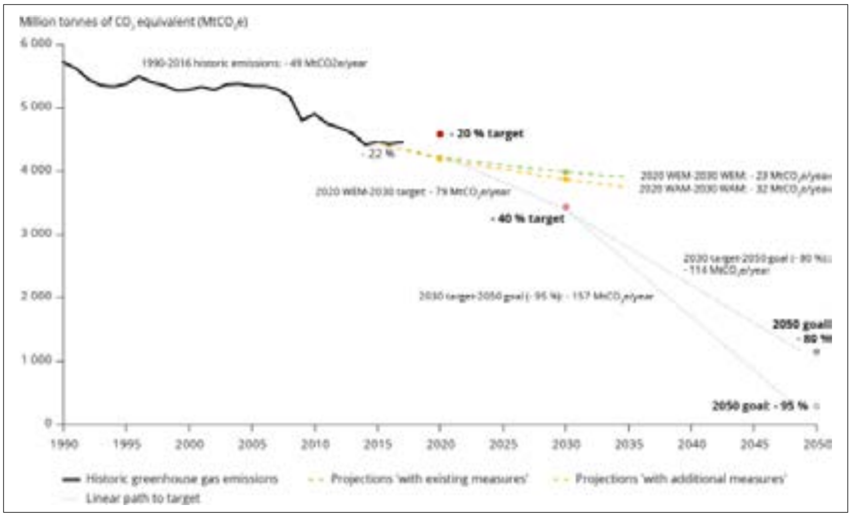

Fig.2 EU-GHG emission historical data and set targets [2].

Hydrogen and fuel cell technologies have proven their performance in several applications, including buses, trucks, cars, forklifts and even passenger trains. Differently, **the use of hydrogen-powered fuel cells for ship propulsion is still at an early design or trial phase with applications in smaller passenger ships, ferries or recreational crafts. The use of hydrogen shows great promises in decreasing ship-generated carbon emissions.**

Making the transition to a new energy source is a major challenge. In the case of fuel cells for marine vessels, **the main hurdles are in the refuelling infrastructure and hydrogen availability in ports**. Before operators can power their vessels using fuel cells, hydrogen supply and fuelling infrastructure needs to be further developed. In the nearer timeframe, hybrid battery/fuel cell applications are viable for certain type of vessels, such as ferries, cruise and river vessels.

Research and development activities in ENEA

ENEA is actively involved in H2Ports project (www.h2ports.eu), facing with the first European application of hydrogen technologies in port handling equipment. ENEA is participating to this European project funded by FCH JU as partner of **ATENA scarl** (www.atenaweb.com) a Research and Technology Hub for Energy and Environment composed of Universities, Research Institutes, and Private Companies mainly based in Campania Region.

H2Ports' main activities are focused on the prototyping, piloting and deployment fuel cell equipment for non-road applications into real port operations. This project will demonstrate and validate in real port environment two innovative solutions based on FC technologies and a hydrogen mobile supply station specifically designed for the project, at the Port of Valencia. A Reach Stacker to be tested in MSC Terminal Valencia and a Yard Tractor to be tested in Valencia Terminal Europa (part of Grimaldi's group) have been selected as those specifically fitted to the use of hydrogen in port facilities. The project will run the equipment on a daily basis during two years of real operational activities and will analyse ways of improving the energy efficiency, performance and safety of operations with Fuel Cells port equipment. The project will also take into account transversal issues such as the social acceptance, regulation, future roll out

Fig.3 Yard Truck for port operation [3].

of the technology on a full commercial basis, and the raise of awareness of the potential of hydrogen adoption as an alternative fuel in ports.
H2Ports aims to boost the transition of the European port industry towards an effective low- carbon/zero-emission and safe operative model, by piloting, evaluating and demonstrating new FC technologies oriented to increase energy efficiency, decarbonisation and safety of port terminals. The main objective of the project is to provide ports with FC technologies and hydrogen use as zero-emission fuel through innovative solutions to be ready for market deployment by the end of the project.
As starting point, H2Ports will take on-going developments that reference port equipment manufacturers have been developing in the last years. These prototypes implement eco-efficient technologies able to reduce the carbon footprint of European ports, which are responsible for a major share of GHG and pollutant emissions generated by the use of diesel powered heavy-duty machinery in 24/7 cycles.
ATENA, together with its members involved in this project (ENEA, University of Naples Parthenope, University of Salerno and Cantieri del Mediterraneo spa) is responsible for developing, realizing and testing a FC Yard Truck in a real-life operation site with the aim of decarbonising port areas (fig.3). The FC Yard Truck will be tested by Grimaldi Group in its Valencia Terminal Europe, Spain.
ATENA selected a hybrid power unit architecture to develop the no-emission Yard Truck based on a Plug-in Fuel Cell Electric Vehicle platform.
The main objective of ATENA and its members activities in H2Ports project are related to:

- Introducing a clean energy solution for port operations within ships, as Yard Truck need to load/unload cars to/from ship car carriers;
- Diversifying the energy options for the port-logistic sector in order to reduce its dependency from fossil fuels;
- Deploying in the market a comprehensive set of low carbon and eco-efficient equipment for European Port Ro-Ro Terminals;
- Developing a commercial strategy and business plans for the market roll-out of the proposed solutions;
- Defining recommendations, best practices and policies based on the project results to ensure effective roll-out along EU ports.

H2Ports will facilitate the generation of significant impacts on the European port-logistic industry, a sector where application of hydrogen and fuel cell technologies to port-equipment and non-road machinery is currently inexistent in real operation environments. Moreover, H2Ports will bridge the existing gaps between research development and industrial application in this strategic sector, thus contributing to implement and deploy clean and low-carbon technologies in the port-logistic sector.

Projects and perspectives

Maritime transport and its logistic infrastructures (maritime ports, inland waterways, logistics platforms, etc.) are essential to keep the European Union in the leading position of world-developed areas. **The impact of this strategic sector in the quality of life of European citizens and in the EU competitiveness is crucial, as maritime transport and the port sector is a powerful key driver for job creation and economic welfare. Promoting innovation on efficiency and sustainability of seaports is a fundamental issue.**
The significant economic growth before the global financial crisis and the increase of foreign trade cargo volumes have driven maritime ports into increasing their capacities from all perspectives.
Infrastructures, services and related equipment have achieved a significant development of capabilities and complexity. This evolution has provided re-

markable benefits for the performance of port logistics. However, **important negative effects like operational inefficiencies remain, resulting in increased energy consumption, Greenhouse Gas (GHG) and pollutant emissions among other externalities due to the intensive use of fossil fuels.** These facts reflected on the "EU Freight Transport Logistics Action Plan" and on the "European Ports Policy Communication" still remain valid:

- Congestion in some parts of the European transport system is negatively affecting costs and time of transport and increasing fuel consumption. Freight transport needs to provide its contribution in addressing the EU's climate change targets and reducing pollutant emissions and noise.
- Freight transport is highly dependent on fossil fuels, a large proportion of them being imported.
- A major technological change marked by the development of container transport, more effective, faster, safer, and cleaner in technology and social issues is required from ports and the cities hosting them.

In the port sector, more than 250 container terminals are currently operating in European countries.
More than 100 million TEUs (Twenty-Foot Equivalent Unit), were overall handled in 2017 in European seaports, resulting in the generation of approximately 1.3 million of CO_2 emission tonnes per year.
This amount of GHG emissions is not included in the EU Emissions Trading System, generating remarkable external costs and it is not properly accounted for the impact on European economy and citizens' quality of life.

High environmental footprints

Facilitating the transition of the existing European port terminals towards low carbon and zero local emissions operative models is a challenging goal that should be promoted with the aim of achieving Europe's 20/20/20 objectives.
Urban air quality, noise pollution and their associated impacts continue to rise up the political and public agenda, with an increasing number of cities and regions pushing for an outright ban on the use of fossil fuels and the promotion of cleaner alternatives. Whilst some see this just as a first step pushing to a low or zero emission urban economy, it is important to take into account all the potential sources of pollutants. In this scenario, the port is a non-negligible actor.
Port facilities are typically located near cities or residential areas, having environmental impact in terms of air and water quality, noise and emissions. To meet regulatory requirements for urban air quality and the establishment of low emission zones within port cities increasingly requires to address emissions from heavy duty port applications in addition to road transport.
The environmental footprints from ports that are close to urban centres are high, not only due to shipping with large diesel engines, but also due to the large number of machineries, vehicles and cranes that move goods within a port. Emissions from port container operations associated with electric power are estimated to contribute approximately 10% of the total port GHG emissions (CO_2) while emission caused by road transport within port areas typically accounts for up to 30%, with the remaining majority of emissions caused by ships generators. Concerning port operations, rubber tired gantry cranes, yard trucks and material handling vehicles dominate fuel consumption (fig. 4).
Some projects supporting the deployment of battery electric vehicles or LNG fuelled vehicles have proven effectiveness to reduce fuel consumption and to enhance port operation. With increasing focus on both local and global emissions, zero emission solutions able to increase current battery electric propulsion technology or cable reel electric supply are required. For such applications, the suitability and viability of hydrogen and fuel cell technologies should be assessed.
Based on this assessment, most promising solutions should be developed and validated in real operational fields, including logistic solutions for hydrogen refuelling and combining fuel infrastructure with supplies to other local users.
Hydrogen and FC technologies can improve autonomy and charging time problems in the short term with the adoption of automotive technologies on board of port vehicles for various applications (Yard Tractors, Reach Stackers, forklifts, etc.). The adoption of hydrogen technologies could have an economic advantage in the port environment that consider at the same time shore mobile applications, on board applications and semi-station-

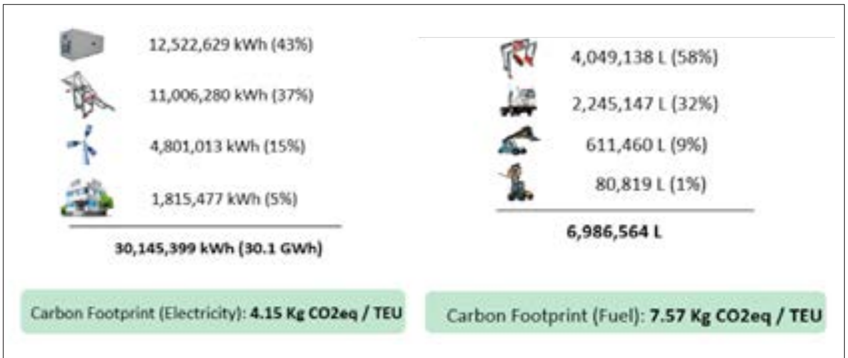

Fig.4 Energy Profile of Container Terminals. Electrical and Fuel Consumption [3].

ary APU (auxiliary power unit) support systems that may be used, for example, to provide shore based electrical power to ships.

Conclusions

Ports are key elements of the European maritime economy, in terms of trade, goods and people's movement. At the same time, **maritime transport is a source of growing concerns since it brings relevant greenhouse gas emissions.** The most critical issues are related to the emissions produced by large ships at dockside, noise, pollution and vibrations produced by the activities in the port area and the handling of goods. **It is essential to identify the key strategies for a systemic approach to the decarbonisation of ports and maritime sector, highlighting best practices and constraints to be overcome**. These actions include energy efficiency of the ports, the electrification of consumption, the development of intermodal logistics based on railway connections with ports, the conversion of naval fleets with vehicles with a lower environmental impact and the digitization of port logistics systems.Ports are places where an excess of renewable energy will be likely available. Therefore, industrial areas near these ports are possibly the first places to benefit from excess renewable energy sources. Converting this power into hydrogen through electrolysis might first become economically feasible in the port areas, while industry can benefit from the products hydrogen, oxygen, heat.

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ENEA Hydrogen Valley, towards an infrastructural hub in Italy

The ENEA Hydrogen demo Valley project aims to create an infrastructural hub for testing and demonstration of hydrogen technologies covering production, storage, distribution and utilisation of hydrogen and blends of natural gas and hydrogen, for applications in the energy, industrial and transport sectors. The multifunctional infrastructure would be implemented in the Casaccia Research Centre of ENEA, north of Rome, to act as a breeding ground for hydrogen value chain technologies and services with the aim of accelerating their deployment in view of the energy transition and overall decarbonisation. The project kicks off with a 14 million euro investment with Mission Innovation funds and will involve universities, research institutes, associations and companies.

Il progetto ENEA Hydrogen demo Valley mira a creare una infrastruttura sperimentale per il test e la dimostrazione delle tecnologie dell'idrogeno che coprono la produzione, lo stoccaggio, la distribuzione e l'utilizzo di idrogeno e miscele di gas naturale e idrogeno, per applicazioni nei settori energetico, industriale e dei trasporti. L'infrastruttura multifunzionale sarà implementata nel Centro Ricerche Casaccia dell'ENEA, a nord di Roma, per fungere da terreno fertile per le tecnologie e i servizi appartenenti alla catena del valore dell'idrogeno con l'obiettivo di accelerarne la diffusione e l'utilizzo in un'ottica di transizione energetica verso la completa decarbonizzazione. Il progetto parte con un investimento di 14 milioni di euro con fondi Mission Innovation e coinvolgerà università, istituti di ricerca, associazioni e imprese.

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by **Paolo Deiana, Stephen McPhail, Giulia Monteleone (*)**

Hydrogen is expected to become one of the building blocks of a low-carbon economy. Several international hydrogen projects, more than 250 funded by the FCH-JU under the FP7 and Horizon 2020, still in progress or already concluded, have made it possible to develop and validate, even in a real environments, single technologies and system solutions as well as to create an extended market of hydrogen ranging from the diffusion of uses in the thermal sector to mobility and industry, or even to address transversal issues such as standardization, legislation and certification, but often without a fully integrated vision.

In parallel with these initiatives, so-called **Hydrogen Valleys** (localized, large-scale integrated "ecosystems" based on hydrogen as a common vector), co-financed by the European Commission, **are under construction especially driven by the industrial sector, in various European countries, aiming at the implementation of hydrogen produced from renewable sources** [1,2]. Among these we can mention: the **Northern Netherlands Hydrogen Valley** initiative, with the development of a 20MW electrolyser and the production of methanol; **Rhine-Neckar in Germany, mainly dedicated to mobility; Leeds in the United Kingdom**, where the H21 project aims to decarbonise the gas network by substituting increasing percentages of hydrogen for methane to power both domestic and industrial heat users; the H4Heat project in the

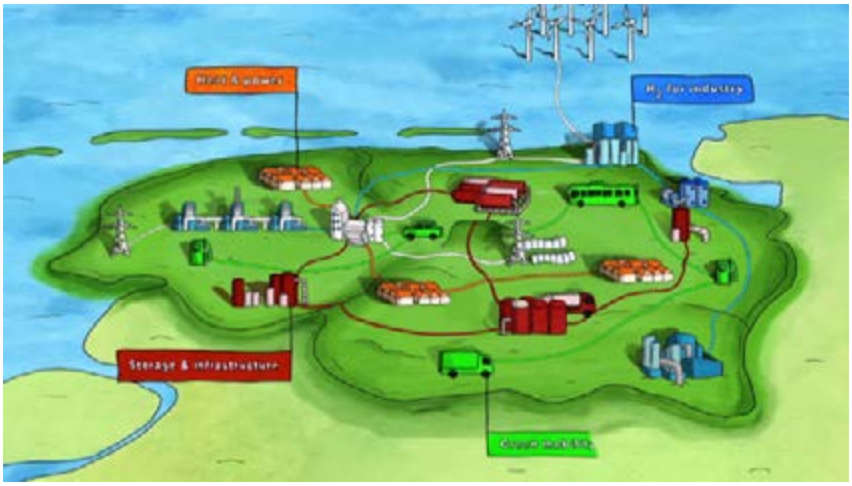

Fig.1 Hydrogen Valley sketch (Source: NewEnergyCoalition NL)

United Kingdom focused on the economic feasibility and safety related to the use of CH_4 / H_2 mixtures instead of NG. **The topic has gained momentum in Italy as well. Multifunctional demonstrators of a hydrogen ecosystem, of significant size, integrated with real users, are however not yet present in Italy. In Bolzano there is the only Italian hydrogen fuelling station open to the public (for vehicles at 350 and 700 bars), which supplies a fleet of about 20 buses and 15 cars. Near Capo d'Orlando (Sicily) there is a small-scale infrastructure, managed by the National Council for Research (CNR), focused on green mobility with hydrogen produced by photovoltaics, for a minibus and a number of hydrogen-powered pedal assisted bicycles.**

At industrial level, SNAM carried out an experimental test campaign near Contursi Terme (near Salerno) on the use of up to 10% hydrogen mixed with natural gas, transported through a section of commercial gas pipeline and serving two industrial thermal generation users [3]. **In Troia (in the Apulia Region), as part of the INGRID and STORE & GO projects, the operation of a pilot plant for the production of hydrogen from electrolysis** (1MWe) was tested and verified, with the storage of hydrogen in gaseous form and in metal hydrides, used in refuelling stations and fuel cells, and, with the aid of CO_2 capture from the air, in the production of synthetic methane, with liquefaction of the gas produced [4]. After conclusion of the mentioned projects, the plant is not currently in operation.

At national research level, CNR and ENEA collaborate in the development of new technologies related to the hydrogen supply chain, with particular reference to Power to Gas applications, as part of the Three-Year Research Plan (PTR) of the "Research on the Electrical System" (RdS) - Program Agreement (AdP) with the Ministry of Economic Development. In this context, ENEA proposed the creation of an integrated Hydrogen Demo Valley (within Casaccia, one of its research centres spread all over Italy) that will be funded by the Ministry of Economic Development in the framework of the Mission Innovation challenge on Renewable and Clean Hydrogen. **The project kicks off with a 14 million euro investment with Mission Innovation funds and will involve universities, research institutes, associations and companies, to boost the energy transition and decarbonisation.**

Research and development activities in ENEA

Within the Casaccia Research Centre of ENEA two gas pipelines will be laid down, fully equipped with auxiliaries and serving various end uses: one pipeline for pure hydrogen and the other for blends of natural gas and hydrogen. These pipelines will connect the sources of hydrogen production (driven by renewable energies) with the end use applications distributed throughout the centre to give rise to a true hydrogen ecosystem.

Specifically, a 200 kWp photovoltaic plant will be installed coupled to a 200 kWe electrolyser for the generation of green hydrogen to be used in pure form or blended with natural gas in the respective pipelines. Innovative systems for hydrogen production will be identified and implemented (solar reforming, high-temperature electrolysis, etc.) that can be hooked up to the pipelines. End use applications will consist of boilers, a microturbine and fuel cells for blend utilisation, and of a hydrogen refuelling station (HRS) for the pure hydrogen, as a mobility hub for people and goods within and outside the centre, as well as heat and power and storage applications.

A real hydrogen network will therefore be developed with the aim of testing diverse technologies as well as operation strategies for supply and demand matching, as well as to provide R&D and engineering services for industrial players in need of to-scale validation of their products in a holistic environment. A network of sensors will be introduced for the monitoring of the pipelines and, at a higher level, an all-encompassing system for data acquisition and analysis (HW and SW), both for integrated management of the Hydrogen Demo Valley and for categorizing information in view of possible replication in similar contexts.

Finally, in-depth studies, analyses and engagement will be carried out vis-àvis the regulatory and normative dimension of the Hydrogen Demo Valley, in order to systematically address safety matters, permitting and other administrative procedures, as well as public acceptance of hydrogen in all its aspects.

Projects and perspectives

The main goal of the project is to create an integrated infrastructure that aims to demonstrate the feasibility, functionality, sustainability, resilience and safety of a hydrogen-based ecosystem, as well as to offer industry the possibility to experiment and validate, in a dedicated ecosystem, the technological solutions with different TRLs, on a significant scale.

Specifically, it is planned to build and operate multifunctional infrastructures that will allow, with a technology neutral approach, the demonstration and integration of hydrogen technologies to help achieve energy transition objectives in the short and longer term.

The objective is therefore to create and test, within this framework, the integration of processes and infrastructures relating to different links in the supply chain:

- **production of hydrogen** from electrolysis through mature technologies to ensure adequate hydrogen production, by coupling the use of renewable energy produced on site with electricity of certified renewable origin coming from the grid;
- **production of hydrogen** from various energy sources with emerging technologies and in the pre-commercial phase according to industrial needs and requests;
- **transport of hydrogen** blended with NG through a dedicated gas pipeline built for the experimentation of CH_4 / H_2 mixtures in different percentages, by injecting hydrogen into the gas network, in order to evaluate the response of the network and the performance of connected utilities as well as the retrofit adaptation of conventional gas transport networks for similar applications;
- **transport and distribution of pure hydrogen** through a dedicated hydrogen pipeline;
- **construction of a direct refuelling station for hydrogen-powered vehicles** dedicated to the movement of people and goods (buses, cars, forklifts);
- **production of electricity from pure hydrogen and in a CH_4/H_2 mixture**, with fuel cells (high-efficiency stationary applications) and with gas micro-turbine systems fed with CH_4 / H_2 mixtures;
- **validation of innovative components (sensors, flow meters, etc.)** and systems for data acquisition, remote management and supervision of components and sub-systems;
- **production of 100% renewable synthetic methane from green hydrogen** and CO_2 of biological origin, with a view to promoting the transport and distribution of renewable gases in the network (in perspective of seasonal geological accumulation) and towards users;
- **separation of hydrogen from the CH_4 / H_2 mixture** upstream of the end user, in order to leverage a sin-

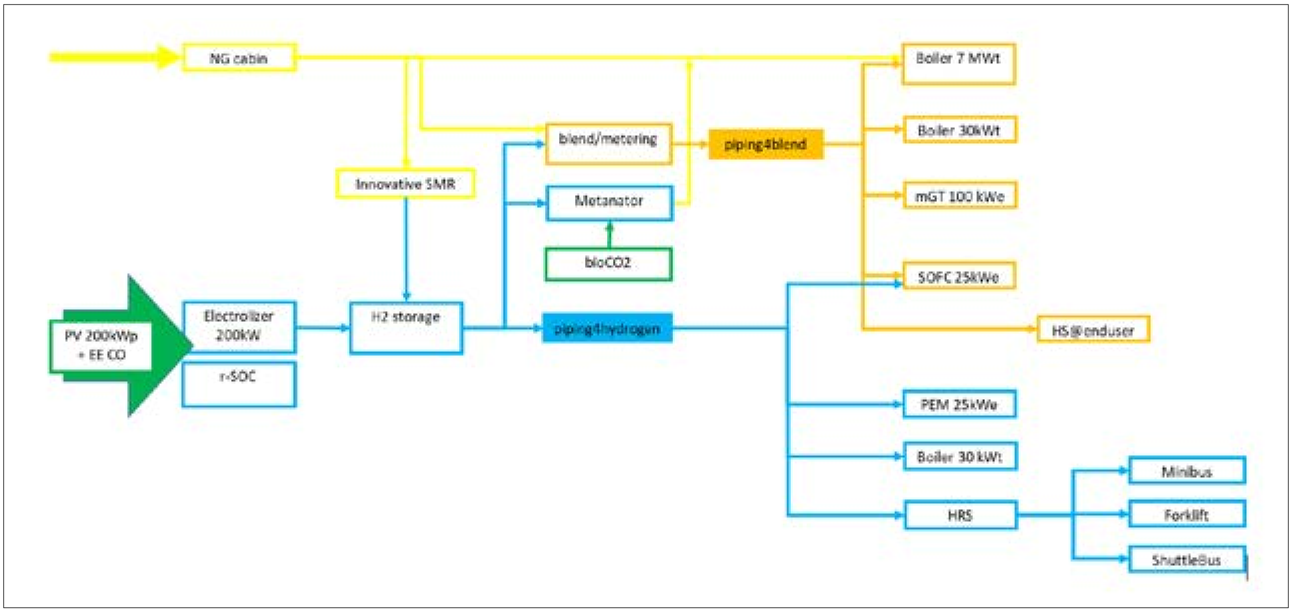

Fig.2 HV@ENEA Casaccia main process flow diagram

gle gas network for CH_4 / H_2, pure hydrogen and pure methane mixtures.
- **studies aimed at evaluating the performance of materials and components** to be used for the distribution of mixtures with hydrogen in the current methane distribution network of the R.C. ENEA Casaccia, through non-destructive tests and checks and through the implementation of a "material test platform" within an appropriate online section of the pipeline.

Parallel and transversal objectives are:
- **definition of guidelines in the legislative,** regulatory, administrative, and authorization fields, as well as information and training actions to promote public acceptance of hydrogen in collaboration with the National Department of Firefighters;
- **identification of enabling technologies,** development of business models and creation of professional figures that favour the development of the hydrogen economy; analysis of the impacts in terms of new professional figures and employment growth.

Conclusions

The ENEA Casaccia Research Centre is a geographically circumscribed area suitable for the creation of a hydrogen ecosystem that, at the same time, represents a replicable cluster for the implementation of integrated projects for production, transport and use of hydrogen based on coordinated management strategies. **In the timeline of three years, the main result of the project will be the creation of a multipurpose platform for testing and validation of technologies related to the hydrogen supply chain as a whole**. The expected results will be of a systemic nature, but will also focus on improving performance and the optimized management of each individual component, also as a function of the overall system performance. Another important result will concern the acquisition and processing of data for monitoring the operating status and predictive diagnostics in the field of the entire infrastructure and individual components and subsystems.

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The role of hydrogen in the circular management of wastewater treatment plants

Hydrogenotrophic methanation process is an interesting solution to improve the sustainability of the biogas upgrading process in wastewater treatment plant. By using hydrogen as energy carrier, hydrogenotrophic methanogenesis ensures renewable energy production and the reduction of GHG emissions. ENEA carry out R&D activities aimed to implement circular management practices and sustainable technologies in wastewater sector, which allows the resource recovery from the sewage sludge treatment.

Il processo di metanazione idrogenotrofica è una interessante applicazione per migliorare la sostenibilità del processo di upgrading del biogas negli impianti di trattamento delle acque reflue. Attraverso lo sfruttamento dell'idrogeno come vettore energetico, la metanogenesi idrogenotrofica garantisce una produzione di energia rinnovabile la contestuale riduzione delle emissioni di gas serra. L'ENEA svolge attività di ricerca e sviluppo finalizzate all'implementazione di pratiche di gestione circolare negli impianti di depurazione e tecnologie sostenibili che consentono il recupero di risorse dal trattamento dei fanghi di depurazione.

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by **Antonio Giuliano, Luigi Petta (*)**

In Italy wastewater treatment sector is still largely based on dissipative models. Although generally complying with the effluent standards set by Italian legislation, the most of small-medium sewage treatment plants can be considered as energy-intensive infrastructures, lacking in technologies able to guarantee an adequate resource recovery during the various treatment steps, especially those applied for sludge treatment [1].
On the other hand, recent industrial and scientific developments in wastewater sector point out the potential to turn existing municipal wastewater treatment plants into strategic facilities, widely spread throughout the national territory, and able to provide efficient resources recovery through the interaction with several productive sectors, in accordance with the pillars of the circular economy [2].
Among the processes applied for sewage sludge treatment, the anaerobic digestion is adopted in most of large size wastewater treatment plants, aiming to the residual organic matter stabilization and ensuring at the same time renewable energy as biogas (approximately, 60% CH_4 and 40% CO_2) for *in situ* production of electricity and/or thermal energy. The amount of biogas produced from excess sludge digestion may ensure a significant contribution in the overall wastewater treatment energy and economic balance.
Nowadays, national energy policies encourage biomethane production from biogas upgrading and cleaning processes. The produced biomethane, once ensured the compliance with quality requirements fixed by the national regulation, can be exploited as a replacement or additional gas in transport and distribution networks.
Such approach, also involves further process efficiency measures aimed, on the one hand, at maximising the methane conversion yields

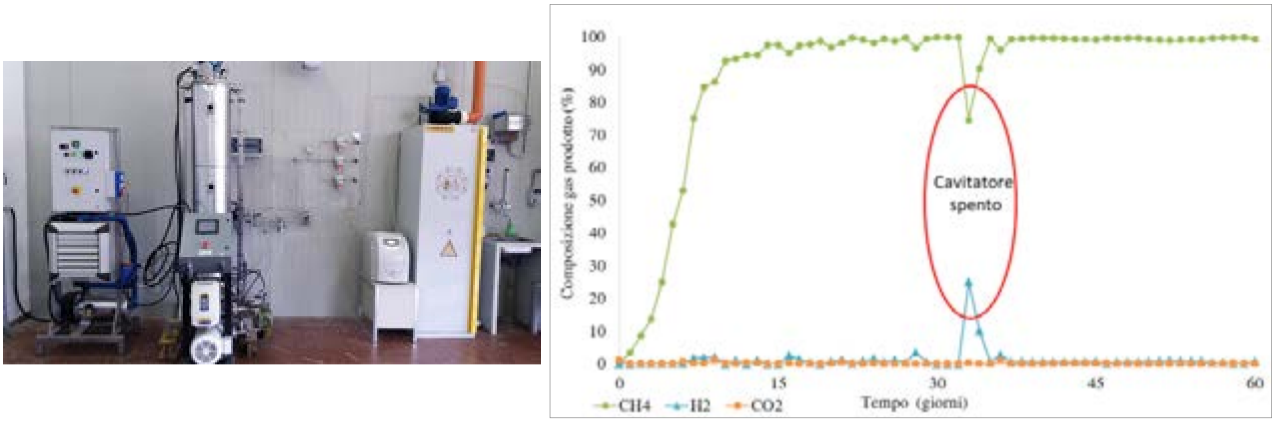

Fig.1 Hydrogenotrophic methanogenic reactor (1a – image on the left) and outlet gas composition (1b – chart on the right).

of sludge, e.g. through the inclusion of pre-treatment phases and, on the other hand, at ensuring a higher exploitation of the anaerobic digestion process due to the possible interaction with the waste management sector, e.g. through the co-digestion of sewage sludge with other biodegradable waste, such as the organic fraction of municipal solid waste (OFMSW) coming from separate collection. [4]
Among the opportunities to optimize the anaerobic digestion process in wastewater treatment facilities in terms of both energy efficiency and reduction of GHG emission, the application of processes involving the exploitation of hydrogen (H_2) as energy carrier for biomethane production represent a very interesting and promising option. Such approach provides a possible link between the wastewater treatment sector and the gas network as well the transport sector, representing an example of circular economy. Furthermore, this strategy is fully in line with the main drivers for technological development given by the current European policies (i.e. Green New Deal) which encourage the use of hydrogen gas as energy carrier to lead the transition towards carbon neutrality. [5]

The hydrogenotrophic methanation process

In this regard, one of the most interesting technologies is represented by the biological hydrogenotrophic methanation (BHM) process, based on the ability of some specialised microorganisms – present in the most extreme natural ecosystems characterised by high temperatures and the absence of oxygen – to use hydrogen to catalyse the conversion of carbon dioxide (CO_2) into biomethane (CH_4), which can be used to replace natural gas for a variety of end uses. The BHM process can guarantee the capture and conversion of CO_2 flows into methane, representing an alternative to current upgrading technologies (based on chemical-physical processes and highly energy intensive) and being able to contribute to reduce GHC emission in accordance with national decarbonisation strategies.
Despite the relevant potential application, one of the main factor still limiting the large-scale application of the BHM process is given by the need to increase energy efficiency of the process, overcoming the technical barriers represented by the low hydrogen solubility in aqueous solutions and the consequent constraint to ensure its transfer to the hydrogenotrophic microorganisms present therein. [7]
The BHM for biogas upgrading to biomethane is one of the biotechnological process tested and developed by ENEA SSPT-USER-T4W (Laboratotory of technologies for efficent management of water and wastewater), which carries out R&D activity on material and energy recovery from urban and industrial wastewater.
The technical feasibility of the BHM coupled with an innovative gas-liquid mass transfer system based on controlled hydrodynamic cavitation (Figure 1a), was investigated in the framework of *+GAS project – Production of biomethane from renewable electricity* (http://www.piugas.enea.it/), funded by Emilia-Romagna Region (ERDF-ROP 2014-2020) and, subsequently, in the one of *Electrical System Research Project* (PTR 2019-2021), funded by the Italian Ministry of Economic Development.
The first experimental trials allowed to verify the technical feasibility to obtain a microbial biomass specialised in converting hydrogen and carbon dioxide into biomethane, starting from an inoculum taken from a full-scale anaerobic treatment plants. That was achieved without record any long-term inhibitory effect on hy-

drogenotrophic microorganisms due to the physical stress promoted by hydrodynamic cavitation, reaching conversion efficiency of hydrogen into methane of 0.20 $m^3CH_4/m^3\ H_2$, recording a stable CH_4 content higher than 98% in the gas produced from the bioreactor (Figure 1b).

Further process development to optimize the gas-liquid mass transfer step is required, in order to guarantee the overall energetic sustainability of this innovative process, towards its subsequent pre-industrial application. required, in order to guarantee the overall energy sustainability of the process. Experimental tests are currently under way in this direction, with the goal of identifying technological solutions able to reduce energy consumptions related to the diffusion and transfer of gaseous fluxes in the liquid phase, and to be applied for subsequent pre-industrial developments.

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NEL PROSSIMO NUMERO PARLEREMO DI:

Green generation: giovani, ambiente e innovazione per un futuro sostenibile

In questo periodo complesso che limita la socialità e le possibilità di apprendimento e crescita culturale, **abbiamo pensato di dedicare il prossimo numero della rivista alle nuove generazioni, ai giovani e ai giovanissimi che stanno dimostrando un interesse crescente ai temi della sostenibilità, dell'ambiente, del clima e dell'energia.** Come mondo della ricerca vogliamo rafforzare il dialogo con loro e con il vasto mondo di adulti dai genitori agli insegnanti agli operatori culturali in generale che ogni giorno si interfacciano con la 'next generation' e cercano di trovare risposte alle loro domande. Per questo abbiamo pensato ad un numero che possa essere utilizzato come supporto didattico, in un format anche multimediale, come e-book da scaricare, come podcast da ascoltare in classe; uno strumento di approfondimento in vista del **"Youth4Climate2021: Driving Ambition"** di settembre a Milano e della COP26 di Glasgow.

I nostri ricercatori tratteranno le tematiche sopra descritte e le possibili soluzioni legate all'innovazione tecnologica ed a comportamenti e scelte individuali. Ma daremo spazio a interventi di rappresentanti delle istituzioni a livello nazionale e internazionale, del mondo della sociologia, dell'istruzione e del giornalismo, esperti di divulgazione scientifica e delle principali organizzazioni, anche giovanili, impegnate nella sensibilizzazione in questi settori. **E daremo voce ai ragazzi, direttamente, anche a coloro che sono scesi nelle piazze con i 'Fridays for future'** prima che il COVID-19 li chiudesse in casa con interviste e articoli sulle iniziative loro dedicate, trattando anche alcune delle nuove sfide che la scuola dovrà affrontare nel post-pandemia con la digitalizzazione e i nuovi format di insegnamento.

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