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GREEN HYDROGEN – THE FUEL OF THE FUTURE. OVERVIEW

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Abstract: Due to the increasing demand in energy consumption a need for a new fuel has risen, a fuel that doesn't add to the greenhouse effect. A new emerging trend in agreement with the green initiative that has begun is hydrogen. Hydrogen is primarily obtained using fossil fuel, natural gas and coal. However, there is a green method, electrolysis can produce hydrogen from water by using electricity, thus by using renewable power supplies like photovoltaic panels and/ or wind turbines, "green hydrogen" can be obtained. Storing the energy of the sun and wind in hydrogen production provides the versatility needed for the renewable power supply field. A case study on green hydrogen production and utilization like the Galati Hydrogen Valley is an example that explains the exploring of new methods for obtaining green hydrogen, focusing on water electrolysis.

Keywords: green hydrogen, hydrogen production, alkaline water, electolyzer, PEM electrolyzer, membrane electrolyzer.

1. INTRODUCTION

The European Green Deal, which is an ambitious set of policy proposals designed to transform the EU into a carbon-neutral economy, aims to reduce greenhouse gas emissions by 55% by 2030 and achieve zero emissions by 2050. To achieve these goals, Europe is transitioning to clean energy sources, including renewable energy. However, renewable energy alone may not be sufficient to meet the energy needs of the entire region, particularly during times of peak demand or when there are seasonal variations in energy demand. Hydrogen has emerged as a promising solution to address this challenge, as it can serve as a vector for renewable energy storage. (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0643&from=EN), (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0301&from=EN)

There are several pathways for hydrogen production, including grey, blue, and green hydrogen. Grey hydrogen is produced from fossil fuels, while blue hydrogen is produced from fossil fuels with carbon capture and storage. However, these methods do not meet the criteria of renewable energy sources. On the other hand, green hydrogen is produced through the electrolysis of water using electricity from renewable sources, such as solar or wind power. This makes green hydrogen the most environmentally friendly form of hydrogen production. (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0643&from=EN), (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0301&from=EN)

However, the cost of green hydrogen production is a significant barrier to its widespread adoption. The cost of producing green hydrogen is 2-3 times higher than that of blue hydrogen. One of the major cost components of green hydrogen production is the cost of renewable electricity needed to power the electrolysis unit. Therefore, locations that have access to low-cost renewable resources, such as solar or wind power, are more likely to produce green hydrogen at a competitive cost. (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0643&from=EN), (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0301&from=EN)

In Romania, there is significant potential for green hydrogen production, as the country has a large and growing renewable energy sector, particularly in wind and solar power. Romania is already home to several pilot projects aimed at exploring the potential of green hydrogen production, such as the HyFlexPower project, which aims to demonstrate the technical feasibility of using green hydrogen in industrial processes. (https://cordis.europa.eu/project/id/884229)

In Europe, several countries, including Germany, France, and Spain, have already launched initiatives aimed at promoting the production and use of green hydrogen. The European Union has also established a hydrogen strategy as part of its broader climate objectives. The strategy includes a target of 6 GW of renewable hydrogen electrolyzers by 2024 and 40 GW by 2030. The European Commission has also proposed a €10 billion investment in clean hydrogen as part of its Next Generation EU recovery plan. (https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions; https://energy.ec.europa.eu/select-language?destination=/node/1; https://www.irena.org/publications/2022/May/Global-hydrogen-trade-Cost)
Water electrolysis is an environmentally friendly method of producing hydrogen from sustainable water sources while also generating oxygen as a by-product. This process involves using water as a reactant and applying an electric potential to dissociate it into hydrogen and oxygen. The rate of energy consumption for hydrogen production via water electrolysis is 53.4 kWh/kg (https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions). Water electrolyzers powered by renewable energy have the benefits of eliminating or reducing transportation and storage costs and can be used as standalone systems for end-user sites. They are also stable and have the potential for exceptional hydrogen production with commercial availability. (J. A. Turner, 2004; A. Ursua, et al., 2012)

Overall, green hydrogen is a promising solution to help meet Europe's energy needs while reducing greenhouse gas emissions. While there are still significant barriers to its widespread adoption, ongoing research and development, as well as government support, are expected to drive down costs and accelerate the transition to a carbon-neutral economy. (https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions; https://energy.ec.europa.eu/select-language?destination=/node/1; https://www.irena.org/publications/2022/May/Global-hydrogen-trade-Cost)
Renewable hydrogen projects play a pivotal role in driving the transition towards a sustainable and decarbonized energy system. By harnessing renewable energy sources such as solar and wind power, these projects utilize processes like water electrolysis to produce hydrogen. The adoption of renewable energy in hydrogen production yields significant environmental advantages, including the reduction of carbon emissions and the decreased reliance on fossil fuels.

This paper consists mainly of presenting a case study on green hydrogen production and utilization in the Galati Hydrogen Valley by exploring methods for obtaining green hydrogen, focusing on water electrolysis. This paper is also analyzing different types of water electrolysis technologies and investigating research trends initiatives in green hydrogen.

This paper is structured by first discussing The European Green Deal targets for carbon neutrality and reducing greenhouse gas emissions. The importance of green hydrogen as a renewable energy carrier is a main point of discussion and also an overview production of hydrogen pathways (grey, blue and green); the cost barrier, emphasizing the high production cost of green hydrogen identifying the major cost component: renewable electricity for electrolysis. The second chapter consists mainly of discussing the four main types of obtaining hydrogen from electrolysis (PEM, AWE, AAEM, and SOE) explaining the advantages and disadvantages. For the third chapter the main focus is research trends in green hydrogen highlighting key journals and topics, regarding technological progress. The forth chapter introduces the concept of Hydrogen Valley highlighting Galati as an ideal location for a Hydrogen Valley due to the existing decarbonization initiative started by Liberty Galati. In conclusions the importance of ongoing research, funding, and case studies for advancing the adoption of green hydrogen is necessary towards a forward-looking perspective on the future of green hydrogen and its contribution to a sustainable and decarbonized energy system.

In summary, renewable hydrogen projects play a vital role in the ongoing shift towards a sustainable and decarbonized energy system. Through the utilization of renewable energy sources, these projects offer substantial environmental benefits, reduce transportation and storage costs, and contribute to the overall goal of achieving energy transition and climate objectives. Their significance lies not only in their immediate impact but also in the knowledge and solutions they provide for effectively integrating renewable energy sources into our energy systems.

2. METHODS FOR OBTAINING GREEN HYDROGEN

First, Green hydrogen is a centerpiece of the green transition to all sectors, but currently, the production capacity for green hydrogen is low, and more knowledge is needed to turn green hydrogen into a scalable, cost-effective enterprise. Water electrolysis is the main way to obtain hydrogen, and is an environmentally friendly method to generate hydrogen from sustainable water and also evolve oxygen as a by-product. (D. Tang *et al,2023*)

Water electrolysis is the main way to obtain hydrogen, and is an environmentally friendly method to generate hydrogen from sustainable water and also evolve oxygen as a by-product. In this technique, water is utilized as a reactant which dissociates into hydrogen and oxygen by applying an electric potential. The water electrolysis have a rate of energy consumption of 53.4 kWh/kg hydrogen production. (N. I. Badea, 2021) The benefits of water electrolyzers powered by renewable energy are: (N. I. Badea, 2021)

- the elimination or reduction of transportation as well as the storage costs and can be employed as stand-alone systems for end-user sites,
- their firmness and prospect of exceptional hydrogen
- commercial availability

Water electrolysis can be categorized into four types, as shown in figure 1, [9] these categories are (I) proton exchange membrane (PEM) water electrolysis (II) alkaline water electrolysis (AWE), (III) anions exchange membranes (AEM) electrolysis, and, (IV) solid oxides electrolysis (SOE), depending on the electrolyte and ions-based agents (i.e. H+, OH-, O2-).(D. Tang *et al,2023*)

2.1. Proton exchange membrane electrolyzer.

The PEM electrolyzer contains an anode and a cathode separated by a PEM, which selectively allows protons (H+) to pass through while blocking electrons (e-) and gas diffusion. PEM's was introduced by General Electric in 1960, have carbon materials which serve as the most common anode and cathode and electrolytes used is typically deionized or distilled water, which serves as a source of protons and hydroxide ions., while (Pt, Ru, Ir, and Pt) catalysts. The PEM electrolyzers are typically operated at a temperature range of 50–80 ◦C. The optimum temperature range depends on the specific catalyst and membrane materials used in the electrolyzer. (L. Wan *et al., 2023;* M. Carmo et al., 2013)

2.2. Alkaline water electrolyzer.

The difference between AWE and PEM is the type of electrolyte used, with PEMs employing a compact polymer membrane electrolyte and AWEs employing a corrosive liquid electrolyte The AWE is an advanced type compared with PEM, as well as easy to manufacture on a large scale. Two electrodes are immersed in a water solution containing 20 to 40 % of the NaOH or KOH. The electrodes are separated by a diaphragm in the electrolyte solution, which allows hydroxide ions and H2O molecules to pass through. For purity and safety, the diaphragm also separate H2 and O2. As a result, the purity of the hydrogen produced ranges from 99.5 to 99.9 %, with catalytic gas purification processes increasing up to 99.99 %. (Y. Guo et al., 2019; M. David et al., 2019)

2.3. Alkaline anion exchange membrane.

In an AAEM (Alkaline anion exchange membrane) electrolyzer, the anode, and cathode are separated by an anion exchange membrane that allows negatively charged hydroxide ions (OH) to pass through while blocking other ions and gases. During electrolysis, water is fed into the anode chamber, where it is oxidized to produce oxygen gas and hydroxide ions. The hydroxide ions are transported across the AAEM to the cathode compartment, where they react with incoming electrons and protons to form hydrogen gas. Compared to a PEM electrolyzer, the AAEM electrolyzer operates at higher pH and lower pressure. This can reduce the cost and complexity of the system, but it also requires different materials that can withstand the highly basic environment. (N. Du et al., 2022) Compared to AWE in an AAEM electrolyzer, instead of 20 to 40 % NaOH and KOH solution, it combines a low-concentration alkaline solution with a polymeric compact electrolyte membrane (i.e., Mg–Al layered double hydroxide). Additionally, the cathode of an AAEM is fabricated from Ni and Ni–Fe components, while the anode is fabricated from Ni foams or titanium components. (C. Santoro *et al, 2022;* M. Paidar et al., 2016)

2.4. Solid oxide electrolyzer.

Solid oxide electrolyzer have the anode and electrolytes ceramics, works at high temperatures, the required electricity amount to power its electrolysis is considerably less than that required for electrolysis at low temperatures. (J. P. Stempien et al., 2013; M. Ni, 2008)
The process for hydrogen generation assume the cathode reaction first converts steam to H2 at cathode, and the oxide anions formed at cathode are the pathways through which solid electrolytes generate O2 at anode side. A schematic illustration of the SOE cell and the equations of water electrolysis reaction can be found in figure 1. (J. P. Stempien et al., 2013)

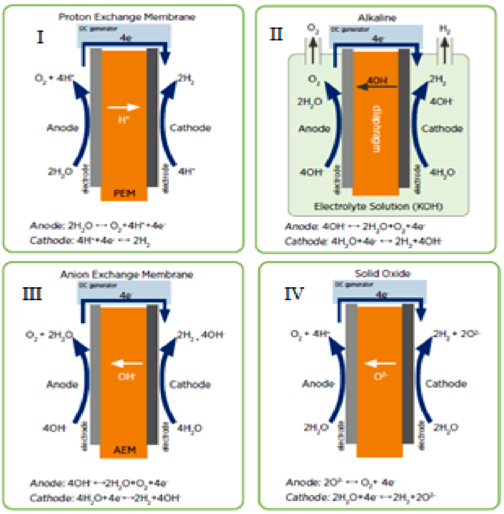

Fig.1. Types of available electrolysis technologies (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0301) (I) - proton exchange membrane (PEM) - water electrolysis, (II) - alkaline water electrolysis (AWE), (III) - anions exchange membranes (AEM) electrolysis and (IV) - solid oxides electrolysis (SOE).

The use of inexpensive thermal energy or waste heat results in an increase in system efficiency. Solid oxide electrolyzers operate within a temperature range of approximately 700°C to 800°C, while PEM electrolyzers function at lower temperatures of 70°C to 90°C, and commercial alkaline electrolyzers typically operate at temperatures below 100°C. The higher operating temperatures of solid oxide electrolyzers are necessary to ensure the proper functioning of solid oxide membranes. (J. P. Stempien et al., 2013; M. Ni, 2008)

3. GREEN HYDROGEN RESEARCH AND DEPLOYMENT

The research trends and potential of green-hydrogen by bringing in a new perspective and analysis based on key phrases, the contribution of open access, in Scopus database was used (Raman et al., 2022) for retrieving the bibliographic based by the journals indexed in this database. The authors indicate in this study that, though the first publication indexed in Scopus can be seen as early in 1997, publications in this area were in the single digits for the next twenty years. Lists of the most productive journals are the International Journal of Hydrogen Energy (92 articles), followed by Energies (38 articles), ECS Meeting Abstracts(21 articles) , Applied Energy (13 articles) and Renewable and Sustainable Energy Reviews (10 articles) A simple search in Scopus (https://www.scopus.com/results/results.uri?sort=plf-f&src=s&st1=green+hydrogen&sid=1d6e3e6e2d539a7a3e8ed8fa279cd54d&sot=b&sdt=b&sl=21&s=TITLE%28green+hydrogen%29&origin=searchbasic&editSaveSearch=&yearFrom=Before+1960&yearTo=Present&sessionSearchId=1d6e3e6e2d539a7a3e8ed8fa279cd54d&limit=10) of articles containing green hydrogen indicates the transition to three digits of articles published in 2021 (177 articles), in 2022 a number of 388 articles and in 2023 until now 158 articles. Most green-hydrogen research is into the journals of materials chemistry, hydrogen energy and cleaner production, applied energy, and fuel cell. (Raman et al., 2022; https://www.iahe.org/)

The research topics of publications are most focused on technological progress (Electrolysis), sustainable technology, and environmental regulations regarding burning of hydrogen in diesel engines, and engine cylinders. Next comes related topics such as hydrogen storage (automobile industry), hydrides, and dehydrogenation (Air Quality Monitoring). Latest subject is about investment in wind-based hydrogen production or solar under economic and physical uncertainties. (Green hydrogen cost reduction Scaling up electrol.pdf.; Meda et al., 2023; L. M. Abadie and J. M. Chamorro, 2023; L. Al-Ghussain et al., 2023)

Table 1 Comparison between electrolysers.

Area	Topic (HORIZON-JTI-CLEANH2-2022…)	Indicative budget in topic (Million EUR)	Proposals submitted	Ineligible or inadmissible proposals	Above threshold proposals	Clean hydrogen JU contribution requested for above threshold proposals (EUR)
Renewable Hydrogen Production	01-04	4	6	-	5	10,058,156.25
	01-05	6	1	-	1	5,295,799.25
	01-08	18	3	1	1	18,344,576.38
	01-10	20	4	2	1	20,000,000.00
Hydrogen Storage and	02-01	2.5	4	-	3	7,602,529.75
	02-04	3	10	-	5	15,111,182.50
	02-05	3	5	-	4	11,930,488.75
	02-06	6.5	3	-	1	6,497,480.00
	02-11	7	0	-	0	0.00

Transport	03-01	7	1	-	1	3,487,156.38
Clean Hydrogen Power	04-01	7	3	-	2	12,937,653.31
Cross - Cutting	05-01	1	10	1	5	5,385,859.50
	05-03	3	3	-	1	2,999,156.25
Hydrogen Valleys	06-01	25	8	2	2	49,344,576.38
	06-02	8	13	-	7	55,429,411.16
Total		121	74	6	39	225,078,274.83

Much uncertainty surrounds the cost-effective deployment of green hydrogen technologies. In this sense, the rapid deployment of green hydrogen initiatives are in Europe through optimized funding of R&I activities by call Clean Hydrogen Partnership. The call have main objective is to contribute to EU Green Deal and Hydrogen Strategy through funding made available for projects to support the creation of cutting-edge hydrogen technologies. This call is the successor of the Fuel Cells and Hydrogen 2 Joint Undertaking (FCH 2 JU) and has taken over its legacy portfolio as of 2021. A summary of the project proposals submitted in 2022 with the indication of the thematic areas, the allocated amounts and the number of projects is shown in table 1. (M. Carmo, 2013; Y. Guo, 2019; M. David, 2019; N. Du, 2022) The projects declared winners in the different thematic areas with the highlighting of their coordinators are shown in table 2. (https://commission.europa.eu/research-and-innovation_en; https://ec.europa.eu/info/funding-tenders/opportunities/portal)

Table 2 Renewable H2 projects.

Project Acronym	Participant Legal Name	COORDINATOR
24_7 ZEN	FUNDACIO INSTITUT DE RECERCA DE L'ENERGIA DE CATALUNYA	Spain
ADVANCEPEM	CONSIGLIO NAZIONALE DELLE RICERCHE	Italy
AMON	FONDAZIONE BRUNO KESSLER	Italy
BRAVA	AIRBUS OPERATIONS GMBH	Germany
COCOLIH2T	COLLINS AEROSPACE IRELAND, LIMITED	Ireland
ELVHYS	NORGES TEKNISK-NATURVITENSKAPELIGE UNIVERSITET NTNU	Norway
FLEX4H2	ANSALDO ENERGIA SPA	Italy
H2Accelerate TRUCKS	SINTEF AS	Norway
H2REF-DEMO	CENTRE TECHNIQUE DES INDUSTRIES MECANIQUES	France
HELIOS	TECHNISCHE UNIVERSITEIT EINDHOVEN	Netherlands

Project Acronym	Participant Legal Name	COORDINATOR
HIGHLANDER	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS	France
HQE	SINTEF AS	Norway
HyLICAL	INSTITUTT FOR ENERGITEKNIKK	Norway
HyP3D	FUNDACIO INSTITUT DE RECERCA DE L'ENERGIA DE CATALUNYA	Spain
HYPRAEL	FUNDACION PARA EL DESARROLLO DE LAS NUEVAS TECNOLOGIAS DEL HIDROGENO EN ARAGON	Spain
HySelect	DEUTSCHES ZENTRUM FUR LUFT - UND RAUMFAHRT EV	Germany
JUST-GREEN AFRH2ICA	UNIVERSITA DEGLI STUDI DI GENOVA	Italy
NIMPHEA	SAFRAN POWER UNITS	France
OPTHYCS	ENAGAS TRANSPORTE SA	Spain
OUTFOX	NEDERLANDSE ORGANISATIE VOOR TOEGEPAST NATUURWETENSCHAPPELIJK ONDERZOEK TNO	Netherlands
PEMTASTIC	DEUTSCHES ZENTRUM FUR LUFT - UND RAUMFAHRT EV	Germany
PROTOSTACK	SINTEF AS	Norway
RHeaDHy	ENGIE	France
ROAD TRHYP	L AIR LIQUIDE SA	France
SUSTAINCELL	SINTEF AS	Norway
THOTH2	SNAM S.P.A.	Italy
RH2IWER	TEKNOLOGIAN TUTKIMUSKESKUS VTT OY	Finland

Compared to the old calls of the legacy program Fuel Cells and Hydrogen 2 Joint Undertaking (FCH 2 JU), this call integrates green hydrogen production in the entire chain from production to end users through the thematic area HYDROGEN VALLEYS. (https://h2v.eu/; https://www.viata-libera.ro/prima-pagina/199681-o-fabrica-de-hidrogen-verde-va-pune-galatiul-pe-harta-europeana-a-energiei) Hydrogen valleys are regional ecosystems that link hydrogen production, transportation, and various end uses such as mobility or industrial feedstock. If in the first call The Clean Hydrogen Partnership, under the Horizon Europe Programme, was invest €105.4 million for funding nine hydrogen valley projects across Europe , in the new call 2023 it finances only two projects with investment only €38 million. The seven smaller-scale hydrogen valleys projects, comprise regions in Bulgaria (Stara Zagora), Greece (Crete and Corinthia), Ireland (Galway), Italy (Lombardy), Turkey (South Marmara), and Luxembourg. (https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52020DC0301; https://www.offshore-energy.biz/nine-hydrogen-valleys-to-repower-europe/)

4. CASE STUDY- GREEN HYDROGEN PRODUCTION AND UTILIZATION IN HYDROGEN VALLEY -GALATI

A hydrogen ecosystem, named "Hydrogen Valley" in EU vision" (https://www.clean-hydrogen.europa.eu/get-involved/mission-innovation-hydrogen-valleys-platform_en), is a defined geographical area, such as a city, region, island, or industrial cluster, where multiple hydrogen applications are integrated to form a cohesive system. This integrated ecosystem consumes a substantial

quantity of hydrogen, resulting in improved project economics. The ideal hydrogen ecosystem encompasses the entire value chain, including hydrogen production, storage, distribution, and utilization.". (https://h2v.eu/)
The global landscape of Hydrogen Valleys can be categorized into three archetypes (https://www.clean-hydrogen.europa.eu/media/news/insights-emerging-hydrogen-economies-around-world-new-report-published-hydrogen-valley-platform-2022-09-23_en):

- Smaller-scale local mobility-centred Hydrogen Valleys (typically 1–10 MW of local electrolyser capacity) for decarbonisation efforts of various regional mobility fleets (hydrogen fuel cell trucks, buses, trains, etc.).

- Medium-scale Hydrogen Valleys focusing on industrial decarbonisation (typically 10-300 MW of local electrolyser capacity) based regional hydrogen production source at the site of one or more large industrial consumers and mobility off-takers.

- Large-scale and ultimately export-oriented Hydrogen Valleys (typically 250-1,000 MW of local electrolyser capacity) characterized by focusing on low-cost production of clean hydrogen for local off-take, to mainly regional and international export.

The European hydrogen strategy anticipates new deployments to take place in so-called 'hydrogen valleys' which cover a substantial part of the hydrogen value chain, from production, storage, and transport to use in sectors like industry, mobility, and energy.(https://www.clean-hydrogen.europa.eu/media/news/insights-emerging-hydrogen-economies-around-world-new-report-published-hydrogen-valley-platform-2022-09-23_en)

South-East of Romania is a prime location for this concept, as hydrogen can be produced and used regionally, and this region is friendly to production and demand reduces the additional costs associated with long-distance transport infrastructure. (https://www.clean-hydrogen.europa.eu/media/news/insights-emerging-hydrogen-economies-around-world-new-report-published-hydrogen-valley-platform-2022-09-23_en)

Significant hydrogen demand can come from industry, especially the existing steel mill (Liberty Galați), and from transport terrestrial and maritime (Constanța, Galați, Tulcea, Brăila). Steel production typically happens in two steps: (https://www.clean-hydrogen.europa.eu/media/news/insights-emerging-hydrogen-economies-around-world-new-report-published-hydrogen-valley-platform-2022-09-23_en)

- Initially, iron ore undergoes a transformation into iron through the use of blast furnaces. These furnaces utilize carbon as an essential component in a chemical process that converts iron oxide and carbon into iron and carbon dioxide. Within the blast furnace, carbon particles react with a limited supply of oxygen, resulting in the formation of carbon monoxide. Subsequently, this carbon monoxide gas reacts with the iron oxide particles, leading to the production of iron and CO2. Therefore, in the process of iron production, CO2 is generated as a by-product through this chemical reaction.

- In the second step, the iron is turned into steel, through the basic oxygen converter process.

In order to decarbonize the iron-making process, it is necessary to substitute carbon/carbon monoxide in this reaction with a gas that does not result in carbon emissions. Hydrogen emerges as a viable option for achieving this goal, as its utilization would enable the complete decarbonization of the process. By using hydrogen (H2), only water vapors would be produced as a chemical by-product, thus eliminating carbon emissions entirely. The iron and steel industry is responsible of anthropogenic CO2 emissions 4% in Europe, and 9 % worldwide, and therefore a significant driver of climate change. To reduce emissions, Liberty Galati launched in 2022 an extensive modernization program of the new electric arc hybrid furnaces in order to transform its operations towards the production of "green steel". To support the "green steel" plan and the decarbonization objective, Liberty Galati has already launched the first 50 MW phase of the 180 MW solar energy project realized on the industrial platform, which will supply green energy directly to the steel mill. (R. R. Wang, 2021; K. Rechberger, 2020)

System design (figure 2) can be optimized to minimise cost and increase flexibility as necessary, depending on:

- the variability of technology used for the stack (e.g. alkaline, PEM and AEM being more flexible than solid oxide);

- the flexibility of hydrogen demand (e.g. constant demand for steel processes).

Storage can significantly help to decouple variable supply from hydrogen demand. This can come in the form of electrochemical storage for short-term fluctuations (before the electrolyser stack), or in the form of hydrogen storage for long-term fluctuations (after the stack, before the downstream off taker).

A recent development further supports the potential of water electrolysis and the production of green hydrogen. According to a news article from Viata Libera a green hydrogen factory is being established in Galati, Romania. This initiative is expected to put Galati on the European energy map by becoming a prominent player in the production of green hydrogen. (A. Ursua, 2012; https://www.viata-libera.ro/interviuri/201072-combinatul-liberty-galati-poate-absorbi-toata-energia-bazata-pe-hidrogen)

Similarly, hydrogen storage in tanks, can help decouple variable hydrogen production from inflexible hydrogen demand (e.g. winter -summer). (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0301)

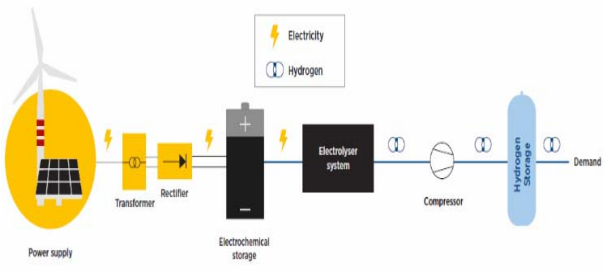

Fig.2. System schematic for green hydrogen production facility that includes electricity and hydrogen storage on site (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0301).

The type of electricity supply and hydrogen demand will drive final system design. At a production of 4500 tons/year, the daily production requirement must be 12330 kg/day. Since the average daily radiation in the Galati area is 3.5 hours/day, it results in an average daily production rate of 3522 kg/h. Considering a purely electrochemical reaction into electrolyzer, the rate of molar production of species x (mol of x/s) is:

$$n_x = \frac{I}{nF} \quad (1)$$

I=current (A)

n=equivalent electrons per mole of reactant x (eq/mol)

F=charge carried on one equivalent mole (C/eq)

If consider a single hydrogen fuel cell at 1 A current input, the molar rate of H2 for the electrochemical reaction is :

$$n_{H2} = \frac{I}{nF} = \frac{1C/s}{(2\,e^{-}eq/mol H_2)(96485C/eq)} = 0.518\cdot 10^{-5} mol H_2/s \quad (2)$$

The rate of hydrogen production in grams per hours will be

$$n_{H2} = \frac{I}{nF}\cdot MW = (0.518\cdot 10^{-5}\cdot mol H_2/s)(18g/mol)(3600s/h) = 25.9\cdot 10^{-9} g_{H2O}/h \quad (3)$$

The rate of water consumption in grams per hours will be

$$n_{H2} = \frac{I}{nF}\cdot MW = \frac{\frac{1C}{s}}{\left(2\frac{e^{-}eq}{mol H_2}\right)\left(\frac{96485C}{eq}\right)}\left(\frac{18g}{mol}\right)\left(\frac{3600s}{h}\right) = 0.335\, g_{H2O}/h \quad (4)$$

Based on the above relations, the electric current requirement of the electrolyzers for the production of 3522 kg/h can be determined and result.

Taking into account that for the production of one kg of hydrogen, 53.4 kWh is consumed, the result for the estimated hydrogen production is an average daily consumption of 667.5MWh. At the level of average daily radiation in the Galati area is 3.5 hours/day, it results in an average installed power of 190MW.

Since the average daily production was considered according to the average duration of solar radiation of 3.5 h in the Galati area in the summer season, the level of radiation being much higher (almost double), it follows that the daily production of hydrogen must be doubled. The commercial electrolyzers [39] with proton exchange membrane (PEM) having Stack Power Consumption of 10 MW fed to Voltage & Frequency 11 to 33kV at 50HZ (EU) have Output (Hydrogen Gas) 4,250 kg / day with water consumption 13 liters per kg of H2 produced. At an installed PV power of 190MW using photovoltaic panels with a power Pp=485W, result 391752 panels numbers. Placing the panels with an inclination of

35° on the south face and an azimuth angle of 21° can

determine a distance between the rows of panels so that the panels do not shade other panels. Taking into account the physical dimensions of a panel it follows that the area occupied by the photovoltaic system must be 184 hectares. (http://www.canadiansolar.cc/wp-content/uploads/2020/06/Canadian_Solar-Flyer-BiHiKu5_CS3Y-MB-AG_EN.pdf)

5. CONCLUSIONS

Water electrolysis is a promising and environmentally friendly method for producing hydrogen from sustainable water sources. It offers the advantage of generating oxygen as a valuable by-product. The energy consumption rate for hydrogen production through water electrolysis is 53.4 kWh/kg, making it a viable option for clean and efficient hydrogen generation.

Water electrolysis, particularly when powered by renewable energy sources, can be implemented as standalone systems for end-user sites, eliminating or reducing transportation and storage costs. Moreover, these systems have shown stability and the potential for exceptional hydrogen production.

The establishment of this green hydrogen factory demonstrates the growing interest and investment in sustainable energy solutions, particularly hydrogen production. By leveraging water electrolysis and renewable energy sources, such as solar or wind power, the factory aims to contribute to the decarbonization of the region's energy sector and support the production of "green steel" at Liberty Galati, aligning with the objective of reducing anthropogenic CO2 emissions. This development highlights the importance of green hydrogen as a key enabler in the transition to a carbon-neutral economy. It not only offers a sustainable pathway for hydrogen production but also provides opportunities for economic growth, job creation, and increased energy independence.

Overall, with advancements in water electrolysis technology and the establishment of dedicated green hydrogen production facilities like the one in Galati, the prospects for widespread adoption of this environmentally friendly method are promising. These developments contribute to a more sustainable and greener energy landscape, offering solutions to mitigate climate change and promote a cleaner, more resilient future.

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