Journal of Energy

VOLUME 73 Number 3 | 2024

journal homepage: http://journalofenergy.com/

Development of Electrolyser Projects for Production of Renewable Hydrogen

Martina Mikulić, Martina Rubil, Ivan Andročec

***Summary* — Hydrogen is one of the important factors in reaching climate neutrality from the European Green Deal, particularly hydrogen made from renewable energy sources. The paper describes electrolysis plants in technical, environmental and regulatory aspects and presents obstacles that need to be overcome for the successful implementation of electrolyser projects, looking at the bigger picture of the energy sector. Part of the paper is dedicated to the research of existing projects and the plans for the development of electrolysers. Possible contribution of the development of electrolysis plants is in the application at the locations of existing thermal power plants that are no longer suitable for operation due to technological, economic or environmental reasons, which would take advantage of the existing location of the power plant for the installation of new technology that meets the concept of low-carbon development.**

***Keywords* — electrolyser, hydrogen, low-carbon development.**

I. Introduction

Given that it does not cause carbon emissions when used, hydrogen can be an important factor in achieving the goal of climate neutrality from the European Green Plan until 2050, especially in the sectors that represent the biggest challenge – energy-intensive industry and transport. The greatest potential for decarbonisation is in hydrogen from renewable energy sources (RES), the so-called clean or green hydrogen.

New circumstances in the energy sector and the expected development, which includes a fall in the price of electricity from renewable sources and technological progress, provide opportunities for increasing the use of hydrogen as a raw material, fuel and energy carrier in different parts of the energy sector.

Hydrogen can be produced in different ways - by catalytic oxidation of hydrocarbons, partial oxidation of heavy hydrocarbons, production from refinery gases and methanol, electrolysis of water, and advanced technologies such as thermochemical gasification of biomass or photobiological production using algae and similar, whereby the creation of different types and the amount of greenhouse gas emissions and costs. The focus of this work is the production of hydrogen by electrolysis of water in electrolysis plants using electricity. Emissions resulting from the production of hydrogen using electricity depend on the method of electricity production. If the electricity is obtained from renewable energy sources, we call such hydrogen renewable, clean or green hydrogen.

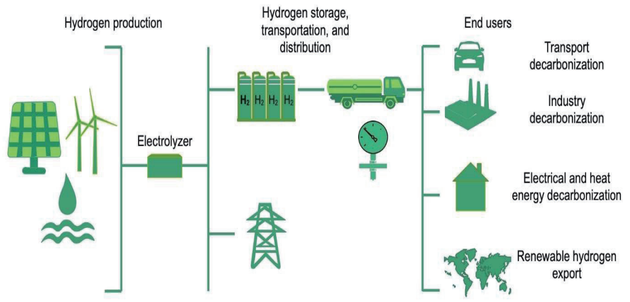

Fig. 1. General scheme of the hydrogen value chain, from production to end-use [1].

As is shown in the paper, the decarbonization of hydrogen production is still in its infancy, but with a strategy goal to support energy transition. Benefiting from a wide variety of production pathways, research and financing policies are needed to accelerate the penetration and cost effectiveness measures to ensure a tangible effect is achieved in a timely manner.

As of December 2022, 97 water electrolysis hydrogen production projects (67 with a minimum capacity of 0.5 MW) were in operation in Europe, totaling 174.28 MW of production capacity. A further 46 projects were under construction (i.e., construction work has begun) and are expected to deliver an additional 1,199.07 MW of water electrolysis capacity once operational (between January 2023 and 2025). In 2022, hydrogen export from Belgium to the Netherlands (25.737 tonnes, or 75% of all the hydrogen traded in Europe) was the single biggest hydrogen flow to and between European countries. [32]. The European goal is production of 10 million tonnes of renewable hydrogen till 2030 (see chapter IV).

The paper is divided into several chapters focusing on concept and different aspects of electrolyser facilities, describing several existing electrolyser projects, presenting different development plans and finally showing some obstacles and guidelines for the way forward.

II. Concept and Aspects of Electrolyser Facilities

The chapter describes the concept of electrolyser facilities and analyzes the technical, environmental and regulatory aspects of the construction of electrolyser projects and hydrogen production.

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Martina Mikulić, Martina Rubil, Ivan Andročec, Development of Electrolyser Projects for Production of Renewable Hydrogen, Journal of Energy, vol. 73 Number 3 (2024), 9–16
https://doi.org/10.37798/2024733518

A. The Concept of Electrolyser Facilities

An electrolyser is an electrochemical device in which hydrogen and oxygen are produced in gaseous phases by means of water electrolysis. The process is called electrochemical because direct electrical energy is used to obtain chemical energy that is stored in the resulting hydrogen. The electrolyser consists of two electrodes that are connected to an external direct current circuit. Between the electrodes, there is a voltage drop that causes the bipolar electrodes to charge so that the part of the electrode that receives electricity is charged positively (anode), and the part that transmits it is negatively charged (cathode). For the electrolysis process, the DC voltage on the electrodes must be equal to or greater than the reversible voltage, which is 1.23 V. As a result of the voltage drop, redox reactions take place on the electrodes - reduction of water (H_2O) takes place at the cathode, and a hydrogen molecule (H_2) is formed, and at the anode, oxidation occurs and an oxygen molecule (O_2) is formed. The amount of hydrogen production is directly related to the number of cells in the electrolyser, that is, the greater the number of cells, the greater the production of hydrogen, provided that a higher voltage is supplied. The chemical reaction of the electrolysis process is shown by (1).

$$2\,H_2O \rightarrow 2\,H_2 + O_2. \tag{1}$$

Three types of electrolysers are mostly used: alkaline electrolyser (AE), proton exchange membrane electrolyser (PEM) and solid oxide electrolysis (SOE). Currently, the most developed and cheapest technology for hydrogen production is with the help of an alkaline electrolyser, in which the membrane is selective and allows only hydroxide ions to pass through. PEM electrolysers use a membrane as an electrolyte, where polymer materials are used to build the membrane. The advantage of this type of electrolyser is greater stability with non-uniform sources of electricity, compactness, greater purity of hydrogen and lower electricity consumption. Electrolysers that use solid oxides as a membrane work at a temperature of 700-800°C, and use the hot water vapor that is created in the process, thus reducing the amount of electricity needed for hydrogen production. [2]

Traditionally, electrolysers are made in small quantities for specific market niches. Despite the fact that some electrolysers are used commercially (alkaline and PEM), traditional hydrogen production technologies are still preferred due to incomparably lower costs. Innovations in electrolyser technologies, greater efficiency and cost reduction (including a drop in the price of electricity from RES) are needed for this technology to play its key role in decarbonisation. According to A Hydrogen Strategy for a climate neutral Europe [3], the price of hydrogen produced from fossil fuels is currently about 1.5 €/kg (about 2 €/kg taking into account the price of released CO_2 into the atmosphere), and the price of renewable hydrogen production is in range from 2.5 till 5.5 €/kg. Price competitiveness of renewable hydrogen production with other forms of hydrogen production is expected in the period from 2025 to 2030 [3].

B. Technical, Environmental and Regulatory Aspects

The decision to invest in electrolyser facilities is preceded by a review of a whole series of technical, environmental and regulatory aspects, which are described in the following chapter.

B.I. Technical Aspects

In addition to the electrolyser stack itself (or several stacks), electrolyser plants include accompanying equipment necessary for operation. The electrolyser is a set of electrolyser stacks, and the stack contain anode, cathode and proton or anion exchange membrane. A schematic view of the electrolysis facility with all the necessary systems can be found in Figure 2.

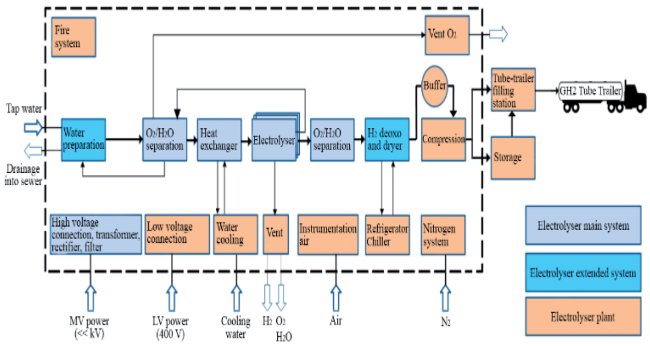

Fig. 2. Schematic representation of the electrolyser facility with all necessary systems [4]

Since direct current is used in the electrolysis process, the basic system of the electrolyser facility includes mains switches, filters, a transformer and a rectifier. Each plant must be equipped with a system for purification and demineralization of water for use in the electrolyser. An essential part of the facility is the cooling system, which is required to maintain the desired operating temperature of the electrolyser (60-75°C), due to heat generation in the electrolysis process, and systems for separating water from the produced hydrogen and oxygen. To achieve the desired purity of hydrogen, a special cooling system for drying hydrogen is required. Additional elements of the system are a hydrogen intermediate tank at the plant exit, a compressor to achieve the desired delivery pressure (up to max. 380 bar) and a high-pressure hydrogen tank. For the safe operation of the electrolysis plant, a system of compressed air required for instrumentation, a system of compressed nitrogen for flushing the system, and a fire alarm and fire protection system are also required.

On the side of safety and technical aspects, it is important to note that a mixture of hydrogen and oxygen can occur in the electrolyser (firecracker gas), which is why manufacturers of electrolysers take precautionary measures. When using hydrogen, there is no risk of the formation of a mixture of hydrogen and oxygen, but hydrogen may leak into the air. However, in an open or closed space with ventilation, there is a low probability of generating the critical amount of hydrogen necessary for ignition (4%), except immediately (up to 30-40 cm) above the point of hydrogen leakage due to the weight of hydrogen, which is 13 times lighter than air.

B.II. Environmental Aspects

The use of hydrogen as a low-carbon form of energy should lead to significant reductions in carbon dioxide and greenhouse gas emissions, as well as significant climate benefits. Hydrogen is the most widespread element in nature and makes up about 90% of all atoms. Its extreme chemical reactivity is the reason why it is not found as a free element in nature, but is bound in compounds, so it must be produced for use.

The method by which hydrogen will be produced for industrial use determines how much positive impact or possible damage there is to the environment. Excess renewable energy can be used

Martina Mikulić, Martina Rubil, Ivan Andročec, Development of Electrolyser Projects for Production of Renewable Hydrogen, Journal of Energy, vol. 73 Number 3 (2024), 9–16
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for production, so such energy is not wasted, but is used to produce hydrogen that can be successfully stored. In addition to gas pipelines, hydrogen can also be stored in fuel cells. Hydrogen fuel cells, unlike batteries, do not need to be recharged and last longer allowing them to be used to power vehicles offering zero emissions and are two to three times more efficient than gasoline internal combustion engines.

Adding hydrogen to the natural gas network results in changes in the physical and chemical properties of the fuel mixture - this mixture is lighter with a higher diffusion coefficient and higher volumetric flow compared to pure methane for the same pressure and flow rate. Following on from the conducted research, if we replace 10% of natural gas with hydrogen, taking into account losses in the distribution network of around 1%, the impact of the newly created mixture on the climate will be reduced due to the weaker GWP (Global Warming Potential) of hydrogen (4.3) in comparison on the GWP of methane (25) over a 100-year period [5].

However, uncontrolled leakage of hydrogen into the atmosphere during its production, storage, distribution and use could reduce the positive environmental impacts achieved by its use and have a detrimental impact on air quality and climate. More than 50% of hydrogen comes from burning fossil fuels and burning biomass, and the rest includes the oxidation of methane and volatile organic compounds. Although it is not a greenhouse gas in itself, hydrogen can participate in chemical reactions in the lower and upper atmosphere that can lead to a harmful effect on the environment. An increase in the concentration of H_2 in the atmosphere leads to a series of chemical reactions that, as a result, have negative effects on air quality, global warming and the destruction of the ozone layer, as well as prolonging the life cycle of methane, which is a greenhouse gas [6]. Changes in H_2 concentration also affect atmospheric water vapor, and the increase in H_2 and H_20 in the stratosphere leads to the production of hydrogen radicals responsible for the destruction of the ozone layer.

The impact of hydrogen on climate change has not been sufficiently investigated, there is only one study that provides an estimate of the GWP for hydrogen, which can be shown as 4.3 t of equivalent CO_2 emissions per ton of hydrogen over a 100-year period, i.e. the GWP for hydrogen is estimated at 4.3 with a relatively large uncertainty. From this it can be concluded that the influence of hydrogen on the global climate is relatively small [7]. Given that we cannot predict the amount of hydrogen that would flow out into the soil uncontrollably, it is difficult to determine the ratio of benefits and harm to the environment. There is a possibility that the increased use and possible leakage of hydrogen will have a negative effect on the climate, but the available results from the conducted studies show that the harmful global atmospheric impact of hydrogen on the climate will be small. The production of hydrogen should be in an environmentally friendly manner with maximum precautions.

B.III. Regulatory Aspects

The legislative framework of the Republic of Croatia (ROC) includes ensuring the transfer of EU legislation into national legislation in accordance with the goals set at the EU level. At the EU level, rules for the production of hydrogen from RES were adopted in June of this year, and steps were taken to establish a hydrogen bank that combines demand and production for hydrogen.

In addition to the Croatian strategy for hydrogen until 2050, laws were passed that regulate the possibilities of using hydrogen, i.e. the introduction of hydrogen on the Croatian market, and define the technical specifications of filling stations:

- Act on Amendments to the Act on Biofuels for Transportation (Official Gazette, No. 52/21),
- Act on the Establishment of Infrastructure for Alternative Fuels (Official Gazette, No. 120/16).

In order to obtain permits for construction projects of electrolyser facility, it is necessary to create project documentation for the installation of the electrolyser with all subsystems, for connection to the power system and potentially for connection to the gas system. The necessary documentation includes the decision of the competent ministry on the need to carry out an assessment procedure on the need to assess the impact of the intervention on the environment, an energy permit and a building permit. As a regulatory obstacle, a certain confuse was observed regarding the way electrolysers are treated as other production facilities and the need for an environmental permit, which is not clearly defined either at the level of the European Union (EU) or Croatia.

B.III. Comparison of different hydrogen production methods

Electrolysis techniques can be categorized based on the electrolytes employed: alkaline electrolysis (AE); polymer electrolyte membrane (PEM) electrolysis; solid oxide electrolysis (SOE); and anion exchange membrane (AEM) electrolysis. For electrolysis efficiency, many internal and external variables can affect both the electrical behavior and efficiency of electrolysis cells, including the concentration and purity of the electrolyte, the type and shape of the electrodes, and the cell temperature and pressure. Table I compares the main characteristics of AE, PEM, and SOE system [29].

Table I

Comparison of Different Characteristics of Water Electrolysis-Based Hydrogen Production Technologies

	AEC[a]	PEM[a]	SOE[a]
TR[L]a	9	8	6
Expected TRL 2050	9	9	9
Typical electrolyte	Aqueous potassium hydroxide (20–40 wt% KOH)	Polymer membrane (e.g. Nafion) [	Yttria Stabilised Zirconia (YSZ)
Anode	Ni or Ni–Co alloys	RuO_2 or IrO_2	LSM/YSZ
Cathode	Ni or Ni–Mo alloys	Pt or Pt-Pd	Ni/YSZ
Cell voltage (V)	1.8–2.4	1.8–2.2	0.7–1.5
Current density (A cm^{-2})	0.2–0.4	0.6–2.0	0.3–2.0
Cell area (m^2)	<4	<0.3	<0.01
Voltage efficiency (%)	62-82	67-82	77-85
Operating temperature (^oC)	60-80	50-80	650-1000
Operating pressure (bar)	<30	30-80	<25
Production rate ($m^3H_2h^{-1}$)	<760	<40	<40
Stack energy ($kWh_{el}m^3H_2^{-1}$)	4.2–5.9	4.2–5.5	>3.2
System energy ($kWh_{el}m^3H_2^{-1}$)	4.5–6.6	4.2–6.6	>3.7
Gas purity (%)	>99.5	99.99	99.9
Cold-start time (min.)	<60	<20	<60
System response	Seconds	Milliseconds	Seconds
Stack lifetime (h)	60,000–90,000	20,000–60,000	<10,000

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Capital cost per stack 2020 (€$_{2021}$/kW)	1000-1200[d]	1860-2320[d]	>2000[d]
Capital cost per stack 2030 (€$_{2021}$/kW, estimated)	611	978	1902
Stack efficiency (LHV) range 2020 (%)	58–70%	58–65%	81–83%
Stack efficiency (LHV) range 2050 (%, estimated)	61–80%	70–74%	88–90%
Advantages	Long life span	High current density	High system efficiency
	Minimal expense	Compact system layout	Less electricity utilization
	High technology readiness level	Fast response to current change	Expected cost reduction
	Large stack size		Integration with other technologies
Disadvantages	Low current density	Noble metal material requirement	Extraction and utilization of cathodic Lanthanide rare earth elements may cause environmental damage
	Corrosive electrolyte	Short life span	Unstable electrodes
		High membrane expense	Sealing problems
Barriers for large-scale application	Accessibility to low cost and abundant electricity	Accessibility to low cost and abundant electricity	Accessibility to low cost and abundant electricity; immaturity of technology

a: AEC: alkaline electrolysis cell; GHG: greenhouse gas; LHV: Low heating value; LSM: $La_{0.8}Sr_{0.2}MnO_3$; PEM: polymer electrolyte membrane; SOE: solid oxide electrolysis; TRL: technology readiness level; wt: weight.

b: The global share of renewable electricity in total electricity output was approximately 27% at the end of 2019, including 11% produced by wind turbines and solar photovoltaic, which potentially can be used to produce sustainable hydrogen.

c: Adequate renewable electricity for large-scale deployment of electrolysis is assumed to be available based on the existing net-zero commitments.

d: Updated capital cost according to Chemical Engineering Plant Cost Index (CEPCI). $CEPCI_{2020}$ = 596.2; $CEPCI_{2021}$ = 708.0. Calculation formula: cost at 2021 = cost at 2020 · $CEPCIindexat2021CEPCIindex at2020$).

III. Existing Electrolyser Facility Projects

Installed capacities in electrolyser facilities have been growing at an accelerated pace for the past few years, but precise data on total world capacities are currently not readily available. According to a report by the International Energy Agency (IEA) [8], electrolysis capacity for dedicated hydrogen production has been growing in the past few years, but the pace slowed down in 2022 with about 130 MW of new capacity entering operation, 45% less than the previous year. However, electrolyser manufacturing capacity increased by more than 25% since last year, reaching nearly 11 GW per year in 2022. Global electrolyser capacity additions slowed in 2022 despite strong momentum, but installed capacity could reach almost 3 GW in 2023. On the other hand, data from the European Commission (EC) from the Hydrogen Strategy [3] and other documents show that only in the European Economic Area (EEA) the total installed capacity of electrolysers is about 1 GW. Examples of interesting and significant electrolyser facility projects in the world are presented below.

In December 2021, the world's largest 150 MW alkaline electrolyser facility powered by a 200 MW solar power plant was put into operation in the Ningxia region, in central China. Although the idea of the electrolyser is to be powered by solar energy, there is the possibility of taking electricity from the grid. The investment in the electrolyser facility amounted to about 200 million euros with a planned production of 27,000 tons of pure hydrogen per year, however, the realistic possibilities are somewhat lower and it is possible to achieve a production of 23,700 tons per year [10]. It is a project of the company that produces coal-based chemicals, Ningxia Baofeng Energy Group, which announced at the beginning of 2023 the construction of the world's largest plant for the production of olefins, i.e. synthetic polypropylene fibers, from pure hydrogen and coal, for which the investment will amount to around 6.5 billion euros. Olefins are widely used raw materials in the chemical industry, in the field of packaging, furniture, household appliances, cars, medicine and aviation. For the production of synthetic fibers, coal and pure hydrogen will be used as raw materials, while oxygen as a by-product will replace part of the coal as fuel. The planned production of 3 million tons of olefins per year would be achieved from 2.6 million tons of coal and 400 thousand tons of pure hydrogen. Compared to pure hydrogen plants, such projects should produce an additional 1.2 million tons of methanol, save more than 2.5 million tons of coal, and reduce carbon emissions by 6.3 million tons every year [11].

Fig.3. Hydrogen Pro Elektrolyser [12]

At the end of 2022, the company Hydrogen Pro installed the world's largest electrolyser with a diameter of 2 m and a weight of more than 80 t in a test facility on the Herøya peninsula in Norway, which was manufactured in a factory in Tianjin, China. A high-pressure alkaline electrolyser can produce 1100 m3/hour of hydrogen, which corresponds to the production of 100 kg of pure hydrogen per hour [12]. With the exception of the project in Norway, there are mostly smaller capacity electrolysis plants in Europe.

As part of the EU-funded GrInHy2.0 project, a demonstration plant for the production of pure hydrogen by steam electrolysis using waste heat from the Salzgitter Flachstahl GmbH iron and steel plant, in the city of Salzgitter in northern Germany, was developed in 2020. The facility is presented as the world's largest high-temperature electrolyser (HTE) for energy-efficient hydrogen production. The nominal power of the electrolyser is 720 kW, and it can produce 200 m3/hour of hydrogen under normal conditions. By the end of 2022, the plant is expected to operate for at least 13,000 hours, producing about

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100 tons of high-purity hydrogen (99.98%), which will be used for annealing processes in integrated steel plants as a substitute for hydrogen produced from natural gas [13]. The Salzgitter Group has selected technology group ANDRITZ to supply one of Europe's largest green hydrogen plants for the SALCOS® program, which aims to achieve virtually CO2-free (green) steel production. ANDRITZ will build a 100 MW electrolysis plant at the Salzgitter Flachstahl GmbH site on an EPC basis, incorporating pressurized alkaline electrolyser technology from HydrogenPro. Starting in 2026, the plant will produce around 9,000 tons of green hydrogen per year, which will be used to produce green steel. [28] The conversion to a virtually CO2-free steel production at the Salzgitter site is to be completed by the end of 2033, well ahead of the statutory requirements.

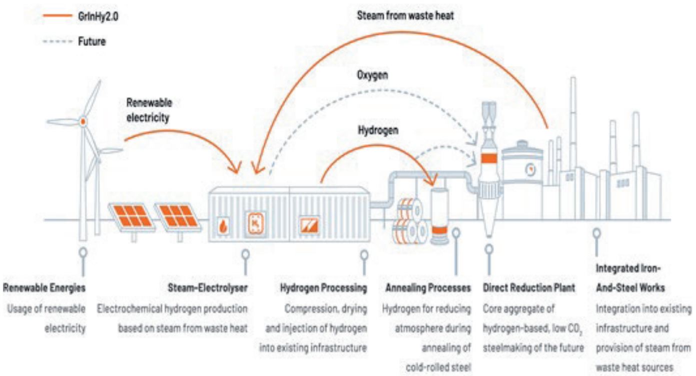

Fig. 4. Project GrInHY 2.0 – process [13]

The Danish company Green Hydrogen Systems designs and manufactures standardized, modular, pressurized alkaline electrolysers intended for the production of hydrogen exclusively from renewable energy sources. With the aim of accelerating the production of pure hydrogen on a large scale, within the GreenHyScale project, funded by Horizon 2020, it is planned to build a 100 MW electrolyser in the GreenLab Skive energy park in Denmark. The project started in 2021 and will last until 2026, the costs amount to 53 million euros, of which 30 million euros are financed from EU funds. In March of this year, the prototype of the electrolyser with a capacity of 6 MW, weighing 70 tons, was completed and testing began, which will last until the end of the year [14].

Apart from the examples of projects shown, the EU finances numerous other projects with the aim of solving the problem of hydrogen production and facilitating the decarbonisation of Europe, whereby the funding from the 2020 Green Deal Call for the development of a 100 MW electrolyser alone amounted to 90 million euros [15]. Examples of supported projects are shown in the following table.

Table II

Examples of Supported Hydrogen Projects from EU Funds [15]

Acronym	Cost (€)	EU funds (€)	Project (Country)
REFHYNE II	147.365.995	32.431.618	Clean Refinery Hydrogen for Europe (Germany)
GreenHyScale	52.982.524	30.000.000	Production of green hydrogen with a capacity of 100 MW in an industrial environment (Denmark)
GREENH2SINES (GREENH2-ATLANTIC)	76.614.020	30.000.000	Flexible green hydrogen production process with a capacity of 100 MW with hybrid RES (Portugal)

IV. Electrolyser Development Plans

According to the IEA report, the realization of all electrolyser projects in preparation could lead to an installed global capacity of 170-365 GW by 2030 [8]. Although the overlooked figures seem large, such a pace of growth, in relation to the currently installed capacities, is not fast enough to achieve the IEA "Net Zero Emissions by 2050" scenario with the goal of zero rate of CO2 emissions in the global energy sector - installed capacities should be above 560 GW by 2030.

Hydrogen valleys are being established around the world to help develop hydrogen projects, and there are currently more than 80 potential hydrogen valleys on five continents (Europe, Asia, North America, South America and Australia), of which the largest number is in Europe (74%) [9]. Hydrogen valley projects cover all the necessary steps in the hydrogen value chain, from production to storage and transportation / distribution of hydrogen to end users. Also, incentive programs for pure hydrogen are being established, such as the program in the United States of America (USA) where there is support for the production costs of pure hydrogen of 3 USD/kg, which makes the USA an attractive market for hydrogen production [16].

The announced significant worldwide development projects include electrolysis plants with the capacity of:

- 260 MW for the production of 20,000 tons of hydrogen per year in the town of Kuqa, on the territory of Xinjiang, Northwestern China (Chinese oil giant Sinopec) – the construction of the electrolyser began in 2021 and is in operation from July 2023, and the construction of the storage tank is also planned for hydrogen storage and pipelines for transporting hydrogen to the nearby oil refinery [17],
- for the production of 30,000 tons of hydrogen and 240,000 tons of oxygen per year in the Inner Mongolia Autonomous Region (Sinopec) - the construction of the electrolyser began in early 2023, the products will be used for carbon reduction in the neighboring pilot project of energy-intensive coal processing [18], and it is planned the construction of a pipeline with a length of more than 400 km from Inner Mongolia to Beijing for long-distance hydrogen transport with an annual capacity of 100,000 tons [19],
- about 840 MW in Louisiana, USA (DG Fuels, HydrogenPro partner) [16].

The announcement of the construction of a global gigafactory of electrolysers in Massachusetts, USA, which should correspond in price and size to a quarter of the cost of comparable PEM or alkaline electrolysers, is interesting, given that they are electrolysers with anion exchange membrane (AEM) designed with the aim of cheap mass production, without precious metals [20]. Factories for the production of electrolysers are being built or are being planned all over the world.

As for European goals, in July 2020 the EC presented the Hydrogen Strategy for a climate-neutral Europe, in which pure hydrogen is highlighted as one of the key levers for a successful energy transition. The strategy expects a gradual development:

- Phase 1 from 2020 to 2024 – increasing the capacity of the electrolyser by at least 6 GW with the production of up to one million tons of renewable hydrogen (compared to the current capacity of about 1 GW),
- Phase 2 from 2025 to 2030 – increase in electrolyser capacity by at least 40 GW of electrolysers with the production of up to 10 million tons of renewable hydrogen (requiring an additional 80 GW of RES),
- Phase 3 from 2030 to 2050 – reaching maturity of renewable hydrogen technologies and wide application.

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The EU strategy for hydrogen also mentions investment plans at the gigawatt level and that the list of global investments includes around 8.2 GW of electrolysers by 2030, of which 57% are in Europe, or 4.7 GW. As in the case of world plans, the European development plans have lagged behind the necessary pace of growth to achieve the goals set out in the strategic documents. However, later reports provide more optimistic indicators of the growth of hydrogen projects. The proposed electrolyser projects that should be in operation in 2024 have a total capacity of 5.2 GW, which is within reach of the set goal of 6 GW by 2024 [21].

The EU has developed several different financial instruments to help finance hydrogen projects, which can be reviewed through the Hydrogen Public Funding Compass, and are structurally divided into EU funding programs and national funding programs [22].

A. The Croatian Hydrogen Strategy and Project Example

The Croatian hydrogen strategy until 2050 [1] was adopted in March 2022, and the basis for its preparation is based on the National Development Strategy of the Republic of Croatia until 2030 and the Energy Development Strategy of the Republic of Croatia until 2030 with a view to the year 2050 . The Croatian strategy has set the goal of reaching 70 MW of electrolysers by 2030 and 2750 MW by 2050, and the movement of the required capacities of electrolysers by year is shown graphically in Figure 5. The figure shows the required capacities of electrolysers that obtain electricity for hydrogen production from network and exclusively from RES. The strategy also sets goals for the share of hydrogen in total energy consumption (0.2% by 2030, 11% by 2050), the number of hydrogen filling stations (15 by 2030, 100 by 2050) and the number of patents related to the economy based on hydrogen (5 by 2030, 50 by 2050), whereby the initial value for all performance indicators is zero (0) according to the situation in 2021/2022 years.

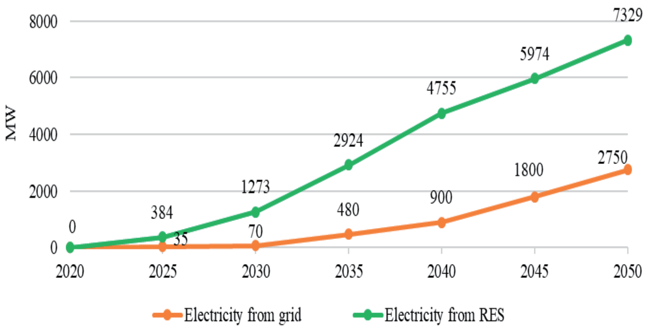

Fig. 5. Projected capacities of electrolysers in Croatia until 2050

The establishment of hydrogen valleys at the world level was mentioned, and one of the potential hydrogen valleys is the Northern Adriatic Hydrogen Valley, for which 25 million euros have been allocated with the aim of developing a transnational hydrogen valley between the Autonomous Region of Friuli Venezia Giulia (Northeastern Italy), Slovenia and Croatia [23]. Key stakeholders from the three countries will develop pilot projects for the production of more than 5,000 tons of renewable hydrogen per year and deal with its storage, distribution and use for the decarbonisation of important industrial sectors (including transport).

In the territory of the Republic of Croatia, INA d.d. started the procedures for the realization of a plant for the production of pure hydrogen with two photovoltaic power plants at the location of the Refinery in Kostrena. The proposed project envisages the construction of an electrolyser with a capacity of 10 MW for the production of 4.5 tons of hydrogen per day, or about 1,500 tons per year, and will be intended for the transport sector of Croatia and for own consumption in INA's refinery. Co-financing of the project is expected from the funds of the National Recovery and Resilience Plan (NRRP), but according to the available information, the project began to be conceived before the preparation of the RRP, i.e. in 2018 [24].

Another well-known project for the construction of a hydrogen production facility in Croatia exists in the HEP group, and it refers to the use of the existing location of KTE Jertovec for the installation of a battery system and an electrolyser for the production of hydrogen with associated systems. According to the environmental permit, the planned exit from KTE Jertovec is on December 31, 2023, which opens up new possibilities for using the location. With regard to the current conditions in the EES, the construction of the infrastructure and the transition to low-carbon energy sources, in December 2021 a conceptual solution and techno-economic analysis of the installation of the battery system and electrolyser with associated systems at the KTE Jertovec location was prepared. The next steps in the development of the project relate to the creation of project documentation for obtaining a building permit, which is expected to be by the end of 2025. Current project plan is 16 MW/16 MWh capacity of battery system and 9 MW electrolyser capacity with storage for at least two day production of hydrogen (at least 4 hours per day in periods of low wholesale electricity prices).

V. Problems, Obstacles and Guidelines

The application of renewable hydrogen is expected mostly to balance the power system based on RES, providing the necessary flexibility, for daily or seasonal storage with the aim of increasing security of supply in the medium term and in traffic [3]. The EC intends to use hydrogen as the main solution for reducing greenhouse gas emissions in sectors that are difficult to decarbonize and where electrification is difficult or impossible (for example, steel production or heavy goods vehicle transport) [25].

The issue of the development of hydrogen projects was addressed through the analysis of technical, environmental and regulatory aspects in chapter 2.2, and various issues were also addressed through several reports at the HRO CIGRE 15th Symposium on the power system management in November 2022, which is also an indicator of interest and topicality topics.

Levačić and Teklić in their report [26] state the main obstacles in the development of hydrogen production according to the document of the International Renewable Energy Agency (IRENA) [27], namely: high production costs, lack of necessary infrastructure for production and further use, significant energy losses (30-35%), lack of recognition of value and benefits and the need to ensure long-term sustainability.

Keeping in mind the development of the circular economy, additional obstacles and issues are:

- where to use waste heat,
- where to use oxygen - release into the atmosphere or additional systems for drying and compressing oxygen required in case of preparation for sale,
- water availability – the problem of water poverty,
- how to solve the problem of transportation and the energy needed for transportation – problems with compression and use of hydrogen in another (remote) location and the consequent increase in the carbon footprint.

Questions that seem to be partially resolved:

- availability of cheap clean electricity for electrolysis - from RES sources, but consequently the problem of increasing inflexibility and intermittency of the system - electrolysis systems with higher operating ranges and faster response

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times are better suited for providing operational flexibility, and systems with higher efficiencies/capacity factors are better suited for providing longer duration flexibility, such as seasonal storage,

- technical and safety obstacles due to the easy flammability of hydrogen - setting safety standards during production, transport and storage, as well as for the monitoring and verification system,
- infrastructure development required for further development – construction of local networks and new transport options, including conversion of existing gas infrastructure.

Further to the described obstacles, guidelines for increasing the production of pure hydrogen include [26]: development of a model for the use of hydrogen in the power system work support functions, removal of regulatory obstacles, establishment of a common market and further development of technology at lower prices.

From the point of view of running the power system as a potential location for the production of pure hydrogen, locations are proposed where more electricity will be produced in relation to the required consumption [26], however, considering that these are usually areas of low level of consumption and other forms of energy / energy sources, thereby increasing the problem of hydrogen transport. The guideline for the development of hydrogen projects, based on the analysis done in this report, would be the development of such projects based on the principles of the circular economy and looking at the wider picture of the utilization of products created by electrolysis. In doing so, priority should be given to existing plant locations that are no longer suitable for operation for technological, economic or environmental reasons, and have a certain part of the infrastructure built that can be used for the production and transport of hydrogen.

Given potential uncertainties—such as the availability of renewable energy sources, the future cost of electricity, policy decisions, techno-economics of hydrogen facilities, or the performance of electrolysers—modeling efforts may include multiple scenarios or probabilistic techniques to capture the range of possibilities. To accurately capture the flexibility of electrolysis-based hydrogen production as a flexible load, modelers need to accurately represent (1) the operating characteristics of hydrogen production, and (2) the flexibility of hydrogen end uses, which also depend on the availability of hydrogen storage buffers. It is crucial to take into consideration the operating regime and goals of the electrolysis plant, recognizing that hydrogen production facilities are unlikely to treat the provision of electricity and flexibility as their primary objectives [33]. Robust business models for both the production and use of clean hydrogen and its derivatives can develop only if the necessary infrastructure is available with sufficient lead time. The techno-economic optimization of hydrogen production plants with water electrolysers is based on a complex system model and depends highly on the boundary conditions and the input parameter. Oversizing the capacity of a plant becomes less attractive except in cases of exceptionally low-cost electricity.

The Commission Delegated Regulation 2023/1184 contains detailed rules on the conditions under which electricity used to produce hydrogen may be counted as fully renewable according to European Union (EU) law [30]. Renewable hydrogen producers will have the possibility to sign long-term renewable power purchase agreements with existing installations (until 1 January 2028) or to conclude power purchase agreements (PPAs) with new and unsupported renewable electricity generation capacity. Fuel producers may count electricity taken from the grid as fully renewable if the installation producing the renewable hydrogen is located in a bidding zone where the average proportion of renewable electricity exceeded 90% in the previous calendar year and the production of renewable hydrogen does not exceed a maximum number of hours set in relation to the proportion of renewable electricity in the bidding zone. Otherwise, in the bidding zone the emission intensity of electricity needs to be lower than 18 gCO_2eq/MJ.

The EU Hydrogen Bank, a pillar of said hydrogen strategy, serves as a bridge between wary investors and, still as of yet, high CAPEX marred projects with stiff commercial competition. Based on an open auction system with a fixed premium for renewable hydrogen production within the EU, the Bank has already implemented its first trial auction with a budget 800 million Euros and the contracts set were awarded in May 2024. The exact consequences of the initial auctions will be hard to determine for some time until a tangible effect can be felt and quantified, however there is available information about the immediate consequences of these auctions. Out of 132 bids, 119 proposals were considered eligible and admissible. The final tally of projects selected amounted to 7 projects located in 4 European nations as shown in Table III. The selected projects have cumulatively been awarded a little under 720 million Euros and are expected to mitigate 10 million tonnes of CO2 emissions. The subsidies per project ranged from 8 million to 24 million Euros [31].

Table III

Projects that were awarded funding under the Hydrogen Bank's pilot auction [31]

Project	Coordinator	Country	Bid volume [ktH_2/10 yrs]	Bid capacity [MWel]	Expected GHG mitigation [$ktCO_2$/10 yrs]	Build price [EUR/kg]
eNRG Lahti	Nordic Ren - Gas Oy	Finland	122	90	836	0,37
El Alamillo H_2	Benbros Energy S.L.	Spain	65	60	443	0,38
Grey2Green-II	Petrogal S.A.	Portugal	216	200	1477	0,39
Hysencia	Angus	Spain	17	35	115	0,48
Skiga	Skiga	Norway	169	117	1159	0,48
Catalina	Renato Ptx Holdco	Spain	480	500	3284	0,48
MP2X	Madošuapo wer 2x	Portugal	511	500	3494	0,48

VI. Conclusion

According to the research of existing projects of electrolysis facilities in the world, it can be concluded that most of them are pilot or test projects financed from research and development projects, or projects of large companies that have factories or industrial facilities where they can use hydrogen or use existing resources (for example waste heat). Examples of projects in the world can be used to acquire new information and ideas, but the construction and application of electrolysis plants should be adapted to the conditions of a certain area, and not blindly copy solutions that are not universally applicable, but specific to a certain area. A good direction is the utilization of existing resources, for example the location of existing facilities that are no longer suitable for operation due to technological, economic or environmental reasons, but even in this case a detailed technological-technical concept is required looking at the broader picture of the energy sector and an economic-financial analysis of the profitability of the investment. Announced clean hydrogen supply globally has reached significant amount of renewable hydrogen production through 2030. However, only 7% of investments in clean hydrogen overall have passed final investment decision (as of December 2023). Continued efforts are nee-

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ded to foster the faster maturing of projects from announcement to deployment. The current support schemes are complex, partly tailor-made and seem to lack simplicity and scalability. Improving feasibility of business models in all techno-economic-regulator aspects are crucial for ambitious renewable hydrogen production deployment.

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