ECOLOGICA, Vol. 32, No 118 (2025), 111-121
https://doi.org/10.18485/ecologica.2025.32.118.4
Originalni naučni rad
UDC: 004.8
502.131.1:620.9(497.11)

Perspectives on the Application of Artificial Intelligence (AI) in the Development of Hydrogen Energy in the Republic of Serbia

Perspektive primene veštačke inteligencije (AI) u razvoju vodonične energije u Republici Srbiji

Dušan Vještica[1], Ilija Ćosić[2], Nikola Gradojević[3], Vladimir Đaković[4]*

[1]Kosmos JSC, Banja Luka, Republic Srpska, Bosnia and Herzegovina /
Kosmos a.d., Banja Luka, Republika Srpska, BiH

[2,3,4]University of Novi Sad, Faculty of Technical Sciences, of Novi Sad, Serbia /
Univerzitet u Novom Sadu, Fakultet tehničkih nauka, of Novi Sad, Srbija

* Corresponding author / Autor za prepisku

Received / Rad primljen: 07.04.2025, Accepted / Rad prihvaćen: 10.05.2025.

Abstract: Green hydrogen has been globally recognized as the fuel of the future, primarily aimed at reducing the footprint of fossil fuels. The concept envisions hydrogen being utilized both as an energy source and as a means of energy storage. Plans include its application in transportation, heating, and various industrial sectors such as the production of copper, iron, aluminum, fertilizers, and cement. Due to its dual role and versatility across different applications, hydrogen energy is gaining prominence and is increasingly acknowledged in the pursuit of a sustainable energy future. To bridge the gap between its high potential and practical implementation. Artificial intelligence (AI) and its applications such as machine learning (ML) are emerging as an indispensable tool in bridging this gap in prediction based on pre-generated variables, and digital twin (DT) as a tool (AI) that provides the possibility of a virtual modeling platform. The Republic of Serbia is facing challenges of a technical, financial and regulatory nature on the hydrogen map, and in order to connect to global development directions in this area, the application of tools (AI) can be a good option related to strategic development. This paper points to the possibility of applying tools (AI) in hydrogen energy at all stages of the life cycle, with a special focus on the optimal design of hydrogen-based (PV) generation systems. As well as the integration of hydrogen systems with wider energy networks and systems. The paper further clarifies the optimal-cost design of a Power-to-hydrogen (PtH) system for hydrogen production. It points to the possibility of application (AI) in this model, and thus gives a recommendation for the application of (AI) and its applications in the strategic development of hydrogen energy in the Republic of Serbia.

Keywords: green hydrogen, artificial intelligence, digital twin, power-to-hydrogen.

Sažetak: Zeleni vodonik je u globalnom smislu proglašen gorivom budućnosti, sa primarnim zadatkom da smanji otisak fosilnih goriva. Ideja je da se vodonik u budućnosti koristi kao energent, ali i kao baterija za skladištenje energije. U planu je da se vodonik upotrebljava za transport, grejanje, industrijske grane kao što su proizvodnja bakra, gvožđa, aluminijuma, veštačkog đubriva i cementa. Zbog dvojne uloge i primene u različitim aplikacijama vodonična energija zauzima primat i postaje sve više priznata u održivoj energetskoj budućnosti. Iz navedenih razloga potrebno je premostiti jaz između visokog potencijala i praktične primene. Veštačka inteligencija (AI) i njene aplikacije kao što su mašinsko učenje (ML) se nameću kao nezaobilazan alat u prevazilaženju ovog jaza u predviđanju na temelju unapred generisnih varijabli, a digital twin (DT) kao alat (AI) koji pruža mogućnost virtuelne platforme za modeliranje. Republiku Srbiju na vodoničnoj mapi očekuju izazovi tehničke, finansijske i regulatorne prirode, a da bi se konektovala na globalne pravce razvoja u ovoj oblasti primjena alata (AI) može biti dobra opcija vezana za strateški razvoj. Ovaj rad ukazuje na mogućnost primene alata (AI) u vodoničnoj

[1]*orcid.org/0009-0003-0744-566X, e-mail: dusan.vjestica@kosmos.ba*
[2]*orcid.org/0000-0001-9796-4452, e-mail: Ilijac@uns.ac.rs*
[3]*orcid.org/0000-0003-4001-3159, e-mail: ngradoje@uns.ac.rs*
[4]*orcid.org/0000-0002-3282-2899, e-mail: v_djakovic@uns.ac.rs*

energiji u svim fazama životnog ciklusa, sa posebnim fokusom na optimalno projektovanje sistema za proizvodnju vodonika na bazi (PV-a, kao i integraciju vodoničnih sistema sa širim energetskim mrežama i sistemima. Rad dalje pojašnjava optimalan-troškovni dizajn sistema Power-to-hydrogen (PtH) za proizvodnju vodonika. Ukazuje na mogućnost primjene (AI) u ovom modelu, te na taj način daje preporuku za primenu (AI) i njenih aplikacija u strateškom razvoju vodonične energije u Republici Srbiji.

Ključne reči: zeleni vodonik, veštačka inteligencija, digitalni blizanac, vodonična energija.

INTRODUCTION

Green hydrogen production is a key factor for decarbonizing the atmosphere and reducing the carbon footprint, and all future climate change mitigation scenarios emphasize the need for hydrogen to account for about 12% of global energy consumption by 2050 (IEA, 2022, 2023; EC, 2020; Department of Energy, 2020). Meeting such energy demand requires an increase in hydrogen production from the current 90 million metric tons (Mt) per year to about 600 (Mt) by 2050 (IEA, 2022; IRENA, 2022). Hydrogen is an energy source, but also an energy carrier that should play a key role in the decarbonization of industry and transport as the branch with the highest carbon emissions (Rissman et al., 2020; IRENA, 2020). Hydrogen is used to store energy from renewable sources of electricity (Terlouw et al., 2022), then as a chemical raw material and precursor of synthetic hydrocarbons for the production of e-fuels (Van der Spek et al, 2022; Ueckerdt et al., 2021). Due to its high calorific value compared to fossil fuels, hydrogen acts as an energy vector, and hydrogen projects and development policies around the world are experiencing great momentum. Hydrogen and fuels derived from it cover a wide range of applications in transportation, heating and industrial production such as production of copper, iron, aluminium, artificial fertilizers and cement. Despite the great potential, green hydrogen production faces the challenges of high capital investments (CAPEX) and operational costs (OPEX). In order to ensure the economic viability of hydrogen production, in addition to finding the optimal combination of renewable energy sources, geographical location, suitable climatic conditions and water electrolysis technologies, it is necessary to find adequate sources of financing, and to adapt the entity government's fiscal policy to development projects. Renewable sources such as wind, water, sun are potential and promising sources of green energy (Terlouw et al., 2022; VanderSpek et al, 2022; Ueckerdt et al., 2021). However, there are still significant limitations to their full development because they are highly variable resources and depend on weather conditions (EU, 2023a), which prevents the optimal use of energy generated by these methods (EU, 2023b). In this context, the need to develop methodologies and strategies to solve these complex challenges becomes imperative. Therefore, it is necessary to optimally design the system for the production of hydrogen from renewable sources, which includes the analysis of the unit costs of hydrogen production (LCOH) as well as the analysis of the costs of energy production (LCOE) (Oliva, Garcia, 2023). This analysis must carefully consider the technology used, the electricity generation environment with meteorology, (CAPEX), (OPEX), the financing rate, the efficiency of renewable and electrolysis systems, as well as the lifetime of these systems (depreciation).These challenges have been addressed by several researchers in the world with a focus on different issues; Hassan et al. (2023) made a detailed review and study on the production of green hydrogen from a techno-economic, ecological and social perspective. Scheepers et al. (2023) determined that the optimal design and operation of the electrolyzer strongly depends on the framework conditions under which the operation takes place, such as the investment costs in the electrolyzer and the price of electricity. A strong dependence (LCOH) on the price of electricity was also found by Superchi et al. (2023) who conducted a techno-economic analysis of green hydrogen production for the decarbonization of steel production. Shams et al. (2021) use a machine learning (ML) algorithm to predict wind and (PV) energy constraints. Based on this, an original planning model was developed to reduce the waste of wind and (PV) energy using battery and hydrogen storage systems. Al-Othman et al. (2022) have comprehensively reviewed the application of (AI) techniques in hybrid renewable energy systems (HRES), especially solar (PV) and wind energy integrated with fuel cells. This study further clarified that the main strengths of the (AI) solution revolved around predicting shortfalls (HRES) during peak load periods as well as intermittent power generation. Al-falahi et al. (2017) conducted a comprehensive review and critical comparison on optimization approaches based on stand-alone solar and wind hybrid energy systems. This study revealed a growing interest in the development of stand-alone optimization algorithms (HRES). To date, reported optimization methods can be roughly classified into classical algorithms, modern techniques, and software tools. Modern techniques, based on some (AI) algorithm, gain an advantage over classical algorithms due to their ability to solve some complex problems. Applications (AI) are powerful tools that could solve the complexity of the energy transition, improve system efficiency, reduce costs, and accelerate the speed of the decarbonization transition (Zhou et al., 2020; Zhou, Zheng, 2020). They are primarily applied to the production of renewable energy sources, demand forecasting, optimization of network operation and energy demand management (Hannan et al., 2021; Abdalla et al., 2021). "The Republic of Serbia is constantly investing in its energy potential, and therefore in renewable sources of sun and wind, so in 2025 it should get new wind power plants with a capacity of 76 megawatts and solar power plants with a power of about 62 MW, which means that it will have wind parks with a power of 684.2 MW on the network, of which the installed capacity of new wind power plants will be 76 MW. The market premium will be used for 94.4 MW, and feed-in tariffs 60.3 MW of electricity will be produced by solar power plants, of which 18.7 MW are new capacities. The projected capacity of the producers is 123.6 MW, of which the new capacity is 61.7 MW. Solar and wind should produce 4.6 percent of the total production. The stated situation is stated in the Energy Balance of the Republic of Serbia for the year 2025, Official Gazette of RS No. 12/2025-28 of February 7, 2025.

The Republic of Serbia currently has two conceptual projects in the field of green hydrogen with the idea of developing experimental facilities on them. The first one is called "Pančevo Hydrogen Valley". It is about a project that would be located on the Danube Corridor 7, one of the most important European roads, which is actually a waterway along the Danube from Germany to the Black Sea. The idea of this project is to use solar and wind energy to produce electricity, in order to further obtain green hydrogen through electrolysis. Floating plants for the production of electricity and hydrogen will be built on the Danube or the Sava, on which mobile wooden platforms would be placed, on which, on the first level, there would be hydrogen tanks, and solar panels or wind generators, or a mix of both, would be placed above the tanks. The Port of Pancevo represents a good technical opportunity to build a pilot plant for the start of hydrogen production from solar panels. The second project is the integration of hydrogen into the existing gas pipeline infrastructure of the pilot project in Sombor. What is important is the percentage of hydrogen that will be released through gas pipeline systems, due to its technical and safety nature. Since hydrogen is technically a different type of gas than natural gas, the existing infrastructure therefore requires certain changes and adaptations. Therefore, it is important to see what those changes are so that hydrogen can be used and transported. In terms of investment, a smaller plant would be developed that would produce hydrogen from solar panels and then inject it into the gas pipeline system. Experiences from Greece, their preliminary tests, showed that hydrogen from 10 to 12% can be mixed with natural gas in certain situations and up to 15% and that it can be used as such in the existing gas system without significant interventions on the system. This is the reason that determines to develop this kind of project, but also to use all the benefits and experiences of this development project". Source, official announcement of the representative of the Ministry of Mining and Energy of the Republic of Serbia in Bloomberg Adria magazine.

The development of such experimental projects requires the use of new technologies and the application of powerful tools for the digitization of engineering systems such as (AI) and its applications such as (ML) and (DT). Artificial intelligence (AI) tools provide the opportunity to model new systems through digitization, work on improving their performance and reducing costs (Tai et al., 2023; Leng et al., 2021). (AI) methods are mainly used to predict variables generated at different stages of the supply chain: renewable sources (wind speed, solar radiation and ambient temperature), system output power, user load and terminal price of electricity. Industry 4.0 marks the transition to interconnected, automated manufacturing, integrating technologies such as the Internet of Things (IoT) and cloud computing. Industry 4.0 represents a significant upgrade in the manufacturing sector, introducing the concepts of a new generation of intelligent manufacturing (Wang et al., 2021). Manufacturing systems have the ability to observe physical processes and generate the corresponding (DT) in the physical domain. These systems are designed to acquire real-time data from the physical environment, facilitating simulation analysis. This strategy aims to improve efficiency and productivity while offering greater flexibility in manufacturing processes, making a step towards more agile and responsive manufacturing systems (Semeraro et al., 2023; He, Bai, 2020). A very important element of this era is (DT) technology, which connects physical and digital entities. In this way, production efficiency and innovation are increased by creating digital versions of physical systems for detailed analysis and optimization. The emergence of (DT) technology has opened new avenues to address this challenge in which production systems possess the ability to observe physical processes and generate the corresponding (DT) in the physical domain. These systems are designed to acquire real-time data from the physical environment, facilitating simulation analysis. This enables the execution of decisions, supported by real-time communication and in cooperation with human operators (Leng et al., 2021).

This paper indicates the importance of hydrogen energy in the context of energy transition globally and in a certain way gives recommendations and achievements for the development of hydrogen energy in the Republic of Serbia. There are many challenges facing hydrogen energy in the Republic of Serbia and they range from producers to regulators to customers, and they are burdened with technical, technological, financial and safety challenges. All these challenges create an opportunity for development in the mentioned areas, these opportunities must be recognized and supported by investors, users, the scientific community, research centers and ultimately the State. Another dimension consists of benefits through the possibility of international financing, access to funds from EU funds, a significant part of which are grants.

The paper aims to identify and propose the best solutions for overcoming the challenges that the green hydrogen sector in the Republic of Serbia should face with the help of (AI) and its applications. In chapter number 2, the system approach is presented and the methodology of design and development (PtH) of the system supported by tools (AI) in order to optimize the process is presented. Chapter 3 provides a brief overview of global challenges in the field of (AI) and green energy to understand the importance of these areas. It further focuses on the regulatory framework and the current situation in the Republic of Serbia in order to identify the entity's potential in future research and development projects..

1. SYSTEM DESIGN METHODOLOGY (PtH) AND THE ROLE OF TOOLS (AI) IN PROCESS OPTIMIZATION

Power-to-hydrogen (PtH) system is shown in Fig.1 (Marocco et al., 2023). The electrolyser is powered by electricity that comes from an on-site solar (PV) system or from the grid. Hydrogen storage is included to reliably cover the end user's hydrogen demand. Battery storage can also be integrated to improve the exploitation of the local solar resource. Finally, excess renewable energy, if not stored, can be fed into the electricity grid to improve the profitability of this business model.

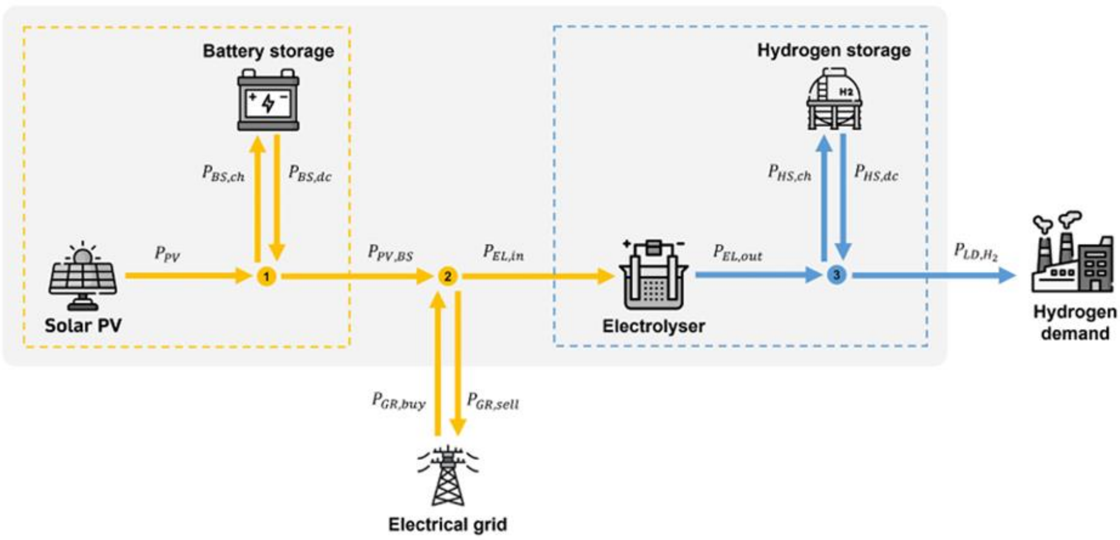

Figure 1. Scheme of the (PtH) system

Here, three different power balances must be satisfied for the simulation time periods. The first power balance (electricity, in kW) is expressed as follows:

$$P_{PV}(t)+P_{BS,dc}(t)=P_{BS,ch}(t)+P_{PV,BS}(t) \quad (1)$$

Where PPV(t) is the power generated by the (PV) plant, $P_{BS,dc}$ is the battery discharge power, $P_{BS,ch}$ is the battery charge power and $P_{PV,BS}$ is the net power output of the solar/battery subsystem. The battery in the (PV) system is designed as a support for maximizing the exploitation of renewable energy sources on site.

The second power balance (electrical energy, in kW) defines the interaction (PtH) of the system with the electrical network. The electricity required for the electrolyser can be taken from a solar (PV) plant or from the grid. That is, excess renewable energy can be delivered to the grid:

$$P_{PV,\,BS}(t)+P_{GR,buy}(t)=P_{EL,in}(t)+P_{GR,sell}(t) \quad (2)$$

Where $P_{GR,bay}$ is the power purchased from the grid, $P_{GR,sell}$ is the power sold to the grid, and $P_{EL,in}$ is the input power of the electrolyzer.

The third power balance (hydrogen, in kW) refers to the production of hydrogen in the subsystem. It determines the output power of the electrolyser and the power exchange with the hydrogen storage to cover the hydrogen demand of the end user. This can be expressed as follows:

$$P_{EL,out}(t)+P_{HS,dc}(t)=P_{HS,ch}(t)+P_{LD,H2}(t) \quad (3)$$

Where $_{EL,out}$ is the output power from the electrolyzer, $P_{HS,DC}$ is the hydrogen storage discharge power, $P_{HS,ch}$ is the hydrogen storage charging power and $P_{LD,H2}$ is the hydrogen demand that must be covered (which is set as input to the problem).

The modulation range of the electrolyzer is defined according to the following expressions:

$$P_{PL,in}(t) \geq y_{EL,min} \cdot P_{EL,rated,aux}(t) \quad (4)$$

$$P_{PL,in}(t) \leq y_{EL,max} \cdot P_{EL,rated,\,aux}(t) \quad (5)$$

Where $y_{EL,min}$ and $y_{EL,max}$ represent the lower and upper limits of the modulation range of the electrolyzer (they are defined as a percentage of the nominal power of the electrolyzer). $P_{EL,rated,aux}$ is an auxiliary variable introduced to describe the product of the design variable $P_{EL,rated}$, rated (continuous) and the variable variable δ_{EL} (binary);

$$P_{EL,\,rated,aux}(t)=P_{EL,rated} \cdot \delta_{EL}(t) \quad (6)$$

Where δ_{EL} is a binary variable that is in state "1" if the electrolyzer is on and in state "0" if the electrolyzer is off. The partial load performance curve is used to model the operation of the electrolyzer (Marocco et al., 2023). For each point of the modulation range, the curve relates the output power of the electrolyzer (for hydrogen) to the input power of the electrolyzer (for electricity). One of the most striking aspects of the application of (AI) is related to electrolysis for hydrogen production, i.e. (AI)-based electrolyzer performance optimization. They are used in the development of new catalysts for hydrogen production, enabling inventions in energy production techniques (Le et al., 2021). In the field of hydrogen fuel cells, AI enables real-time operational optimization by predicting the performance of solid oxide fuel cells while taking into account other important parameters such as CO_2 hydrogenation and hydrogen power density (Peksen, 2023).

Energy storage technologies, at any time step, the amount of energy in the battery storage can be calculated based on the energy stored in the previous time step and the working power of the battery:

$$E_{BS}(t+1) = (1-\sigma_{BS}) \cdot E_{BS}(t) + \eta_{BS,ch} \cdot P_{BS,ch}(t) \cdot \Delta t - (P_{BS,dc}(t) \cdot \Delta t)/\eta_{BS,dc} \quad (7)$$

Where E_{BS} (in kWh) is the energy stored in the battery storage, and σ_{BS} (in %/h) is the self-discharge coefficient for storage batteries (that is, energy losses expressed as a percentage of the nominal energy in each time step), $\eta_{BS,ch}$ (expressed in %) is the battery charging efficiency, $\eta_{BS,dc}$ (expressed in %) is the battery discharging efficiency and Δt (in hours) is the duration of the time step. Analogously, the behavior of hydrogen storage technology is described by the following linear function:

$$E_{HS}(t+1) = E_{HS}(t) + P_{HS,ch}(t) \cdot \Delta t - P_{HS,dc}(t) \cdot \Delta t \quad (8)$$

Where E_{HS} (in kWh) is the energy stored in the hydrogen storage. It should be noted that, unlike battery storage, the self-discharge coefficient does not appear in the energy balance of Eq. (8) because self-discharge losses for hydrogen storage are negligible. Inequalities (9) and (10) are introduced to limit the amount of energy that can be stored (with j = BS, HS):

$$E_j(t) \geq E_{j,rated} \cdot y_{j,min} \quad (9)$$

$$E_j(t) \leq E_{j,rated} \cdot y_{j,max} \quad (10)$$

Where $y_{j,min}$ and $y_{j,max}$ are min and max state of charge (SOC) values of the jth storage technology (Marocco et al., 2023).

Artificial Intelligence (AI) is becoming an essential factor in optimizing hydrogen storage systems to provide balancing for seasonal electricity needs, reduce energy insecurity for vulnerable communities and lower seasonal price spikes (Izadi et al, 2022). Figure 2. shows multiple approaches to store hydrogen, such as liquid, gaseous and solid fuel, and then using fuel cells can be converted into energy (Yun et al., 2024). One of the obstacles to hydrogen storage is the storage conditions as it requires low temperatures, high pressures and chemical processes. Applications (AI) and (ML) optimize hydrogen storage systems as they can analyze vast amounts of material data and improve the stored density and material properties. By integrating storage monitoring and data collection systems, they enable predictive maintenance as it can track wear and potential failure events to increase safety. Hydrogen can also be separated from natural gas and drawn from the pipeline network for end uses that require pure hydrogen. (AI) can play a constructive role in enabling the use of hydrogen in two ways namely; the first way is to set the appropriate concentration of the mixture considering the real-time data on pipeline characteristics and natural gas composition and the second way is to optimize the locations for injection and withdrawal of pure hydrogen from the natural gas pipeline (Melaina et al., 2013).

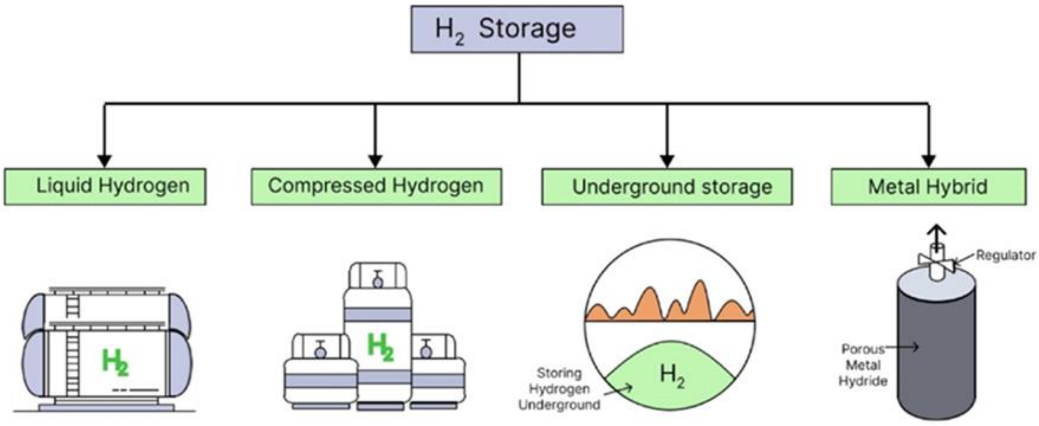

Figure 2. Conductor storage technologies, (Yun et al., 2024)

The function of optimizing the hydrogen supply system during its life cycle includes total net costs (NPC)O. Total NPC ($C_{NPC,tot}$) includes capital (CAPEX) and operating (OPEX) costs:

$$C_{NPC,tot} = C_{NPC,capex,tot} + C_{NPC,opex,tot} \quad (11)$$

The term $C_{NPC,capex,tot}$ is the investment in the project which is the sum of all the capital investments in the (PtH) system, including the (PV) generator, storage batteries (PV), electrolyser, hydrogen storage and infrastructure network equipment for (PV) and conductor.

$$C_{NPC,capex,tot} = C_{capex,PV} + C_{capex,BS} + C_{capex,EL} + C_{capex,HS} \quad (12)$$

The $C_{NPC,opex,tot}$ term is instead calculated according to the following expression (with j = PV, BS, EL, HS):

$$C_{NPC,opex,t} = \sum_{n=1}^{N} \frac{\sum_j C_{opex,j} + C_{GR,bay}}{(1+d)^n} \quad (13)$$

Where N (expressed in years) is the lifetime of the project, $C_{opex,j}$ is the annual operating cost of the jth component, $C_{GR,buy}$ is the annual cost due to electricity purchased from the grid and d is the discount rate (expressed in %). $C_{opex,j}$ is calculated as part (CAPEX) of the jth component. It also includes replacement costs in case the jth component has to be replaced during the nth year. It is important to point out that the target is the function of $C_{NPC,tot}$, it does not include revenues from the sale of surplus (PV) energy. This exclusion aims to prevent the (PtH) system from being oversized for the purpose of selling electricity to the grid, which is not even its primary goal (Marocco et al., 2023).

Artificial intelligence (AI) and its algorithms are key in enhancing the accuracy and efficiency in the performance of various power generation systems. By integrating historical data with meteorological forecasts, AI systems can develop highly accurate predictive models for energy output parameters (Sarma, Parmar, 2024).

In order to provide general criteria for the design (PtH) of the system and to describe its techno-economic and environmental performance, it is necessary to introduce different indicators, namely; System design indicators, energy indicators, economic indicators and environmental indicators and indicators.

Power ratio (PV) ratio (R_{PV} is defined as the ratio between (PV) rated power and electrolyzer rated power:

$$R_{PV} = P_{PV,rateo}/P_{EL,rated} \quad (14)$$

Electrolyzer ratio (R_{EL}) is defined as the ratio of electrolyzer power to the average hydrogen load:

$$R_{EL} = (P_{EL,rated} \cdot \eta_{EL,rated})/P_{LD,H2,avg} \quad (15)$$

Where $\eta_{EL,rated}$ (expressed in %) is the efficiency of the electrolyzer under nominal conditions, and $P_{LD,H2,avg}$ (in kW) is the average hydrogen load that should cover the power.

Autonomy of hydrogen storage (A_{HS}, in h) means the time period during which the hydrogen storage is able to cover the average hydrogen demand. It can be defined as the ratio of HS size to average hydrogen demand:

$$A_{HS} = E_{HS,rated}/P_{LD,H2,avg} \quad (16)$$

Battery storage autonomy (A_{BS}, in h) shows how long battery storage is able to cover the electrolyzer's energy needs under nominal conditions. It is determined by the ratio of the storage size of the battery to the nominal power of the electrolyzer;

$$A_{BS} = E_{BS,rated}/P_{EL.\ rated} \quad (17)$$

It is important to note that battery storage autonomy is defined in relation to the load that the battery (rated capacity) should meet, especially the rated power of the electrolyzer.

Energy indicators, Utilization (U_{PV}, in %) indicates the share (PV) of energy used by the electrolyser for hydrogen production, the remaining share (PV) of energy can be limited or delivered to the grid. This indicator is thus defined from the perspective of the (PtH) business case:

$$U_{PV} = \frac{\sum_{t=1}^{T}(P_{EL,in}(t)\Delta t - P_{GR,buy}(t)\Delta t)}{\sum_{t=1}^{T}(P_{PV,BS(t)\Delta t})} \quad (18)$$

Electrolyzer utilization (U_{EL}, in %) measures the energy utilization of the electrolyzer compared to the maximum amount it can use without any interruption:

$$U_{EL} = \frac{\sum_{t=1}^{T}(P_{EL,in}(t)\Delta t)}{\sum_{t=1}^{T}(P_{EL,roted}\Delta t)} \quad (19)$$

The share of the grid (y_{GR}, in %) represents the part of the electricity consumed by the electrolyser that comes from the grid, and the rest is produced locally by the (PV) plant:

$$y_{GR} = \frac{\sum_{t=1}^{T}(P_{GR,buy}(t)\Delta t)}{\sum_{t=1}^{T}(P_{EL,in}(t)\Delta t)} \quad (20)$$

The Share (PV) expressed as (y_{PV}, in %) represents the part of the electricity consumed by the electrolyser that comes from the (PV) plant on site. It can be calculated based on network participation as follows:

$$Y_{PV}=100\%-y_{GR} \quad (21)$$

Economic factors, the levelized cost of hydrogen (C_{H2}, price per kg) indicates the average net present cost of hydrogen production for a (PtH) system over its lifetime. It can be expressed by the following expression:

$$C_{H2} = \frac{C_{NPC,tot} - C_{GR,sell}}{\sum_{n=1}^{N}\frac{M_{H2}}{(1+d)^n}} \quad (22)$$

Where $C_{NPC,tot}$ is the NPC of the (PtH) system during its lifetime, calculated by formula (11), and C_{GR} is the annual revenue from the sale of excess electricity to the grid, and M_{H2} (kg in y) is the amount of hydrogen produced annually by the (PtH) system.

Environmental indicators, carbon footprint of hydrogen (ε_{H2}, in $kg_{CO2,e}/kg_{H2}$) indicates kilograms of CO_2 equivalents (CO_2,e) emitted per kilogram of hydrogen produced:

$$\varepsilon_{H2} = \frac{\sum_{t=1}^{T}(P_{GR,buy}(t)\Delta t\varepsilon_{GR}10^{-3})}{\sum_{t=1}^{T}(P_{EL,out}(t)\Delta t\Delta h_{H2}^{-1})} \quad (23)$$

Where ε_{GR} (in $g_{CO2,e}$/kWh) is the carbon intensity of electricity (ECI), i.e. how many grams of CO_2 are released per kilowatt-hour of electricity drawn from the grid (refers to the country mix) and Δh_{H2} (in kWh/kg_{H2}) because the heating value (LHV) of hydrogen is lower (Marocco et al., 2023).

Levelized cost of energy production (LCOE) per megawatt is the sum of investment in electricity production assets and operating costs during the life of the project, divided by production capacity in the same period, discounted at a financing rate that recognizes the time value of money (Burdack et al., 2023). To determine levelized energy costs:

$$LCOE = \frac{I_0 + \sum_{t=1}^{n}\frac{At(1,15)}{(1+i)^t}}{\sum_{t=1}^{n}\frac{M_{tl}}{(1+i)^t}} \quad (24)$$

Where different variables are considered: (I_0) represents the initial investment of the project, which includes mainly (CAPEX), i.e. investment in fixed assets, (A_t) indicates (OPEX) operating costs of the project, among which maintenance costs and profit tax (in the Republic of Serbia at a rate of 15%) are distinguished. The financing rate is denoted as (i), and (t) corresponds to the analysis period, usually set at 25 years, (Mt) represents the electricity generated in megawatt hours (MWh). The LCOE decreases over the years because the initial investment is reduced due to the fact that the technology has come down in price as it progresses and becomes more widely used, making it feasible to undertake projects involving this type of energy.

The levelized cost of hydrogen production (LCOH) represents the total cost of producing one kilogram of green hydrogen, taking into account both the initial investment and the operating and asset-related costs involved in the production process (Burdack et al., 2023):

$$LCOH = \frac{I_0 + \sum_{t=0}^{n-1}\frac{At(1,15)}{(1+i)^t}}{\sum_{t=1}^{n-1}\frac{P_t}{(1+i)^t}} \quad (25)$$

Where (P_t) represents the production of hydrogen per year in kilograms (kg). This cost is an encouraging prospect, as it is predicted to decrease significantly over the years, which will allow a competitive price to be achieved compared to fossil fuels.

It is applications (AI) such as machine learning (ML) architectures integrating technologies such as the Internet of Things (IoT) and cloud computing that can connect complex interdependencies in large data sets, but also simulate human cognitive processes to improve system efficiency. In parallel, (ML) algorithms autonomously continue to improve their predictive accuracy in a self-learning algorithm by importing new data into the models, which helps to model the complex physical and operational properties of energy systems (Sarma, Parmar, 2024; Burdack et al., 2023). Thus improving production performance with decreasing costs at the same time. These multi-domain applications (AI) are essentially illustrative of the revolutionary capabilities of (AI) in redefining hydrogen-based energy systems to support sustainable energy technologies (Kalinci et al., 2015). These technologies enable condition-based monitoring for fault removal, condition-based maintenance, and control of other variables to achieve optimal hydrogen production with the least amount of energy consumed, while offering real-time monitoring of the electrolysis process (Oladosu et al., 2024; Lv et al., 2024; Abdelkareem et al., 2022; Shoaei et al., 2024).

2. GLOBAL CHALLENGES AND REGULATORY FRAMEWORK IN THE FIELD (AI) and (OIE) in the REPUBLIC OF SERBIA

2.1. Global perspectives on artificial intelligence (AI) and green energy

The hydrogen-based economy has attracted the attention of more than 75 countries around the world to address the challenges of energy security, climate change and carbon emissions. The economies of these 75 countries account for more than half of the world's GDP, and their governments are investing billions of dollars in green hydrogen projects. Total hydrogen investment globally is likely to reach $300 billion by 2030, accounting for 1.4% of the global energy stock. In order to achieve net zero emissions by 2050, CO_2 emissions must be reduced by 45% by 2030 (Raman et al., 2022). Tools (AI) are recognized as being able to contribute to change, providing new ways to maximize the utility of energy systems operation, automation and control. A competitive policy framework related to the circular economy should be developed, adapting to new trends, forming sustainable development, which will improve the circular economy (Danish, Senjyu, 2023).

2.2. Regulatory framework in the field of Artificial Intelligence (AI)

The current projection shows that the value of the artificial intelligence market at the world level is more than 184 billion dollars, and that by the end of 2030 this market will reach the value of 826 billion dollars. According to the report of the European Commission: artificial intelligence will significantly contribute to the automation of 14% of jobs, while another 32% of occupations will experience major transformations. The Government of the Republic of Serbia has adopted the Strategy for the Development of Artificial Intelligence for the period from 2025 to 2030. This strategy will continue the accelerated development of artificial intelligence in Serbia, as a continuation of the strategy adopted in 2019. Serbia, as the first in the region of Southeast Europe, made a step forward in the management of the development of artificial intelligence and positioned itself as a leader in the region, which was also recognized through the chairmanship of the Global Partnership for Artificial Intelligence. The strategy includes further development in the areas of the legislative framework, investments in education, innovation and infrastructure, as well as increased application in the public sector. By adopting this strategy, the plans are aligned with the latest developments in the field of artificial intelligence, while the further development and application of this technology traces the path to the modernization of the state and society as a whole, following the goals of the "Leap into the Future 2027" program. The strategy was created as a result of a wide range of consultations of the professional community with the expert opinion of the Government Council for Artificial Intelligence.

2.3. Integrated energy and climate plan as a basis for development (OIE)

It is important to note that in the Republic of Serbia, progress has been made in the field of the legal and political framework for the implementation of projects to reduce emissions and decarbonize the atmosphere, because on March 23, 2021, the Law on Climate Change (Official Gazette of RS No. 26/2021) was adopted, which more closely defines the area of decarbonization, reduction of carbon dioxide emissions and fulfillment of obligations under the Paris Agreement and other acts of international law (EU regulations). Also, in the Republic of Serbia, there is a noticeable increase in collective awareness of environmental protection and pollution reduction, which primarily relates to air quality, which is threatened by the emission of carbon dioxide and other harmful substances.

In addition to the above, the following strategic documents were also adopted: Decision on determining the Energy Balance of the Republic of Serbia for the year 2025 (Official Gazette of RS No. 12/2025-28 of 07.02.2025); Energy Development

Strategy of the Republic of Serbia until 2040 with projections until 2050; Initial basis of the energy infrastructure development plan until 2028 with projections until 2030; Integrated national energy and climate plan of the Republic of Serbia for the period up to 2030 with a vision up to 2050. "By adopting the Integrated National Energy and Climate Plan for the period up to 2030 with projections up to 2050, we have defined a "road map" in the process of energy transition. In accordance with the imperative of decarbonization, the most significant changes are foreseen in the way of electricity production, where the determination is to significantly increase the capacities that use RES (Andrejević Panić et al., 2024).

Our goal is to provide 3.5 GW of new green energy from solar and wind power plants by the end of the decade, which means that almost every other megawatt-hour of electricity produced must be from RES". This was announced by the Ministry of Mining and Energy of the Republic of Serbia and published on the official website.

CONCLUSION

Artificial intelligence (AI) is the fastest growing branch of computer science and engineering, and hydrogen energy is the most important area in achieving energy security with a positive impact on climate change. Hydrogen energy acquires a special importance and role in the decarbonization of industry and transport as the branch with the highest carbon emissions, then in balancing the power and capacity of electric power networks, scientific and technological development, the development of innovative financing models, the influence on the creation of the profile of the optimal price of electricity and ultimately the development of the entity's economy. On the other hand, artificial intelligence (AI) plays a key role in modeling different energy systems, with a special focus on (OEI). (AI) methods enable more intelligent planning, management, forecasting of variables in supply chains, more convenient configuration, optimization, control and prognostic maintenance of both individual and integrated energy systems.

The paper provides a methodological approach to the development of hydrogen energy through development (PtH) model and brings examples of good practice of application (AI) globally in all phases of development, implementation, production, transport and storage. It further focuses on the energy market, the price movement of energy equipment and the analysis of the economic justification of hydrogen energy production with examples from the environment. The Republic of Serbia is constantly investing in the energy sector, with a focus on renewable energy sources, but also in the field of (AI) where significant progress has been achieved. This paper points to good practices and in a certain sense recommends the synergistic action of the energy sector and (AI) which should jointly generate benefits and give strong momentum to the development of hydrogen energy. Only the synergistic action of these sectors, the transfer of knowledge and scientific and technological achievements can contribute to the development of hydrogen energy. The development of hydrogen energy in the Republic of Serbia should certainly be adapted to the existing electricity and gas development plans in order to avoid multiplying resources and costs. This approach would create a well-founded scientific platform for adopting a hydrogen strategy as a key document for the future development of hydrogen energy. Global trends and scientific research show that challenges in the hydrogen energy sector exist with goals up to half a century, and the development chance should be based on such a platform. While the challenges in the sector (AI) and green energy there are opportunities for growth and development is based on realistic assumptions for the realization of multiple benefits, which is ultimately reflected in GDP growth. The recommendation for future research can be directed to the analysis of the state of the existing power and gas infrastructure, the technical and economic justification of the establishment of new production capacities, the possibility of integrating hydrogen energy into existing energy capacities, prognostic maintenance, security and resilience of energy networks and capacities.

Acknowledgement

This research was supported by the Ministry of Science, Technological Development and Innovation and the Faculty of Technical Sciences, Department of Industrial Engineering and Management, University of Novi Sad through the project "Improving the quality of teaching in the Department's study programs through the implementation of the results of scientific research in the field of Industrial Engineering and Management".

REFERENCES

[1] Abdalla, A.N., Nazir, M.S., Tao, H., Cao, S., Ji, R., Jiang, M., Yao, L. (2021). Integration of energy storage system and renewable energy sources based on artificial intelligence: an overview. *J Energy Storage*, 40, 102811.

[2] Abdelkareem, M.A., et al. (2022). Progress of artificial neural networks applications in hydrogen

production. *Chem. Eng. Res. Des*., 182, 66-86, doi:10.1016/j.cherd.2022.03.030.

[3] Al-Falahi, M.D.A., Jayasinghe, S.D.G., Enshaei, H. (2017). A review on recent size optimization methodologies for standalone solar and wind hybrid renewable energy system. *Energy Convers Manage*, 143, 252-274.

[4] Al-Othman A, Tawalbeh, M., Martis, R., Dhou, S., Orhan, M., Qasim, M., Ghani Olabi, A. (2022). Artificial intelligence and numerical models in hybrid renewable energy systems with fuel cells: advances and prospects. *Energy Convers Manage*, 253, 115154.

[5] Andrejević Panić, A., Miličević, S., Cvetanović, S., Mulić, D. (2024). Reevaluation of economic growth through the prism of natural capital sustainability. *Ecologica*, 31(116), 331-338. doi: 10.18485/ecologica.2024.31.116.1.

[6] Burdack, A., Duarte-Herrera, L., Lopez-Jimenez, G., Polklas, T., Vasco-Echeverri, O. (2023). Techno-economic calculation of green hydrogen production and export from Colombia. *Int. J. Hydrogen Energy*, 48(5), 1685-1700, doi:10.1016/j.ijhydene.2022.10.064.

[7] Danish, M.S.S., Senjyu, T. (2023). Shaping the future of sustainable energy through AI-enabled circular economy policies, *Circ. Econ*., 2(2), 100040, doi:10.1016/j.cec.2023.100040.

[8] Department of Energy, (2020). Office of Fossil Energy. *Hydrogen Strategy: Enabling A Low-Carbon Economy*. Technical Report.

[9] European Commission. A hydrogen strategy for a climate-neutral Europe [COM(2020) 301 final]. Technical Report. (EC, 2020).

[10] European Commission. Delegated regulation (EU) 2023/1184 on Union methodology for RFNBOs https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2023.157.01.0011.01.ENG&toc=OJ%3AL%3A2023%3A157%3ATOC. (EU, 2023a).

[11] European Commission. Delegated regulation (EU) 2023/1184 for a minimum threshold for GHG savings of recycled carbon fuels https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2023.157.01.0020.01.ENG&toc=OJ%3AL%3A2023%3A157%3 ATOC. (EU, 2023b).

[12] Hannan, M.A., Al-Shetwi, A.Q., Ker, P.J., Begum, R.A., Mansor, M., Rahman, S.A., Dong, Z.Y., Tiong, S.K., Mahlia,T.M.I., Muttaqi, K.M. (2021). Impact of renewable energy utilization and artificial intelligence in achieving sustainable development goals. *Energy Rep*., 7, 5359-5373.

[13] Hassan, Q., Abdulateef, A.M., Hafedh, S.A., Al-Samari, A., Abdulateef, J., Sameen, A.Z., Salman, H.M., Al-Jiboory, A.K., Wieteska, S., Jaszczur, M. (2023). Renewable energy-to-green hydrogen: a review of main resources routes, processes and evaluation. *Int. J. Hydrogen En, Miličeergy*, 48(46), 17383-17408. doi:10.1016/j.ijhydene.2023.01.175.

[14] He, B., Bai, K.-J. (2020). Digital twin-based sustainable intelligent manufacturing: A review. *Advances in Manufacturing*, 9, doi:10.1007/s40436-020-00302-5

[15] IEA, (2022). Global Hydrogen Review 2022. Technical Report.

[16] IEA, (2023). Global Hydrogen Review 2023. https://www.iea.org/reports/global-hydrogen-review-2023. Retrieved Oct 3rd, 2023.

[17] International Renewable Energy Agency (IRENA), (2020). Scaling up electrolysers to meet the 1.5 C climate goal.

[18] International Renewable Energy Agency (IRENA), (2022). Global hydrogen trade to meet the1.5°C climate goal: Part I - Trade outlook for 2050 and way forward, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jul/IRENA_Global_hydrogen_trade_part_1_2022_.pdf.

[19] Izadi, A., Shahafve, M., Ahmadi, P. (2022). Neural network genetic algorithm optimization of a transient hybrid renewable energy system with solar/wind and hydrogen storage system for zero energy buildings at various climate conditions, *Energy Convers. Manag*., 260, 115593, doi:10.1016/J.ENCONMAN.2022.115593.

[20] Kalinci, Y., Hepbasli, A., Dincer, I. (2015). Techno-economic analysis of a stand-alone hybrid renewable energy system with hydrogen production and storage options. *Int. J. Hydrogen Energy*, 40 (24), 7652-7664, doi:10.1016/j.ijhydene.2014.10.147

[21] Le, V.T., Dragoi, E.N., Almomani, F., Vasseghian, Y. (2021). Artificial neural networks for predicting hydrogen production in catalytic dry reforming: a systematic review, *Energy*, 14(10), doi:10.3390/EN14102894/S1.

[22] Leng, J., Wang, D., Shen, W., Li, X., Liu, Q., & Chen, X. (2021). Digital twins-based smart manufacturing system design in Industry 4.0: A review. *Journal of Manufacturing Systems*, 60,119-137.

[23] Lv, Q., et al. (2024). Modeling thermo-physical properties of hydrogen utilizing machine learning schemes: viscosity, density, diffusivity, and thermal conductivity, *Int. J. Hydrogen Energy*, 72, 1127-1142, doi:10.1016/j.ijhydene.2024.05.280.

[24] Marocco, P., Gandiglio, M., Santarelli, M. (2023). Optimal design of PV-based grid-connected hydrogen production systems. *Journal of Cleaner Production*, 434, 140007.

[25] Melaina, M.W., Antonia, O. & Penev., M. (2013). Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues. National Renewable Energy Lab., Technical Report NREL/TP-5600-51995, March 2013. https://www.nrel.gov/docs/fy13osti/51995.pdf

[26] Oladosu, T.L., Pasupuleti, J., Kiong, T.S., Koh, S.P.J., Yusaf, T. (2024). Energy management strategies, control systems, and artificial intelligence-based algorithms development for hydrogen fuel cell-powered vehicles: a review. *Int. J. Hydrogen Energy*, 61, 1380-1404, doi:10.1016/j.ijhydene.2024.02.284.

[27] Oliva, S.H., Garcia, M.G., (2023). Investigating the impact of variable energy prices and renewable generation on the annualized cost of hydrogen, *Int. J. Hydrogen Energy*, 48(37), 13756-13766, doi:10.1016/j.ijhydene.2022.12.304.

[28] Peksen, M.M. (2023). Material and performance optimisation for syngas preparation using artificial intelligence (AI)-based machine learning (ML), *Hydrogen*, 4(3), 474-492, doi:10.3390/hydrogen4030032.

[29] Raman, R., Nair, V.K., Prakash, V. Patwardhan, A., Nedungadi, P. (2022). Green-hydrogen research: what have we achieved, and where are we going? Bibliometrics analysis, *Energy Rep.*, 8, 9242-9260, doi:10.1016/j.egyr.2022.07.058.

[30] Rissman, J., et al. (2020). Technologies and policies to decarbonize global industry: Review and assessment of mitigation drivers through 2070. *Appl. Energy*, 266, 114848.

[31] Sarma, A., Parmar, M.M. (2024). Appraising Universally Applicable Ai Ml and Q-Gis Models for Feasibility Study of Green Hydrogen Production: A Case Study for Potential States of India.

[32] Scheepers, F., Stähler, M., Stähler, A., Müller, M., Lehnert, W. (2023). Cost-optimized design point and operating strategy of polymer electrolyte membrane electrolyzers. *Int. J. Hydrogen Energy*, 48(33), 12185-12199, doi:10.1016/j.ijhydene.2022.11.288

[33] Semeraro, C., Aljaghoub, H., Abdelkareem, M.A., Alami, A.H., & Olabi, A.G. (2023). Digital twin in battery energy storage systems: Trends and gaps detection through association rule mining. *Energy*, 273, 127086, doi:10.1016/j.energy.2023.127086

[34] Shams, M.H., Niaz, H., Na, J., Anvari-Moghaddam, A., Liu, J.J. (2021). Machine learning-based utilization of renewable power curtailments under uncertainty by planning of hydrogen systems and battery storages, *J. Energy Storage*, 41,103010. doi:10.1016/j.est.2021.103010

[35] Shoaei, M., Noorollahi, Y., Hajinezhad, A., Moosavian, S.F. (2024). A review of the applications of artificial intelligence in renewable energy systems: an approach-based study. *Energy Convers. Manag.*, 306, 118207, doi:10.1016/j.enconman.2024.118207.

[36] Superchi, F., Mati, A., Carcasci, C., Bianchini, A. (2023). Techno-economic analysis of wind-powered green hydrogen production to facilitate the decarbonization of hard-to-abate sectors: a case study on steel making. *Appl. Energy*, 342, 121198. doi:10.1016/j.apenergy.2023.121198.

[37] Tai, X.Y., Xing, L., Christie, S.D.R., & Xuan, J. (2023). Deep learning design of functionally graded porous electrode of proton exchange membrane fuel cells. *Energy*, 283, 128463-128480.

[38] Terlouw, T., Bauer, C., McKenna, R. & Mazzotti, M. (2022). Large-scale hydrogen production via water electrolysis: a techno-economic and environmental assessment. *Energy Environ. Sci*., 15, 3583-3602.

[39] Ueckerdt, F., et al. (2021). Potential and risks of hydrogen-based e-fuels in climate change mitigation. *Nat. Clim. Change*, 11, 384-393.

[40] Van der Spek, M., et al. (2022). Perspective on the hydrogen economy as a pathway to reach net-zero CO_2 emissions in Europe. *Energy Environ. Sci*., 15, 1034-1077.

[41] Wang, B., Tao, F.,Fang, X., Liu, C., Liu, Y., & Freiheit, T. (2021). Smart manufacturing and intelligent manufacturing: A comparative review. *Engineering*, 7(6), 738-757.

[42] Yun, P., et al. (2024). On the utilization of artificial intelligence for studying and multi-objective optimizing a compressed air energy storage integrated energy system. *J. Energy Storage*, 84, 110839, doi:10.1016/j.est.2024.110839.

[43] Zhou, Y., Zheng, S. (2020). Machine-learning based hybrid demand-side controller for high-rise office buildings with high energy flexibilities. *Appl. Energy*, 262, 114416.

[44] Zhou, Y., Zheng, S., Zhang, G. (2020). Machine-learning based study on the on-site renewable electrical performance of an optimal hybrid PCMs integrated renewable system with high-level parameters' uncertainties. *Renew. Energy*, 151, 403-418.