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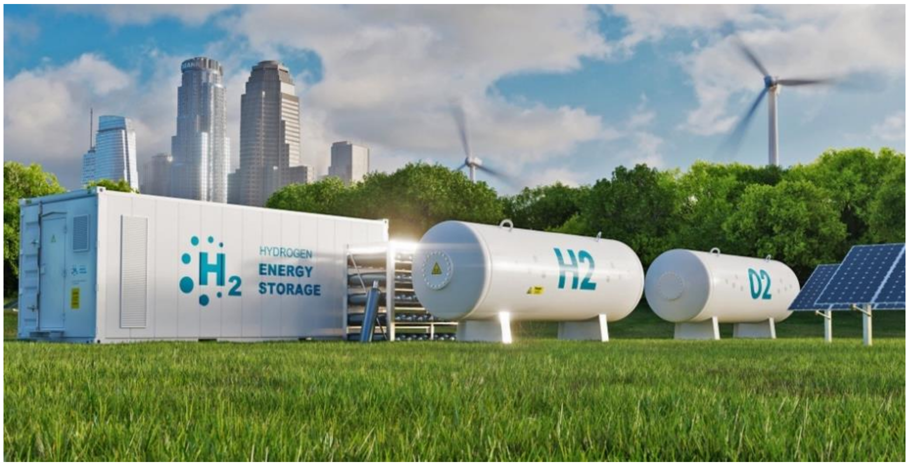
Annotated bibliography on

Technology and New Method for Hydrogen Production, Storage, and Applications



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National Scientific & Technical Information Center

NSTIC

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Introduction:

The development of hydrogen and fuel cell technologies in stationary electricity, portable power, and transportation depends heavily on hydrogen storage and manufacturing. Although hydrogen has the highest energy density per mass of any fuel, it has the lowest energy density per unit volume due to its low ambient temperature density, necessitating the development of new storage technologies with the potential for higher energy density.

There are numerous feedstocks from which hydrogen can be created. These include renewable and fossil resources, such as biomass and water, as well as natural gas and coal with input from renewable energy sources (e.g., sunlight, wind, wave, or hydropower). Process technologies can be chemical, biological, electrolytic, photolytic, and thermo-chemical. Every technology is at a different level of development and has its chances, advantages, and difficulties. The choice and timing of the many options for hydrogen generation will be influenced by several factors, including the feedstock availability in the area, the technology's level of maturity, market uses and demand, legislative concerns, and cost.

Few substances are as full of potential and aspiration as hydrogen. The first element on the periodic chart has transformed in recent years from a global term to one of the most promising paths toward decarbonizing transportation, industry, and power generation.

This annotated bibliography aims to assist the Petroleum Research Center, and especially the Optimization of Petroleum Refinery Processes (OPRP) program by providing a list of most recent articles that cover the topic: Technology and New Method for Hydrogen Production, Storage, and Applications.

This annotated bibliography contains articles abstracts from 2023-2022.

E-resources used: Scopus – OnePetro.

Contact NSTIC to request full-text articles

Articles Abstracts:

1. Adebisi, J. A., Denwigwe, I. H., & Babatunde, O. M. (2023). Hydrogen storage for micro-grid application: a framework for ranking fuel cell technologies based on technical parameters. *International Journal of Electrical and Computer Engineering, 13*(2), 1221-1230.

Abstract: To securely address energy shortage and various environmental issues attributed to fossil fuel, the adoption of renewable energy is growing across the globe. However, wind and solar which form the bulk of the emerging renewable energy for micro-grid applications are intermittent and need energy storage device for backup. Due to its environmentally friendly nature, the use of hydrogen as storage mechanism is now being explored for micro-grid applications. However, due to the various technical criteria attributed to various fuel cell (FC) technologies used for hydrogen production, selecting the most suitable alternative remains a challenge. This study uses evaluation based on distance from average solution, a multicriteria decision making tool to rank FC technologies that can be used to produce of hydrogen energy storage in micro-grid applications. The analysis was based on 4 FC technologies and 6 technical criteria. The results of the study show that the most preferred FC technology for micro-grid application is the polymeric electrolyte membrane while the least preferred is molten carbonate FC. It is expected that future analysis would explore the inclusion of socio-economic criteria in the evaluation of the most preferred FC technology for micro-grid application.

2. Amin, M., Butt, A. S., Ahmad, J., Lee, C., Azam, S. U., Mannan, H. A., Naveed, A. B., Farooqi, Z. U. R., Chung, E., & Iqbal, A. (2023). Issues and challenges in hydrogen separation technologies. *Energy Reports, 9*, 894-911.

Abstract: Depleting energy resources, global warming and environmental problems associated with conventional fuels are serious global challenges of the modern world. The substitution of conventional energy resources with more efficient and sustainable resources is inevitable. In this scenario, hydrogen (H_2) has emerged as the ultimate choice due to its superior characteristics such as low carbon emissions, cleanliness, and efficiency. However, for the successful implementation of making H_2 as the next-generation fuel source, the hurdles of production, separation, and storage

of H_2 should be resolved. This paper summarizes the issues and challenges in the separation of H_2 gas from various production streams by using available separation technologies. Different types of H_2 separation technologies, including membranes, adsorption processes, metal hydrides, and cryogenic separation technologies, have been considered and discussed. The review encompasses the types, advantages, and disadvantages of each technology, followed by a detailed account of issues and challenges observed in each separation method. More attention has been given to membrane technology because it is the most promising technology for the production of high-purity H_2. Finally, this review provides an outlook for future directions and developments in H_2 separation technologies.

3. Anaya, K., Olufemi Oni, A., & Kumar, A. (2023). Investigating the techno-economic and environmental performance of chemical looping technology for hydrogen production. *Sustainable Energy Technologies and Assessments*, 56.

Abstract: There is limited research assessing the techno-economic feasibility and environmental footprint of direct partial oxidation of methane using chemical looping technology for hydrogen production. The available studies have not investigated essential aspects of the impact of hydrogen storage cost or economies of scale on hydrogen production cost. In this study, process models were developed based on fundamental science for hydrogen production using chemical looping technology. The results show that for a production plant capacity of 607 tonnes/day, the hydrogen cost is $3.66/kg. When the uncertainty in the input parameters is considered, the hydrogen cost ranges from 3.51 to 4.70 $/kg. The parameters that most influence hydrogen cost are discount rate and hydrogen storage. The hydrogen cost versus capacity profile shows that operating chemical looping at a higher capacity is financially beneficial because of economies of scale. The developed scale factor is 0.64. The net energy ratio is 0.84, indicating chemical looping is a better energy producer than the traditional method of hydrogen production, i.e., steam methane reforming. The greenhouse gas emissions are 2.86 $kgCO_2/kg\text{-}H_2$. The results show that chemical looping partial oxidation of methane provides better energy efficiency and a better environmental footprint than conventional steam methane reforming.

4. Ang'u, C., Muthama, N. J., Mutuku, M. A., & M'IKiugu, M. H. (2023). Determinants of the sustained use of household clean fuels and technologies: Lessons from Vihiga county, Kenya. *Energy Reports, 9*, 1990-2001.

Abstract: Sustainable energy for household application is currently a top priority in developing countries with clean modern energy sources dominating the energy policy agenda. Nonetheless, more research evidence is required for policy and practise. This study's objective was to evaluate the determinants of household cooking and lighting energy choices. In contrast to other studies, this study employed a holistic approach by considering all the energy technologies utilised by a household. It was hypothesised that socioeconomic and demographic characteristics influence household energy choices. Probit model was used to determine causation using data from a random sample of 487 households drawn from Vihiga county. The marginal effects indicate that the decision of a household to utilise clean cooking fuels is enhanced by income (0.14), access to credit (0.10), male as the household head (0.56), higher education attainment (0.22), increasing age (0.08), and increasing household size (0.02). In addition to these factors, room count (0.04) and marital status (0.06) also enhanced a household's decision to utilise clean energy for lighting. These results emphasise the importance of socioeconomic and demographic factors in achieving sustainable household energy access. To a large extent, a household's decision to utilise clean energy is determined by its income and level of education.

5. Ballal, V., Cavalett, O., Cherubini, F., & Watanabe, M. D. B. (2023). Climate change impacts of e-fuels for aviation in Europe under present-day conditions and future policy scenarios. *Fuel, 338*.

Abstract: ‘E-fuels’ or ‘synthetic fuels’ are hydrocarbon fuels synthesized from hydrogen (H_2) and carbon dioxide (CO_2), where H_2 can be produced via electrolysis of water or steam reforming of natural gas, and CO_2 is captured from the combustion of a fossil or biogenic source or directly from the atmosphere. E-fuels are drop-in substitutes for fossil fuels, but their climate change mitigation benefits are largely unclear. This study evaluates the climate change impacts of e-fuels for aviation by combining different sources of CO_2 and H_2 up to 2050 under two contrasting policy scenarios. The analysis includes different climate metrics and the effects of near-term climate forcers, which are particularly relevant for the aviation sector. Results are produced for European average conditions and for Poland and Norway, two countries with high and low emission intensity from their electricity production mix. E-fuels can either have higher or lower climate change impacts than fossil fuels, depending on multiple factors such as, in order of importance, the electricity mix, the origin of CO_2, the technologyfor H_2 production, and the electrolyzer efficiency. The climate benefits are generally higher for e-fuels produced from CO_2 of biogenic origin, while e-fuels produced from CO_2 from direct air capture or fossil fuel combustion require countries with clean electricity to outperform fossil fuels. Synthetic fuels produced from H_2 derived from natural gas have higher impacts than fossil fuels even when coupled with carbon capture and storage, if CO_2 is sourced from fossil fuels or the atmosphere. Climate change impacts of e-fuels improve in the future, and they can all achieve considerable climate change mitigation in 2050 relative to fossil jet fuel, provided that strict climate policy measures are implemented to decarbonize the electricity sector. Under reduced policy efforts, future climate impacts in 2050 of e-fuels from atmospheric or fossil CO_2 are still higher than those of fossil jet fuels with an average European electricity mix. This study shows the conditions to maximize the climate change mitigation benefits of e-fuels, which essentially depend on progressive decarbonization of the electricity sector and on reduced use of CO_2 sourced from fossil fuels.

6. Chen, S., Wang, Y., Lang, X., Fan, S., & Li, G. (2023). Rapid and high hydrogen storage in epoxycyclopentane hydrate at moderate pressure. *Energy, 268*.

Abstract: Hydrogen storage in clathrate hydrate is considered to be a potential technology with high energy density. However, the problems of low gas storage capacity and slow hydrate formation hinder its application. In this work, several strengthen methods were investigated to improving hydrogen storage capacity and rate in epoxycyclopentane (ECP) hydrates at moderate pressure. The results showed that the ECP hydrate particles could promote the formation of hydrate. It was found that the gas storage capacity and the rate increased with the decrease in ECP hydrate particle sizes. After dispersing ECP hydrate particles on stainless steel mesh, the gas storage capacity can be further increased to 71.2 $cm^3/cm^3_{hydrate}$ (0.64 wt%), and the average gas storage rate can be further increased to 26.51 $cm^3/(cm^3_{hydrate}h^{-1})$. It was found that decreasing particle size of hydrate could increase the gas-solid interface area and raised the gas adsorption

rate and adsorption amount. The stainless-steel mesh partitions improved the hydrogen storage capacity due to the good thermal conductivity that reduced the influence of hydrate formation heat and dispersing the hydrate particles that reduced the diffusion distance of hydrogen in the pores. These findings provide fundamental insights into the development of clathrate hydrate-based H_2storage technology.

7. Donald, R., & Love, J. G. (2023). Energy shifting in wastewater treatment using compressed oxygen from integrated hydrogen production. *Journal of Environmental Management, 331*.

Abstract: Integrating renewable hydrogen production via electrolysis with wastewater treatment is an opportunity to manage environmental resources more sustainably while providing a pathway to producing sustainable hydrogen at industrial scale. The synergies of integrating oxygen production from water electrolysis and oxygen use in wastewater treatment benefit both hydrogen production and wastewater industries. However, the understanding of the most suitable integrated process configuration and scale of renewable equipment is not known. A novel energy shifting process is proposed here using compressed and stored oxygen produced by water electrolysis and used in the activated sludge process, replacing traditional aeration in the wastewater treatment plant and eliminating the high energy consuming blowers supplying air to submerged fine bubble diffusers. In the proposed energy shifting process, excess oxygen produced by water electrolysis at times of peak renewable electricity production is stored and used for wastewater treatment at times of peak oxygen demand. Wastewater treatment data from the activated sludge process was used to calculate oxygen demand in 1-h intervals over a 24-h period, and the system response of the integrated plant was simulated at hourly intervals and equipment size determined according to an optimisation algorithm that balances oxygen and electricity supply and demand over a 24-h period. Sensitivity analysis of operational parameters is assessed and the case for replacing traditional WWTP aeration with newer technologies is quantified using a high efficiency oxygen transfer system such as a Speece cone as an example that is shown to be a prerequisite for the feasibility of the process. The results produced by this study provide valuable information to the hydrogen and wastewater industries on how an integrated plant could be configured. Besides the environmental advantages of sustainably produced hydrogen, using oxygen as a biochemical energy storage medium in this configuration means WWTP powered from renewable electricity becomes more viable reducing the industries reliance on fossil fuels.

8. Gautam, R., Nayak, J. K., Ress, N. V., Steinberger-Wilckens, R., & Ghosh, U. K. (2023). Bio-hydrogen production through microbial electrolysis cell: Structural components and influencing factors. *Chemical Engineering Journal*, *455*.

Abstract: Microbial electrolysis cell (MEC) is a significantly sustainable bio-electrochemical system for biological hydrogen production. MEC is also regarded as an environmentally friendly method for producing clean biohydrogen from a variety of waste organic matters and for its low greenhouse gas emissions. This technology involves the oxidation of organic matter at the anode and the reduction of proton at the cathode under the nominal external voltage supply. However, bio-hydrogen production efficiency and operating costs of MEC still need further optimization to implement in large-scale applications. For optimization, a detailed explanation of MEC components and major operational parameters should be available. This review discusses the principle, main components, and major operational parameters of MEC for significant performance. It also provides a brief overview of types of MECs, reactor configuration, and their advantages. Thermodynamically important aspects of the MEC for efficient performance are also discussed. It also conferred the critical structural components which are essential for the functioning MECs. Furthermore the performance evaluating parameters and indices for the biohydrogen yield and MEC performance are also addressed. Additionally, crucial influencing factors that affect the MEC performance such as microorganism, methanogens and their inhibition, various electrode materials, membranes and different substrates are also discussed. Afterwards needs and challenges for future development of the MEC technology are highlighted and suggested. The review aims to put forward the fundamental understandings of MEC technology to the research fraternity for further advancement for the large-scale applications.

9. Gea-Bermúdez, J., Bramstoft, R., Koivisto, M., Kitzing, L., & Ramos, A. (2023). Going offshore or not: Where to generate hydrogen in future integrated energy systems? *Energy Policy*, *174*.

Abstract: Hydrogen can be key in the energy system transition. We investigate the role of offshore hydrogen generation in a future integrated energy system. By performing energy system optimisation in a model application of the Northern-central European energy system and the North Sea offshore grid towards 2050, we find that offshore hydrogen generation may likely only play a limited role, and that offshore wind energy has higher value when sent to shore in the form of electricity. Forcing all hydrogen generation offshore would lead to increased energy system costs. Under the assumed scenario conditions, which result in deep decarbonisatiton of the energy system towards 2050, hydrogen generation – both onshore and offshore – follows solar PV generation patterns. Combined with hydrogen storage, this is the most cost-effective solution to satisfy future hydrogen demand. Overall, we find that the role of future offshore hydrogen generation should not simply be derived from minimising costs for the offshore sub-system, but by also considering the economic value that such generation would create for the whole integrated energy system. We find as a no-regret option to enable and promote the integration of offshore wind in onshore energy markets via electrical connections.

10. Geng, B., Guene Lougou, B., Shuai, Y., Zhang, H., Pan, Q., Han, D., Jiang, B., Wu, L., & Wang, Z. (2023). Design of gas-liquid two-phase separation device with application in solar hydrogen production system. *Renewable and Sustainable Energy Reviews, 175*.

Abstract: Currently, solar thermochemical energy conversion technology has attracted more and more attention because of the increasing global need for clean fuel and chemical energy demand. The thermochemical hydrogen production technology uses solar radiation with concentrated high-density as a high-temperature heat source to produce hydrogen by decomposing water through two-step cycle redox reactions. It is an environment-friendly technology based on artificial photosynthesis utilizing water vapor as the reaction gas. However, limited by the separation efficiency, current gas-liquid separation devices cannot output stable high-purity water vapor and sophisticate the experimental processes. In this research, intensive numerical investigations were carried out on the widely-used corrugated plate steam separators. The structural parameters are designed by the multi-objective optimization method combining the artificial neural network and the genetic algorithm. Nine optimized structures are designed by adding hydrophobic hooks, streamlined, and reducing the plate distance optimization methods. The results give

engineering application conditions of different optimized separators. The streamlined single-hook corrugated plate separator with rounded corners exhibited the best separation efficiency under the heat state condition, which is 97.27%. It can also completely separate droplets over 28.5 μm. The applicability of the cyclone steam separators indicated that it is more suitable for pretreatment. The benchmark experimental system was built for the measurement of the separation efficiency resulting in only a 0.73% error. The designed steam separator was successfully applied to the solar thermochemical hydrogen production experiment, which ensures its practicability and pertinence in the process of solar fuel synthesis.

11. Gherairi, S. (2023). Design and implementation of an intelligent energy management system for smart home utilizing a multi-agent system. *Ain Shams Engineering Journal, 14*(3).

Abstract: Green Hydrogen Microgrid System has been selected as a source of clean and renewable alternative energy because it is undergoing a global revolution and has been identified as a source of clean energy that may aid the country in achieving net-zero emissions in the coming years. The study proposes an innovative Microgrid Renewable hybrid system to achieve these targets. The proposed hybrid renewable energy system combines a photovoltaic generator (PVG), a fuel cell (FC), a supercapacitor (SC) and a home vehicle power supply (V2H) to provide energy for a predefined demand. The proposed architecture is connected to the grid and is highly dependent on solar energy during peak periods. During the night or shading period, it uses FC as a backup power source. The SC assists the FC with high charge power. SC performs this way during load transients or quick load changes. A multi-agent system (MAS) was used to build a real energy management system (RT-HEMS) for intelligent coordination between components (MAS). The scheduling algorithm reduces energy consumption by managing the required automation devices without the need for additional network power. It will meet household energy requirements regardless of weather conditions, including bright, cloudy or rainy conditions. Implementation and discussion of the RT-HEMS ensures that the GHS is functioning properly and that the charge request is satisfied.

12. Gholami, R. (2023). Hydrogen storage in geological porous media: Solubility, mineral trapping, H2S generation and salt precipitation. *Journal of Energy Storage, 59*.

Abstract: Hydrogen as a significant energy vector plays an important role in the decarbonization of heavy industry. However, the intermittency and sessional availability of renewable energy sources, as well as the demand for energy at different times and places, require a medium- to long-term storage technology. Underground storage of hydrogen in depleted gas reservoirs and saline aquifers could be a good option given their storage capacity and availability in different geological settings. However, these geological porous media may suffer from many operational, geological, and geochemical complications. This paper attempts to evaluate the geochemical interactions posed by the injection of hydrogen into porous media. The results obtained from a series of thermodynamic and kinetic geochemical modeling calibrated against experimental data show that dissolution of carbonates, anhydrate and halite can occur over time, leading to precipitation of calcite, formation of H_2S and long-term closure of the pore structure due to scale formation. The reduction of pyrite to pyrrhotite is likely to occur at a temperature above 90 °C, which may enhance the formation of H_2S in the absence of microbial activity. The formation of scale (halite) is a long-term process that only starts after 10 years of operation due to the slow dissolution of halite in porous media. However, during hydrogen injection, salt diffusion, the formation of a dry-out zone and the phenomenon of salting out occur, depending on the salinity and temperature of the formation water. The results of this study can help to better understand and select geological porous media for large-scale hydrogen storage.

13. Hren, R., Vujanović, A., Van Fan, Y., Klemeš, J. J., Krajnc, D., & Čuček, L. (2023). Hydrogen production, storage and transport for renewable energy and chemicals: An environmental footprint assessment. *Renewable and Sustainable Energy Reviews, 173*.

Abstract: Hydrogen applications range from an energy carrier to a feedstock producing bulk and other chemicals and as an essential reactant in various industrial applications. However, the sustainability of hydrogen production, storage and transport are neither unquestionable nor equal. Hydrogen is produced from natural gas, biogas, aluminium, acid gas, biomass, electrolytic water splitting and others; a total of eleven sources were investigated in this work. The environmental

impact of hydrogen production, storage and transport is evaluated in terms of greenhouse gas and energy footprints, acidification, eutrophication, human toxicity potential, and eco-cost. Different electricity mixes and energy footprint accounting approaches, supported by sensitivity analysis, are conducted for a comprehensive overview. H_2 produced from acid gas is identified as the production route with the highest eco-benefit (−41,188 €/t H_2), while the biomass gasification method incurred the highest eco-cost (11,259 €/t H_2). The water electrolysis method shows a net positive energy footprint (60.32 GJ/t H_2), suggesting that more energy is used than produced. Considering the operating footprint of storage, and transportation, gaseous hydrogen transported via a pipeline is a better alternative from an environmental point of view, and with a lower energy footprint (38 %–85%) than the other options. Storage and transport (without construction) could have accounted for around 35.5% of the total GHG footprint of a hydrogen value chain (production, storage, transportation and losses) if liquefied and transported via road transport instead of a pipeline. The identified results propose which technologies are less burdensome to the environment.

14. Huang, J., Balcombe, P., & Feng, Z. (2023). Technical and economic analysis of different colours of producing hydrogen in China. *Fuel, 337*.

Abstract: This paper explores the different types of hydrogen production by exploring them and giving each a different colour. From dark to money in descending order, they represent a gradual reduction in pollution. The basic principles, advantages and disadvantages of the respective production methods are explored at a technical level. The learning curve theory calculates the individual learning rates for different hydrogen production methods to increase the installed capacity while reducing the capital investment and cost of hydrogen production. The study concludes that coal-based hydrogen production is currently the primary method of hydrogen production in China in the short term due to its high resource endowment of coal. As CCUS technology matures, converting brown hydrogen to blue hydrogen and grey hydrogen to turquoise hydrogen are the two more economically viable options. For the cleanest form of green hydrogen, the fundamental problems are the impediments of electrolyser technology (PEM, SOEC cannot be commercialised) and the high wind and photovoltaic power cost. The solution is to use wind and light abandonment to increase hydrogen production in the short term and replace fossil energy with renewable energy generation in the long term to achieve clean hydrogen production. For hydrogen energy, the vigorous development of hydrogen fuel cell vehicles and the massive reduction of greenhouse gas emissions in transport is essential to achieving carbon neutrality while ensuring the supply of hydrogens such as blue hydrogen and green hydrogen.

15. Javaherian, A., Yari, M., Gholamian, E., Carton, J. G., & Mehr, A. S. (2023). Proposal and comprehensive analysis of power and green hydrogen production using a novel integration of flame-assisted fuel cell system and Vanadium-Chlorine cycle: An application of multi-objective optimization. *Energy Conversion and Management, 277*.

Abstract: Present research attempts to introduce a novel solution for dispatch-down renewable electrical power using an integration of compressed air energy storage with a pressurized flame-assisted solid oxide fuel cell. The proposed system can generate electrical power and green hydrogen using flame-assisted fuel cell and Vanadium-Chlorine thermochemical cycle. Performance of the system has been perused from 4E perspectives, and three multi-objective optimizations with different objective functions have been carried out. The effects of key parameters such as current density, fuel utilization efficiency, fuel cell operating pressure and anode recycle coefficient on the performance of the cogeneration system have been investigated for various values of fuel-rich combustion chamber's equivalence ratio. Results reveal that the proposed system can offer both electrical power and green hydrogen with high overall efficiency. According to the optimization results, system efficiency, Levelized cost of products, and carbon dioxide emission index are obtained 93.48 %, 0.08318 $/kWh, and 0.3437 kg/kWh, respectively.

16. Li, J., Hatami, M., Huang, Y., Luo, B., Jing, D., & Ma, L. (2023). Efficient photothermal catalytic hydrogen production via plasma-induced photothermal effect of Cu/TiO2 nanoparticles. *International Journal of Hydrogen Energy, 48*(16), 6336-6345.

Abstract: Developing appropriate photocatalyst with high efficiency is still the basic strategy for practical application of emerging technology. Herein, non-noble metal copper (Cu) nanoparticles were in situ hybrided with TiO_2 by a chemical reduction method. The crystal phase and structure were characterized by XRD, SEM, and TEM measurements. Hydrogen production results showed

that Cu nanoparticles significantly improved the photocatalytic hydrogen production rate. The hydrogen production rate was as high as 24160.69 μmol g^{-1} h^{-1} at 100 °C, which was 36.25 and 8.46 times higher than the hydrogen production rates of pure TiO_2 and 0.13 wt% Cu/TiO_2 at room temperature, respectively. PL spectra, UV–vis spectra, IR images and photoelectrochemical measurements showed that the plasma-induced photothermal effect of Cu/TiO_2 nanoparticles, which raised the temperature of the reaction system and promoted photothermal catalytic performance. Briefly, this work provides a facile fabrication method of noble-metal-free photocatalysts featuring in low-cost and high efficiency. In the future, coupling the photothermal effect of plasmonic Cu to further speed up the kinetics should be another promising research direction for further improving hydrogen production.

17. Li, X., Raorane, C. J., Xia, C., Wu, Y., Tran, T. K. N., & Khademi, T. (2023). Latest approaches on green hydrogen as a potential source of renewable energy towards sustainable energy: Spotlighting of recent innovations, challenges, and future insights. *Fuel, 334*.

Abstract: Today, the generation of carbon-neutral hydrogen from renewable energy can be considered a significant achievement toward a circular bioeconomy in this industry. In contrast, carbon production is rising globally, with energy-related carbon emissions accounting for two-thirds of global emissions. Now, an energy factor is required to mitigate the correlation between economic growth and rising carbon emissions. This is where green hydrogen generation can enter the renewable energy equation. Hydrogen can contribute to reducing gas emissions in the coming decades, not only as a potential technology for the future but also as a successful technologyalready being implemented globally. This review aims to contribute to reducing greenhouse gas emissions, including carbon, by examining the possible pathways to a hydrogen-capable clean energy future. To this end, this article has challenged a deeper perspective on the relationship between hydrogen as a green fuel and renewable energy, as well as the economics of hydrogen supply considering the steadily declining costs of renewables and the role of hydrogen in energy transport as well as provides strategic considerations and applications.

18. Liu, S., Gu, X., Yang, S., & Qian, Y. (2023). Can green hydrogen and waste heat utilization improve energy conservation and emission reduction of coal-based cogeneration processes? *Journal of Cleaner Production, 389*.

Abstract: Power-to-gas offers a new path for carbon emission reduction by integrating renewable energy hydrogen with traditional chemical process. However, its application is limited by the product fluctuation and high cost of green hydrogen. To further improve the level of energy conservation and emission reduction, this research explored the novel integration process of large-scale green hydrogen system and coal-based cogeneration process. The green hydrogen with a low fluctuation was obtained from the wind-solar coupled power equipped with conservative energy storage system. The results showed that the carbon emission was significantly reduced by 9.2%, while the total operating cost was increased by 18.7%. To alleviate the high operating cost caused by green hydrogen, various waste heat utilization systems were introduced to decrease the utilities consumption. It was found that the total site waste heat utilization was capable of further reducing carbon emission by 13.3%, and the increase in total operating cost can be controlled within 15.3%. Economic analysis proved that the expensive cost could be saved by lower hydrogen usage or hydrogen cost. By incorporating waste heat utilization, the cost increase could be as low as 6.0% and 4.8% under 50% green hydrogen flowrate or 40% energy storage system. With the progress of renewable energy hydrogen production and waste heat utilization technology, the proposed integration process will be more environmentally friendly and economically feasible in the future.

19. Muhammed, N. S., Haq, M. B., Al Shehri, D. A., Al-Ahmed, A., Rahman, M. M., Zaman, E., & Iglauer, S. (2023). Hydrogen storage in depleted gas reservoirs: A comprehensive review. *Fuel, 337*.

Abstract: Hydrogen future depends on large-scale storage, which can be provided by geological formations (such as caverns, aquifers, and depleted oil and gas reservoirs) to handle demand and supply changes, a typical hysteresis of most renewable energy sources. Amongst them, depleted natural gas reservoirs are the most cost-effective and secure solutions due to their wide geographic distribution, proven surface facilities, and less ambiguous site evaluation. They also require less cushion gas as the native residual gases serve as a buffer for pressure maintenance during storage.

However, there is a lack of thorough understanding of this technology. This work aims to provide a comprehensive insight and technical outlook into hydrogen storage in depleted gas reservoirs. It briefly discusses the operating and potential facilities, case studies, and the thermophysical and petrophysical properties of storage and withdrawal capacity, gas immobilization, and efficient gas containment. Furthermore, a comparative approach to hydrogen, methane, and carbon dioxide with respect to well integrity during gas storage has been highlighted. A summary of the key findings, challenges, and prospects has also been reported. Based on the review, hydrodynamics, geochemical, and microbial factors are the subsurface's principal promoters of hydrogen losses. The injection strategy, reservoir features, quality, and operational parameters significantly impact gas storage in depleted reservoirs. Future works (experimental and simulation) were recommended to focus on the hydrodynamics and geomechanics aspects related to migration, mixing, and dispersion for improved recovery. Overall, this review provides a streamlined insight into hydrogen storage in depleted gas reservoirs.

20. Olabi, A. G., Abdelkareem, M. A., Al-Murisi, M., Shehata, N., Alami, A. H., Radwan, A., Wilberforce, T., Chae, K. -., & Sayed, E. T. (2023). Recent progress in Green Ammonia: Production, applications, assessment; barriers, and its role in achieving the sustainable development goals. *Energy Conversion and Management, 277*.

Abstract: Fossil fuels are no longer accepted as the sole energy source with their environmental impacts and fluctuating price. Green hydrogen is considered a potential candidate for fossil fuel soon—however, hydrogen is facing the challenges of storage and transportation. Green ammonia, with its ease of transport and storage, is another promising alternative. Decarbonizing ammonia production is an environmental press toward achieving net-zero emissions by 2050. This work summarizes the up-to-date progress in the green ammonia production methods. An assessment of the different production methods was conducted to highlight the merits and constraints of each approach. Moreover, the promising applications of green ammonia in the energy sectors were discussed. The various barriers, i.e., technical, economic, environmental, and regulations and policies, facing the widespread of green ammonia were also discussed. Finally, the contribution of green ammonia in achieving the different sustainable development goals was elaborated, focusing on the contribution of green ammonia in achieving climate change (SDG 13), clean energy (SDG

7), and other sustainability-related goals. Low efficiencies, high cost, and negative environmental impacts are the common challenges of the various production methods. The progress in green ammonia is essential for achieving SDG2, "Zero hunger". SDG3 "healthy life and well-being" and SDG13 "Climate action", will be achieved by eliminating 3.85 kg CO_2-eq/kg NH_3 emitted from conventional ammonia-based processes. Ease storing of green ammonia in liquid form (at 9 bar or cooling to −33°); makes it the best green energy source, i.e., achieving SDG7 "green and affordable energy". By 2050, green ammonia is expected to represent 99 % of marine fuel, thus contributing to SDG9 "Industry and Infrastructure". Moreover, green ammonia production will save 35.2 GJ of natural gas, thus achieving SDG12 "Responsible consumption/production".

21. Peng, T., Wan, J., Liu, W., Li, J., Xia, Y., Yuan, G., Jurado, M. J., Fu, P., He, Y., & Liu, H. (2023). Choice of hydrogen energy storage in salt caverns and horizontal cavern construction technology. *Journal of Energy Storage, 60*.

Abstract: This study investigated the large-scale hydrogen storage in several forms of underground space (depleted gas reservoirs, aquifers, hard rock caverns, and salt caverns,). according to relevant geological, technical, environmental, health and financial factors, different alternatives of underground hydrogen storage were evaluated. It is pointed out that salt caverns are the most favorable underground space for large-scale hydrogen storage, so at least at present, we should pay more attentions to the scientific research and engineering practice of underground hydrogen storage in salt caverns. China is rich in salt resources, but most of these resources have the characteristics of bedded structures, thin salt layers, and complicated geological conditions, which make it very difficult to construct energy storage caverns in the these strata. Moreover, salt mining and gas storage have occupied a large part of salt resources with large thickness and high ore grade. Three methods of salt cavern construction were detailed described and compared, which consists of Single-well-vertical, Two-well-vertical (TWV), and Two-well-horizontal. Therefore, for the construction of hydrogen storage caverns in China, we suggest to adopt the technology of Two-well-horizontal cavern, which is more suitable for the construction of caverns in the remaining thinly bedded salt rocks. The highlights of Two-well-horizontal caverns method were presented and it has better construction efficiency and larger cavern volume. Influencing factors of construction technology were summarized: water injection direction, tubing/oil-blanket lifting, water injecting rate and inter-well distance. Based on "TWHSMC V2.0", a series of tests were carried out, and multi-factor influences analysis were also carried out. The recommended process parameters in the process of Two-well-horizontal cavern construction are: repeatedly alternating "Injection" and "Withdrawal" operation every 30 days; lifting tubings/oil-blanket every 30 days; setting the inter-well distance to 130 m and water injecting rate at 300 m^3/h. This study shows that Two-well-horizontal cavern has higher cavern construction rate than traditional Single-well-vertical cavern, and has high suitability in thinly bedded salt rocks, thus it is capable of providing caverns for ample scale hydrogen storage in China.

22. Pocha, C. K. R., Chia, W. Y., Silvanir, Kurniawan, T. A., Khoo, K. S., & Chew, K. W. (2023). Thermochemical conversion of different biomass feedstocks into hydrogen for power plant electricity generation. *Fuel, 340*.

Abstract: Most hydrogen production technologies are dependent on non-renewable resources, which are not sustainable in the long run. However, H_2 can be produced in the future from renewable sources, becoming one of the cleanest energy carriers. Compared to other biomass treatment methods, the thermochemical pathways from biomass for sustainable H_2 generation offers a considerable promise for its industrial use. The most studied routes are biomass gasification and reformation of the bio-oil generated by biomass pyrolysis, while some works on supercritical water gasification and bio-oil gasification are extensively developed to improve hydorgen production efficiency. This review discusses the most current developments in research on the methods of pyrolysis, gasification, steam reformation, and microwave-induced plasma for producing hydrogen from various types of biomasses, including lignocellulosic and woody biomasses. By utilizing the hydrogen produced from biomass, possibilities of creating a sustainable city were analyzed. There are many upgraded technologies to generate electricity using hydrogen produced from biomass such as gas turbines, combined cycle power plants, and fuel cells. The environmental feasibility of hydrogen usage was also evaluated, along with the status quo of hydrogen power plants in several countries. This review contributes to the large-scale implementation of hydrogen energy with in-depth discussion on the latest development.

23. Rubio, F., Llopis-Albert, C., & Besa, A. J. (2023). Optimal allocation of energy sources in hydrogen production for sustainable deployment of electric vehicles. *Technological Forecasting and Social Change, 188*.

Abstract: We analyze the use of hydrogen as a fuel for the automotive industry with the aim of decarbonizing the economy. Hydrogen is a suitable option for avoiding pollutant gas emissions, developing environmentally friendly technologies, replacing fossil fuels with clean, renewable energies, and complying with the Paris Agreement and Glasgow resolutions. In this sense, renewable energies such as wind, solar, photovoltaic, geothermal, biomass, etc. can be used to produce the necessary hydrogen to power vehicles. In this way, the entire process from hydrogen production to its consumption as fuel will be 100% clean. If we are to meet future energy demands, it is necessary to forecast the amount of hydrogen needed, taking into account the facilities currently available and new ones that will be required for its generation, storage, and distribution. This paper presents a process for optimizing hydrogen production for the automotive industry that considers the amount of hydrogen needed, the type of facilities from which it will be produced, how the different sources of production are to be combined to achieve a competitive product, and the potential environmental impacts of each energy source. It can serve as a frame of reference for the various actors in the hydropower and automotive industries so that more efficient designs can be planned for the gradual introduction of hydrogen fuel cell vehicles (HFCVs). The methodology implemented in this paper sets an optimization problem for minimizing energy production costs and reducing environmental impacts according to the source of energy production. The EU framework with respect to the decarbonization of the economy, the percentages of the different types of energy sources used, and the non-polluting vehicle fleet in the automotive sector will be considered.

24. Sai Ramesh, A., Vigneshwar, S., Vickram, S., Manikandan, S., Subbaiya, R., Karmegam, N., & Kim, W. (2023). Artificial intelligence driven hydrogen and battery technologies – A review. *Fuel, 337*.

Abstract: The world has recognized the importance of renewable energy and is moving towards a rapid transition to renewable energy and energy efficiency. Advances in electrolysis and cost

reductions, as well as the availability of renewable energy sources, have paved the way for the creation of green hydrogen, a completely carbon-free fuel, making it a real contender to revolutionize the energy market. The recent incorporation of artificial intelligence into the energy sector has provided a major breakthrough for the industry. Artificial intelligence algorithms and models such as artificial neural networks, machine learning, support vector regression, and fuzzy logic models can greatly contribute to improving hydrogen energy production, storage, and transportation. They play an important role in predicting various parameters, safety protocols and management of hydrogen production. Furthermore, advances in artificial intelligence are expected to bring huge state-of-the-art technologies and tools for hydrogen and battery technology that could help solve the current energy-oriented crises and problems. This review provides insight into the feasibility of state-of-the-art artificial intelligence for hydrogen and battery technology. The primary focus is to demonstrate the contribution of various AI techniques, its algorithms and models in hydrogen energy industry, as well as smart battery manufacturing, and optimization. Meanwhile, AI models integrated into battery technology play a key role in material discovery, battery design, improved battery manufacturing, diagnostic tools, and optimal battery management systems for smart batteries. With improved performance and longer life, these smart batteries will be integrated into modern robotics, electric vehicles, aerospace and other fields.

25. Salehabadi, A., Dawi, E. A., Sabur, D. A., Al-Azzawi, W. K., & Salavati-Niasari, M. (2023). Progress on nano-scaled alloys and mixed metal oxides in solid-state hydrogen storage; an overview. *Journal of Energy Storage, 61*.

Abstract: Hypothesis: With increased development and electricity generation, great care to energy storage systems is crucial to overcome the discontinuity in the renewable production. Hydrogen is an ideal energy carrier for near future mobility, like automotive applications. Solid-state hydrogen storage materials including nanomaterials and layered systems are the key enablers to the future energy needs. However, the current materials are unable to meet all requirements in the storage capacity and commercialization. The hydrogen storage mechanisms (physical and chemical) are the key-points addressing the shortcomings in hydrogen absorption/adsorption in the interlayer space or on the surface of the material. All above require strategy for designing new hydrogen storage materials. Experiments: This review lays the recent foundations in the materials suitable for hydrogen storage particularly alloys, mixed metal oxides (MMOs), and their respective nanocomposites. Alloys and MMOs are two classes of materials with high discharge capacities, appropriate electrochemical performances, chemical stability, easy production pathways, and almost low cost. In the same vein, highly porous materials with a large surface area such as metal organic frameworks (MOFs), MXenes and carbon materials are thermodynamically and kinetically more favorable. Findings: The literature review illustrates that it is crucial to develop new materials with large-surface area, homogeneous texture, active-conductive profiles, large oxygen vacancies and low-cost. Multiphase materials (nanocomposites/hybrids) composed of at least two of above-mentioned materials can meet the established requirements in this field. Also, the present paper demonstrates a general overview of promoted understanding of hydrogen storage mechanisms on alloy/MMOs-based compounds in the energy storage systems. It is hoped that these observations pave the potential exploration directions to dominate imminent challenges in solid-state hydrogen storage.

26. Tetteh, D. A., & Salehi, S. (2023). The Blue Hydrogen Economy: A Promising Option for the Nearto- Mid-Term Energy Transition. *Journal of Energy Resources Technology, Transactions of the ASME, 145*(4).

Abstract: Hydrogen is recently being promoted immensely as the primary energy carrier to replace fossil fuels for the envisioned environmentally friendly and sustainable future energy system, given its peculiar properties and advantages over conventional fuels and other alternative energy sources. Hydrogen is classified into various color categories based on the type of feedstock, technology, and CO2 emissions in its production pathway. This paper focuses on blue hydrogen, discussing its potential as the most promising hydrogen production pathway for the near-to-mid-term transition into a hydrogen economy. First, a comprehensive overview of the hydrogen economy is given with a detailed description of hydrogen's color-code categorization. Blue hydrogen production methods are explained, and blue and green hydrogen are compared on the subject of the grand energy transition. Furthermore, the arguments favoring blue hydrogen as the most promising alternative for the near-to-mid-term energy transition are explained. Finally, a comparative life cycle analysis (LCA) of environmental emissions and resource usage in blue hydrogen and other selected commonly used fuel production pathways is conducted using the greenhouse gases, regulated emissions, and energy use in technologies (GREET) model to analyze the potentials of the blue hydrogen production pathway. The LCA results showed that more efforts need to be committed to reducing nitrous and sulfur oxides in the blue hydrogen production pathway and improving energy and CO2 capturing efficiencies in carbon capture and storage (CCS) plants.

27. Naikoo, G. A., Salim, H., Awan, T., Hassan, I. U., Tabook, M. A., Pedram, M. Z., Mustaqeem, M., & Saleh, T. A. (2022). Recent trends in MXenes hybrids as efficient 2D materials for photo- and electrocatalysis hydrogen production. *Materials Today Chemistry, 26*.

Abstract: With fossil fuel consumption and elevated energy demands, the world is focusing on more reliable, sustainable, and inexhaustible sources of energy. The production of high energy density fuels, such as hydrogen, is an essential chemical reaction that implements one of the ideal and environment-friendly technologies called photochemical water splitting. Therefore, over the last decade, strenuous efforts have been made to explore the competent, inexpensive, and abundant non-noble-metal class of two-dimensional (2D) materials like MXenes because of their pivotal role in incredible catalytic and storage applications. In this review, we highlight the introduction of MXenes for the hydrogen evolution reaction (HER), band structure, and their hydrophilic nature. Subsequently, in the next section, we systematically explored the recently developed MXenes and MXene-based photochemical and electrochemical catalysts for efficient HER performance with insightful understanding terms of mechanisms, stability, current density, and various other factors which pave the ways for the improvement of potential electrocatalytic candidates in the future. We concluded it by highlighting the major technical challenges, advantages, and disadvantages with critical scientific developments to alleviate these challenges in the field of HER accentuating major obstacles and focus toward the ultimate goal of developing of advance MXenes as efficient photocatalysts.

28. Rasul, M. G., Hazrat, M. A., Sattar, M. A., Jahirul, M. I., & Shearer, M. J. (2022). The future of hydrogen: Challenges on production, storage and applications. *Energy Conversion and Management, 272*.

Abstract: With the demand for hydrogen being expected to increase by about 8-folds in 2050 over 2020, there are several factors that can turn into challenges for effective roll out of hydrogen applications in energy sector. Hydrogen has the second highest calorific value, 120-142 MJ/kg, which is the best energy-weight ratio among all conventional fuels. Among all hydrogen production processes, the green hydrogen production through mature water electrolysis process, with technology readiness level of ∼7-8 (demonstration/system development) and commercial readiness index of ∼ 4-5 (deployment) contributed about 30% to market share with efficiency of 55-80% and production cost of ∼ \$4-7/kg H_2. This study found that the current hydrogen production costs may reduce to desired 1-2 \$/kg H_2 within a couple of decades, but there is still a lack of plans for combining various hydrogen production processes where necessary, rather than only focusing on producing hydrogen in mass scale. Among all the hydrogen storage systems, the specific volumetric storage cost of metal hydride is less, about \$125/m^3, than other systems. Ammonia has lowest specific energy cost, about \$13/GJ amongst other storage systems. There is a requirement of rapid progression in relevant infrastructure development for efficient supply chain management for storage, transportation, and delivery of hydrogen to the stakeholders. This paper reviewed 400+ articles and summarised hydrogen production processes, storage options, production costs and applications. The synthesis of key information and deep analysis of limitations of existing studies has been provided followed by deep discussion on the challenges of hydrogen as energy carrier for future. To achieve sustainable development goals, integrated plans, infrastructure development, reduction of production costs, achieving net zero emissions and novel storage development need to be achieved within 2050. This reviews thus could be used as a guideline by policymakers, researchers, and scientists for shaping future of hydrogen.

29. Shin, J. -. (2022). Hydrogen Technology Development and Policy Status by Value Chain in South Korea. *Energies, 15*(23).

Abstract: Global transitions from carbon- to hydrogen-based economies are an essential component of curbing greenhouse gas emissions and climate change. This study provides an investigative review of the technological development trends within the overall hydrogen value chain in terms of production, storage, transportation, and application, with the aim of identifying patterns in the announcement and execution of hydrogen-based policies, both domestically within Korea, as well as internationally. The current status of technological trends was analyzed across the three areas of natural hydrogen, carbon dioxide capture, utilization, and storage technology linked to blue hydrogen, and green hydrogen production linked to renewable energy (e.g., water electrolysis). In Korea, the establishment of underground hydrogen storage facilities is potentially highly advantageous for the storage of domestically produced and imported hydrogen, providing the foundations for large-scale application, as economic feasibility is the most important national factor for the provision of fuel cells. To realize a hydrogen economy, pacing policy and technological development is essential, in addition to establishing a roadmap for efficient policy support. In terms of technological development, it is important to prioritize that which can connect the value chain, all of which will ultimately play a major role in the transformation of human energy consumption.

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References

Hydrogen Storage. Energy.gov. (n.d.). Retrieved February 6, 2023, from https://www.energy.gov/eere/fuelcells/hydrogen-storage

Willige, A. (n.d.). *4 ways of storing hydrogen from renewable energy*. Spectra. Retrieved February 6, 2023, from https://spectra.mhi.com/4-ways-of-storing-hydrogen-from-renewable-energy