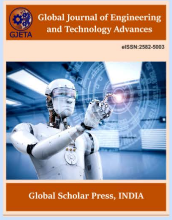
GJETA

Global Journal of Engineering and Technology Advances

eISSN: 2582-5003

Cross Ref DOI: 10.30574/gjeta

Journal homepage: https://gjeta.com/



(REVIEW ARTICLE)

Technological advances of ammonia as energy storage solution

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Global Journal of Engineering and Technology Advances, 2023, 16(03), 151–155

Publication history: Received on 25 July 2023; revised on 12 September 2023; accepted on 15 September 2023

Article DOI: https://doi.org/10.30574/gjeta.2023.16.3.0185

Abstract

The renewable energy is playing an important role in transitioning to the decarbonization of the entire energy value chain. But how will the global energy industry accelerate this transition? Renewables and electrification of energy could be a perfect solution. However, intermittency of renewable energy production is the single biggest challenge faced by renewable energy sources, which can be mitigated when it is coupled with an appropriate energy storage system. First, you need to generate electricity from renewable sources and then store it so that it can be extracted whenever there is a demand. There are several energy storage systems that can be coupled with renewables such as fossil fuel storage, mechanical storage, thermal storage, electrochemical storage, and chemical storage. Studies have shown that chemical storage technologies provide clear advantage in terms of storage time and range of power it can store over other similar technologies. It also justifies the recent research activities around various new chemical storage technologies. A combination of the above energy systems works very well for most of the abundant and affordable energy. However, one area where there can be a significant improvement is the carbon emissions associated with fossil fuel-based storage systems. As a result, the energy industry is recently interested in the transition to renewables coupled with non-carbon storage of power as a long term solution to environmental issues. So the possible solution is producing chemical storage options from surplus renewable energy which solves both the hurdles of emissions as well as carbon-free energy storage system. This article analyses whether ammonia can be viewed as an efficient and technological solution to the problem of large-scale and long-duration energy storage in the decarbonized energy systems of the future. Throughout the article, references have been drawn from a wide range of resources and author's academic and industrial experience. It is intended to use the article as a vehicle to share knowledge with a wide range of audience on utilization of ammonia for energy storage.

Keywords: Ammonia; Energy storage; Renewable energy; Decarbonized energy; Emissions

1. Introduction

The Paris Climate Agreement aims to limit the human-induced global temperature rise to less than 2°C. Meeting that goal will require a global energy system with net zero emissions by 2050 or sooner. Renewable energy sources, such as wind and photovoltaics (PV), will help make a zero-emission energy system a reality. However, the variable nature of these energy sources limits their practical use for electricity generation (Cavicchioli et al 2019). One of the main factors driving research in ammonia combustion is the need for large-scale energy storage. The ability to regenerate power from energy stored in ammonia's chemical bonds will allow far greater penetration of intermittent renewable resources like wind and solar, enabling deep decarbonization of power grids and broader energy economies (Olivier et al 2017).

To date, several mechanical, electrical, thermal, and chemical approaches have been developed for storing electrical energy for utility-scale service. The only sufficiently flexible mechanism allowing large quantities of energy to be stored over long time periods at any location is chemical energy storage. Ammonia, with its established transportation network and high flexibility, could provide a practical next generation system for energy transportation, storage and use for

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power generation. Therefore, this review highlights previous influential studies and ongoing research to use this chemical as a viable energy vector for power applications, emphasizing the challenges that each of the reviewed technologies faces before implementation at a larger scale (Klein et al 2017).

2. Chemical storage energy technologies

There are four major chemical storage energy storage technologies in the form of ammonia, hydrogen, synthetic natural gas, and methanol. The use of ammonia and hydrogen as fuel or energy storage has been attracting a lot of traction in recent years. Hydrogen has great potential, however, issues associated with hydrogen storage and distribution are currently impeding factors for its implementation (Cavicchioli et al 2019). On the contrary, the infrastructure and distribution systems currently in place are far more compatible with ammonia. Additionally, from the point of view of physical properties, ammonia can be easily liquefied at room temperature at about 10 bar or at-33 degrees Celsius under ambient pressure, which is similar in properties to Liquefied Natural Gas (LNG) thus offering easy transportation or storage in the liquid phase (Pattabathula et al 2016).

Overall, ammonia seems a very promising energy storage medium and carrier, but most of the ammonia produced globally is used for fertilizers and comes from the consumption of about 2 percent of the world's energy which leads to about 1.6 percent of global CO_2 emissions. The ammonia produced by utilizing renewables via the Haber-Bosch process, also known as green ammonia, could help reduce above mentioned vast emissions in the ammonia industry. Jiang et al (2017) said that green ammonia has very good energy storage properties to solve the problem of electricity storage for renewable energy plants, like wind farms and photovoltaic solar systems. Ammonia can be produced at these sites to mitigate this issue by utilizing excess renewable energy (Pachauri et al 2014).

2.1. Ammonia-based thermal energy storage system

In the ammonia-based thermal energy storage system, liquid ammonia (NH_3) is dissociated in an energy storing (endothermic) chemical reactor as it absorbs solar thermal energy. Later, the gaseous products hydrogen (H_2) and nitrogen (N_2) are reacted on demand in an energy releasing (exothermic) reactor to resynthesise ammonia and recover the stored solar energy. Because the solar energy is stored in a chemical form at ambient temperature, there are no energy losses in the store regardless of the length of time that the reactants remain in storage(Jiang et al 2017). The reactors are packed with standard commercial catalyst materials to promote both reactions. Counter-flow heat exchangers transfer heat between in-going and out-going reactants at each reactor to use the energy most effectively. Apart from the ability of the ammonia system to allow for solar energy storage, other advantages, that are not necessarily shared by other solar thermochemical or photochemical systems, make this process unique. The result showed a high energy storage density, by volume and mass (Olivier et al 2017).

The reactions are easy to control and to reverse and there are no unwanted side reactions. There exists a history of industrial application with the associated available expertise and hardware. A readily achievable turning temperature of 400–500°C, depending on the pressure. This helps to reduce thermal losses from dish receivers, avoids some high temperature materials limitations, and allows lower quality (and hence cheaper) dish optics to be used. At ambient temperature the ammonia component of reactant mixtures condenses to form a liquid, whilst the nitrogen and hydrogen remains\ as a gas (Klein et al 2017). Thus, only one storage vessel is required for reactants and products. Ammonia re-synthesis could occur at a site some distance from the solar plant, by transporting the ammonia, nitrogen and hydrogen in high-pressure pipelines to and from the plant. In this configuration the pipelines would be forming part of the storage volume. The ammonia storage process was originally developed for arrays of large dishes, but could also be implemented on central tower or trough systems (Myllyvirta et al 2020).

2.2. Ammonia for Power: Internal Combustion Engines

The review summarizes ongoing global investigations into the use of ammonia as a fuel for internal combustion engines, including systems that propose using ammonia as a solo fuel, a dual fuel, and a drop-in fuel, with details on ammonia emulsions and blends. It covers almost every end-use for power generation, from light-duty vehicles to diesel locomotives and industrial power. The combustion of ammonia is challenging, due primarily to its low reactivity, but yields nitrogen gas and water, with a stoichiometric Air Fuel Ratio (AFR) of 6.06 by weight (Cavicchioli et al 2019). Analyses of the feasibility of ammonia as a sustainable fuel in internal combustion engines based on thermodynamic performance, system effectiveness, driving range, fuel tank compactness and cost of driving have also been performed. Not surprisingly, the studies concluded that to make ammonia a viable fuel in ICEs, ammonia needs to be mixed with other fuels as combustion promoters due to ammonia's low flame speed and high resistance to auto-ignition. A dual-fuel approach was usually chosen to implement ammonia combustion in IC engines. Studies have shown that ammonia fueled engines have low power losses, no more corrosion and no more lubricant consumption than conventional fuels (Pachauri et al 2014).

It has been demonstrated that high performance can be achieved using ammonia/gasoline fueling, a three-way catalytic converter capable of cleaning emissions under stoichiometric and rich conditions over short and long distances. Replacement of diesel with diesel/ammonia has also been attempted showing promising results with modification to current diesel engines. Some of the results demonstrated that peak engine torque could be achieved by using different combinations of diesel and ammonia, with a monotonic CO2 reduction for the same torque output for systematic NH3 increase (Pattabathula et al 2016). Additionally, lower NOx emissions were measured for ammonia fuel mixes not exceeding 60% NH3. Combinations such as gasoline/ammonia and ethanol/ammonia, ammonium nitrate/ammonia and even pure oxygen using 100% ammonia have been also attempted, showing that these fuel mixtures can provide elevated power outputs under stable conditions, although mainly conditioned by the NOx emissions product of the combustion process (Myllyvirta et al 2020).

2.3. Ammonia-hydrogen mixtures for efficient power

The most interesting area of research is in the use of ammonia-hydrogen mixtures, which enable dual-fuel combustion despite requiring only one fuel tank. Of particular interest is the use of hydrogen in the ammonia blends, as the molecule can be recovered through splitting of ammonia, with the previously stated improvements in combustion performance. Studies show that ammonia can be blended with hydrogen at levels as low as 5% H2, still providing good power response (Cavicchioli et al 2019). Higher doping ratios have also been deployed, showing, for example, that 10% hydrogen addition provided optimum efficiency and effective power. Liquid ammonia contains 1.7 times as much hydrogen as liquid hydrogen itself. An ammonia tank (1 MPa) contains 2.5 times as much energy as a hydrogen tank (at 70 MPa) by volume, i.e. a hydrogen tank of 770 L (350 kg) could be replaced by an ammonia tank of 315 L (172 kg).

The fast growing of ground photovoltaic (PV) installation and restricted consumption of generated PV electricity result in massive unused/excess PV electricity globally. Zhang et al (2020) proposes a solution using ammonia (NH_3) as an energy medium to convert the excess solar energy into stable chemical energy. Analysis of the energy efficiency, technical feasibility and economy of solar-to-ammonia conversion concludes that ammonia is a promising medium for large scale storage of renewable energy, e.g. PV electricity. The solar-to-ammonia conversion offers a great advantage of storing massive amounts of excess energy for wider application (Jiang et al 2017).

3. Conclusion

The relationship between ammonia and hydrogen is unique: ammonia can be used either as a fuel or as a source of hydrogen fuel, enabling hydrogen fuel technologies like the PEM fuel cell. In terms of energy density, liquid ammonia contains 15.6 MJ/L, which is 70% more than liquid hydrogen (9.1 MJ/L at cryogenic temperature) or almost three times more than compressed hydrogen (5.6 MJ/L at 70 MPa). In terms of driving range, a 60.6 L fuel tank of ammonia provides a driving range of 756 km, almost twice the range of the same volume of liquid hydrogen (417 km) and three times the range of the same volume of compressed hydrogen (254 km). Ammonia still faces a long way before being entirely recognised as a fuel for power applications. Although technical barriers are overcome by continuous, high quality research combined with advanced innovation. One of the main reasons of this trend is the fierce competition between ammonia and other fuels. As stated, ammonia should not be regarded as a competitor to the hydrogen economy, but as an enabler. Therefore, ammonia can find its niche of application amongst some other fuels that are currently under research. To recognise these applications, it is necessary to know some specific characteristics of ammonia to allow comparison with other hydrogen sources employed in power systems.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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