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The nitrogen economy: Economic feasibility analysis of nitrogen-based fuels as energy carriers

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HIGHLIGHTS

- An economic feasibility of a model nitrogen-based fuel.
- A levelized cost of energy storage index is used in technology assessment.
- Critical factors for the suggested technology implementation are outlined.
- Nitrogen economy is applicable in both fertilizer and energy sectors.

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ABSTRACT

Production of transportable and environmentally friendly synthetic chemical fuels using hydrogen produced by water splitting, using renewable energy will facilitate energy storage and incorporation of renewable energy into the grid. Both carbon and nitrogen can serve as hydrogen carriers leading to carbon- or nitrogen-based fuels carriers. Although the carbon route is vastly reported, the nitrogen-based analog is only scarcely described in the literature, and its economic potential is completely overlooked. Using levelized cost of storage analysis, this work evaluates for the first time the economic feasibility of a nitrogen economy, where liquid nitrogen-based fuels serve as alternative hydrogen carriers. The results indicate that an aqueous solution of ammonium hydroxide and urea is competitive with other future large-scale energy storage solutions such as methanol and batteries. At a hydrogen price below 2.5 \$/kg, this fuel can be competitive with currently-used mature technologies.

1. Introduction

Continued use of fossil fuels to power the current energy grid can lead to undesirable effects to our health, climate and environment [1]. Therefore, an increase in the usage of renewable energy resources in our energy portfolio is required. However, increasing the share of renewables such as wind and solar in our electric grid presents an inherent problem since these are intermittent energy resources, both on a short daily term and over longer periods, necessitating large scale storage solutions to accommodate a per-demand electrical power supply [2]. Several energy storage approaches are suggested by the scientific community [3]. Clearly, it is naïve to think that one approach will resolve the whole problem, and alternative solutions should be developed and critically analyzed. Therefore, there is need to assess each approach and to demonstrate its feasibility and economic competitiveness.

Currently, the most favourable mature large-scale energy storage technologies are compressed air energy storage (CAES) and pumped hydro storage (PHS) [4,5]. The principle of both technologies is to use excess off-peak power to pump either air or water increasing their potential energy, which can be converted efficiently back to electricity upon demand [6]. However, both technologies offer local solutions since they can be implemented only where proper geological or geographical conditions are available [5–7]. An alternative approach would be to invest the renewable energy to produce hydrogen fuel from water using water-splitting technologies.

1.1. The hydrogen economy

Hydrogen is a promising environmentally clean fuel, since it yields only water and energy when oxidized. It is an abundant element, and could be directly produced through water electrolysis,

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using seawater as a feedstock. Hydrogen was suggested as a promising energy storage solution based on an energy-return basis, but further improvements are needed for the economy to be implemented on a large scale [8]. The current cost for producing renewable hydrogen depends on the cost of electricity, energy resources and the technology system efficiency. Wind power-based electrolysis can currently produce renewable hydrogen at a price range of 3.74–5.86 \$/kg H_2 without any federal tax credit [9]. For comparison, the price of hydrogen produced from coal and natural gas (NG) is in the range of 0.36–1.83 \$/kg and 2.48–3.17 \$/kg, respectively [10,11]. Currently, hydrogen production is predominately (>90%) based on reforming of fossil fuels [12], which in most cases today is more economical than electrolysis. However in the advent of cheaper electricity in the future and potentially more efficient photo-electrolysis (i.e. PEC technology), the price of water-based hydrogen will be more attractive.

Hydrogen has a relative high gravimetric energy density of 120 MJ kg^{-1} (low heat value). However, as a gas at ambient conditions it has poor volumetric energy density. To resolve this problem, hydrogen can be either compressed or liquefied [13,14]. Liquefying hydrogen increases its volumetric energy density, but with an energy penalty estimated at up to 30%. In addition, liquefied H_2 involves boil-off losses during storage at a rate of up to one percent per day [15]. Compressed or liquefied hydrogen on a large global scale currently presents unresolved challenges in terms of safety and infrastructure costs [12]. Therefore, although hydrogen is a key ingredient in renewable synthetic fuels, it cannot serve as the energy coin.

The use of alternative fuels, especially in a liquid form, is one of the most attractive storage approaches since liquid fuels are unmatched in terms of transportability and energy density and they can rely on existing infrastructure. Hydrogen can be stored as a liquid fuel using carbon or nitrogen as the main carriers. An example of using carbon as a hydrogen carrier is the production of methanol from CO_2 and hydrogen (or CO_2 and water), a key step in the "Methanol Economy" concept suggested by Olah [16]. However, large scale CO_2 separation from the atmosphere is a complex engineering challenge [17], while the large scale collection of CO_2 from existing power plants is not simple either. An alternative route is to use atmospheric nitrogen that is available everywhere, to produce nitrogen-based fuels. It should be mentioned that separation of nitrogen from air is not cost-free, but the costs are relatively much smaller than those of CO_2 separation [18].

1.2. The nitrogen economy

The nitrogen economy is a proposed future system in which nitrogen compounds are produced to help meet the demands of the fertilizer and energy sectors. Nitrogen-based fuels can be used as hydrogen carriers, which can be safely stored and handled [19,20], relying on existing infrastructure. Once the energy is needed, these materials can provide high pressure, environmentally-clean fuels to drive turbine-generators and various other heat engines.

Ammonia is the simplest representative of the nitrogen economy, referred to as the ammonia economy [21,22], and also the second-largest synthetic commodity produced worldwide [23]. Currently, about 80% of ammonia production is consumed by the fertilizer industry [24]. Ammonia can be produced from renewable intermittent energy sources using current technologies [25] and can be used in gas turbines with little modifications [26,27]. A recent study assessed the levelized cost of energy for ammonia in an integrated energy storage system to be 251 \$/MW h, which can be competitive with other suggested large scale storage technologies [28]. In terms of safety ammonia is not flammable in air and requires higher concentration to pass the explosion limit than gasoline vapors and NG [29]. However, ammonia is much more toxic than gasoline or methanol, with dangerous health effects for human depending on the exposure time and dose [30]. For this reason the utilization of ammonia as a transportation fuel has been hampered. It should be mentioned that we are studying the use of aqueous solutions of ammonia and its derivatives, solutions that have lower vapor pressure that pure ammonia, and hence would have a lower impact upon a spill. In addition, the use of ammonia-based fuels in stationary applications poses a considerably lower risky than the transportation sector. Nevertheless, more effective and safe containment technologies should be developed before widespread use of ammonia and its derivatives as fuels will be practiced. Safe solutions of ammonia and its derivatives could play an important role as alternative fuels [18,22].

A recent energy-return based analysis demonstrated that an aqueous solution of ammonia derivatives can be effective hydrogen carriers [18]. The fuel suggested is an aqueous solution of ammonium hydroxide and urea (AHU). This is a low carbon nitrogen-based fuel, can produce a relatively clean combustion effluent products: nitrogen, water and relatively low levels of carbon dioxide:

$$NH_4OH_{(aq)} + 0.3NH_2CONH_{2(aq)} + 1.4H_2O_{(l)} + 1.3O_{2(g)} \rightarrow 0.8N_{2(g)} + 4.6H_2O_{(l)} + 0.3CO_{2(g)} \quad \Delta\widehat{H}^{o}_{Rxn} = -571\ \frac{kJ}{mol} \qquad (R1)$$

A preliminary investigation of this fuel in a closed pressurized chamber with pure oxygen at 20 bar and fuel/oxygen stoichiometric ratio is underway. We have found that the fuel undergoes spontaneous thermal ignition above 400 °C without a catalyst or a spark. A similar model nitrogen-based fuel (based on an aqueous solution of ammonium nitrate and urea; UAN), was previously investigated in a continuous combustion reactor. That study demonstrated that a nitrogen-based fuel can be combusted cleanly, complying with strict standard regulations [31]. The safety issue of aqueous solutions of a related nitrogen-based fuel (UAN) was published elsewhere [20]. When used in aqueous solution format, the solution is non-flammable and non-explosive. In fact, the water has a large stabilizing effect on the ignition of these fuels, driving the ignition point upward towards 400oC, depending on pressure. In addition, Nitrogen-based fuels consist of known commodities that are already in widespread use on an industrial scale with well-developed production and transportation processes [32–34]. Nitrogen-based fuels have not been included in previous studies of large scale storage systems [35,36], and hence, their economic feasibility has not been compared to other alternatives [3,4,37–39]. In addition, the economic competitiveness of the two tracks (carbon- or nitrogen-based fuels) has not been fully assessed [18,40]. This paper addresses the above points for the first time.

In this paper, we analyze the economic merit of utilizing AHU fuel. An economic index based on levelized cost is defined for each of the storage technologies and used to compare aqueous AHU with other large-scale energy storage alternatives. The critical factors for implementation of the suggested technology are outlined and used to identify the breakthrough point at which this proposed solution is economically feasible.

2. Results and discussion

2.1. Economic analysis for the energy sector

An economic feasibility analysis of a promising model nitrogen-based fuel: aqueous AHU [18], is presented herein. The steps in the project lifecycle are illustrated in Fig. 1. The first step is the fuel's components production (ammonia and urea) from their feedstocks. The second step is mixing the components to produce the aqueous