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The Nitrogen Economy: Economic Feasibility Analysis of Nitrogen-Based Fuels as Energy Carriers

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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. 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.

Keywords

The nitrogen economy, nitrogen-based fuel, economic analysis, energy carriers, alternative fuels

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 of these is to use excess off-peak power to pump either air or water increasing their potential energy and when needed to convert it back to electricity[6]. However, both technologies offer local solutions since they can be implemented only where geological or geographical conditions are appropriate [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, 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, most of the hydrogen production (above 90%) is from fossil fuels [12], which in most cases is more economical than electrolysis.

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 [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 [18]. It should be mentioned that separation of nitrogen from air is not cost-free, but the costs are relatively much smaller than those in CO_2 separation.

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 as energy storage system to be 251 \$/MWh, 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 and methanol, with dangerous health effects for human depending on the exposure time and dose [30]. Therefore, more effective and safe technologies should be developed before widespread use of ammonia as a fuel. 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, which has the potential to produced relatively clean effluent combustion products: nitrogen, water and relatively low levels of carbon dioxide:

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

A preliminary investigation of this fuel found that it can be spontaneously ignited above 400°C without introducing a catalyst in a closed pressurized chamber with pure oxygen at 20 bar and fuel to oxygen stoichiometric ratio. A similar model nitrogen-based fuel (based on an aqueous solution of ammonium nitrate and urea), 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]. In addition, Nitrogen-based fuels are consisting 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) is not 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 Figure 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 solution and storing the fuel. When the energy is needed the fuel is combusted to produce electrical power, relaying on existing power conversion units and infrastructure with some modifications. In this analysis, a base value of 3,000 tons/day is assumed for the production rate of ammonia. All the other rates and costs are derived from this base production rate.

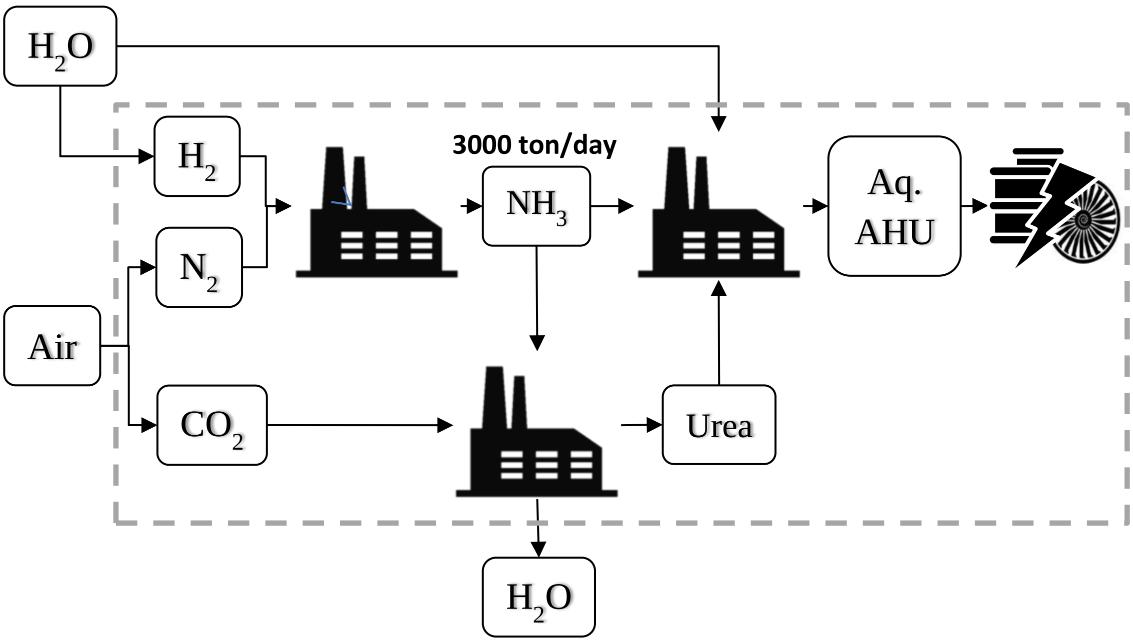

Figure 1. Illustration of the case study system. System boundaries are marked by dashed lines.

In this conservative economic case study based on economy of scale, the feedstocks for the fuel are hydrogen produced from water splitting process, nitrogen via cryogenic air separation, carbon dioxide via atmospheric air separation unit and desalinated water. The feedstock costs for the case study are based on previously reported values (Table S1). In addition, the total production costs are estimated while taking into consideration the cost of manufacturing (COM) (Table S2). In the current case study, negligible general expenses (such as sales-related and administrative expenses) were assumed, since the main consumer is the energy grid. The fixed capital costs for the ammonia, urea and aqueous AHU production plants are estimated based on similar previously constructed plants data (Table S3). In addition, costs associated with the fuel and feedstock storage are also introduced into this analysis (Table

S3). Chemical Engineering Plant Cost Index ($CEPCI_{2015}$=562.9) [41] was used to update the capital costs to the present time while taking into account the appropriate capacity ratio:

$$Cost_2 = Cost_1 \cdot \left(\frac{CEPCI_2}{CEPCI_1}\right) \cdot \left(\frac{Capacity_2}{Capacity_1}\right)^m \qquad (E1)$$

The power factor *m*, can vary from 0.38 to 0.9 for many chemical production plants, with an average value of 0.6 [42]. In this analysis factors of 0.53, 0.7 and 0.65 where used for the ammonia, urea and aqueous AHU production plants, respectively [43].

For estimation of the economic feasibility, a levelized cost of energy storage (LCOES) index [44–46] is defined herein as the ratio of all the expenditures associated with the fuel production, such as costs of capital investment (I_t) and operation and maintenance costs (M_t), to the electrical energy produced (E_t) in the project lifetime taking into account the discount rate, *r*:

$$LCOSE = \frac{\text{sum of costs over lifetime}}{\text{sum of electrical energy produced over lifetime}} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \qquad (E2)$$

The electrical energy produced is estimated assuming 50% combustion efficiency (HHV) in a combined cycle gas turbine (CCGT) plant (gas turbine (Brayton) and steam turbine (Rankine)) for aqueous. AHU [18]. The expected lifetime of the system (*n*) is assumed to be 20 years. An assumed fixed discount rate (*r*) of 3%, noting that varying the discount rate in the range 3-10% had minor effect on the obtained LCOES value. The LCOES is expressed per unit of energy and takes into account the technology life time. This provides a better indicator for economic evolution of energy storage technologies than methods which do not incorporate the technology life time or life cycle [47]. The accuracy of the obtained LCOES value has an estimated error of ±30%, as discussed in the supplementary materials.

2.1.1 Present scenario

The obtained value of LCOES was compared to the LCOES values of other alternative large scale storage technology such as batteries, compressed air, pump hydro [48] and a representative of liquid carbon-based renewable fuels: methanol, under reasonable assumptions (see supplementary material). The LCOES value for renewable synthetic methanol [49] was updated to present value and adjusted to the price of hydrogen (5$/kg), used in this analysis. As shown in Figure 2, aqueous AHU is competitive with methanol and with lithium ion battery technology, but less effective than compressed air and pumped hydro. However, it is important to note that both of the last-mentioned technologies offer a local storage solution since they can only be implemented when geographical or geological conditions permit it. The LCOES of ammonia was calculated and found to be 302±30% $/MWh in agreement with a previously-estimated value[28]. In addition the levelized cost of production of ammonia and urea were calculated and found to be 30 and 10% higher than the highest prices of ammonia and urea produced from fossil fuels, respectively (Table S4).

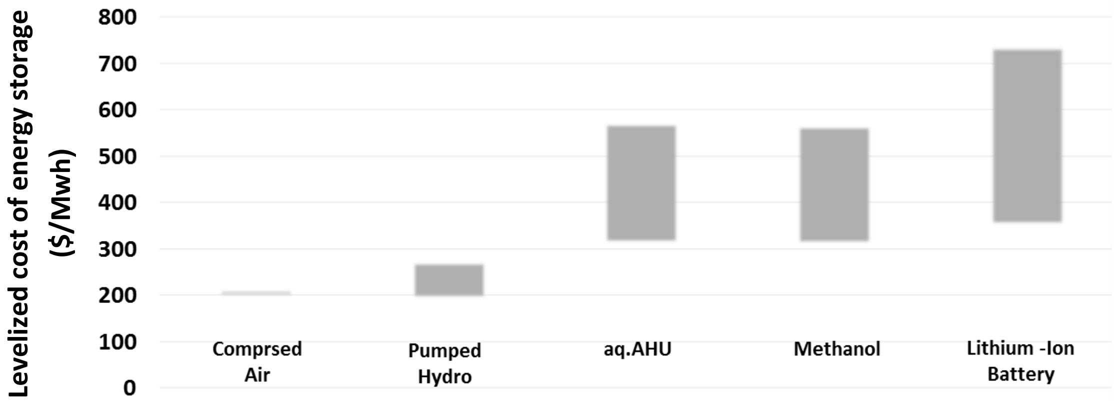

Figure 2. Levelized cost of energy storage (LCOES) of different large-scale energy storage solutions alternatives. For this basis case the hydrogen price is 5 $/kg (only relevant to aq. AHU and methanol).

To evaluate the critical parameters that influence the LCOES for aqueous AHU, the normalized sensitivity is defined and calculated as a function of a change in the parameter, *x* (shown in Table 1 below):

$$\left(\frac{x}{LCOSE}\right)\cdot\left(\frac{\partial LCOSE}{\partial x}\right) \qquad (E3)$$

Thus, the normalized sensitivity value indicates the fractional change in the LCOES index for a change in the parameter, *x*. These values can be used to rank the parameters, since higher absolute values means greater influence on LCOES. A shown in Table 1, the production cost of hydrogen has the highest normalized sensitivity value, while the combustion efficiency is rated second with a significant absolute value as well. The combustion sensitivity value is negative since a decrease in the efficiency leads to less effective use of the fuel and lower electrical power output relative to the costs for its production.

Table 1. The normalized sensitivity of the LCOES index to its major contributing factors

Parameters	Normalized sensitivity
H_2 production costs	0.675
Combustion efficiency	-0.236
Electricity grid price	0.127
CO_2 production costs	0.107
Capital investment NH_3	0.051
Capital investment Urea	0.026
N_2 production costs	0.011

The parameter that has the largest effect on LCOES is the one whose actual variation changes it the most. Thus, the normalized sensitivity alone is insufficient, since in principle, a parameter can have high value of normalized sensitivity but the value itself might only vary in a narrow range. The upper and lower bounds between which each parameter can decrease or increase are estimated by thermodynamic limitations or reasonable estimations (see Table S5). For example the combustion efficiency of aqueous AHU cannot extend beyond the Carnot efficiency of this fuel. Figure 3 shows the absolute increase or decrease in the LCOES when each of the investigated parameters is changed independently. Hydrogen production costs is the most critical parameter for the implementation of aqueous AHU, since it has both the highest normalized sensitivity and the largest absolute influence on the LCOES value.

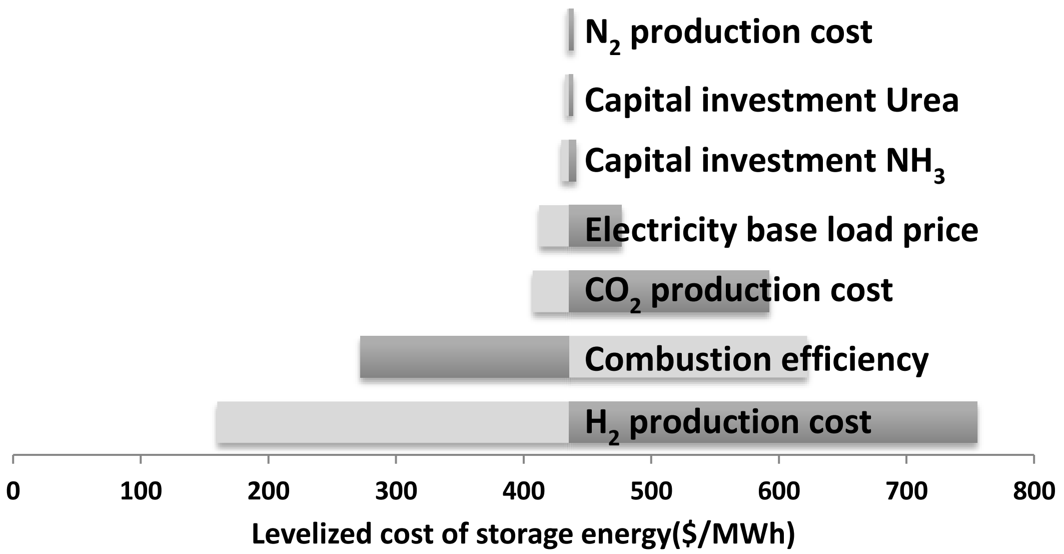

Figure 3. Absolute sensitivity of levelized cost of energy storage (LCOES) for the different major parameters. Light bar- decrease in the parameter value, dark bar-increase in the parameter value.

Figure 4 shows the sensitivity of LCOES to variations in the hydrogen production price. The obtained values are compared to mature technologies used today for balancing the electrical grid and storing energy. Below a price of 2.5 $/kg of hydrogen aqueous AHU can be competitive with pump hydro technology. Below a price of 1.6 $/kg of hydrogen aqueous AHU can be competitive with compressed air technology and peaking power plants.

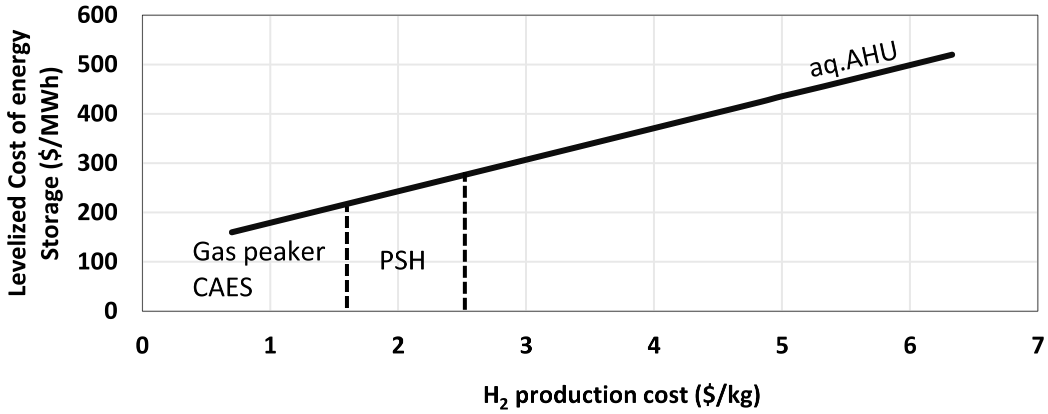

Figure 4. Levelized cost of energy storage (LCOES) of aq. AHU at different hydrogen price.

Currently the hydrogen price from renewables is higher than 3 $/kg [9], depending mostly on the energy source (i.e. wind or solar). Future technological development and government subsidies can decrease the price of hydrogen for the appropriate range for implementation of aqueous AHU as energy storage solution.

2.1.2 Scenario for the near future

For a near future scenario, the investments costs were updated using equation (E1), where the estimated CECPI in 2020 is 604.8 (based on a scenario that predicted relatively more accurate CECPI values in the past years [27]). Once a cost effective technology for producing hydrogen will be available, aqueous AHU could be produced when excess power is available at low price. Then this fuel could be converted back to electrical power at higher price when the power demand peaks. For this technology to be economically feasible, the net present value (NPV) for the mentioned process needs to be positive. The selling price of electrical energy to achieve a positive NPV depends on the hydrogen price. As shown in Figure 5, at lower hydrogen price, the demand electricity price can decrease, still yielding a positive NPV.

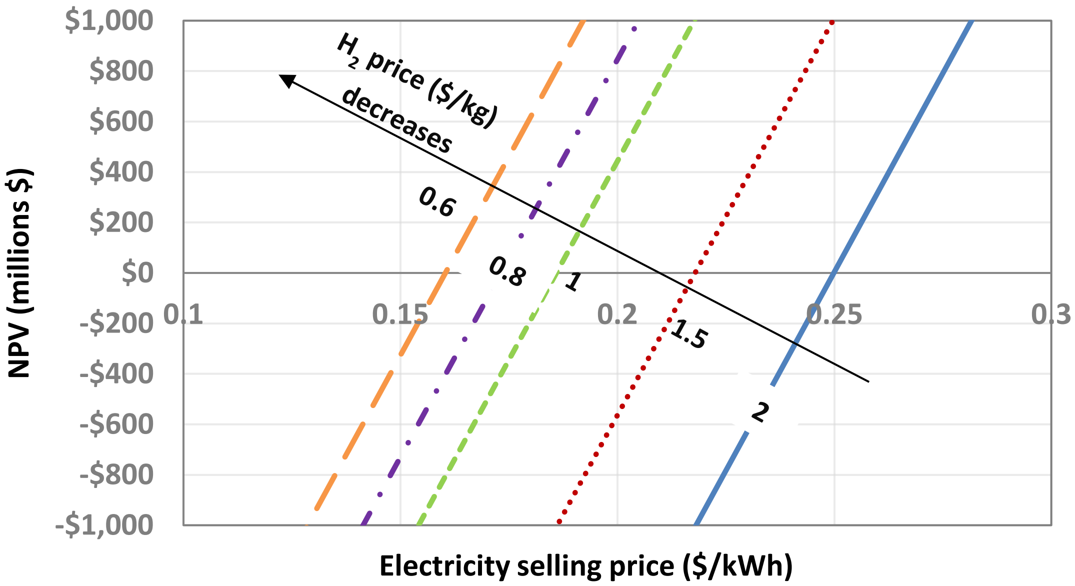

Figure 5. Net present value (NPV) as function of electricity selling price for deferent hydrogen costs. Assumed a fixed 3% discount rate over the project lifetime.

The minimum selling of electricity back to the grid at a given hydrogen price can be calculated for the case where NPV=0 (Figure 6). Below 0.8 $/kg, this technology becomes competitive (in terms of current electricity price), with some fossil fuels used to supply grid power [50,51].

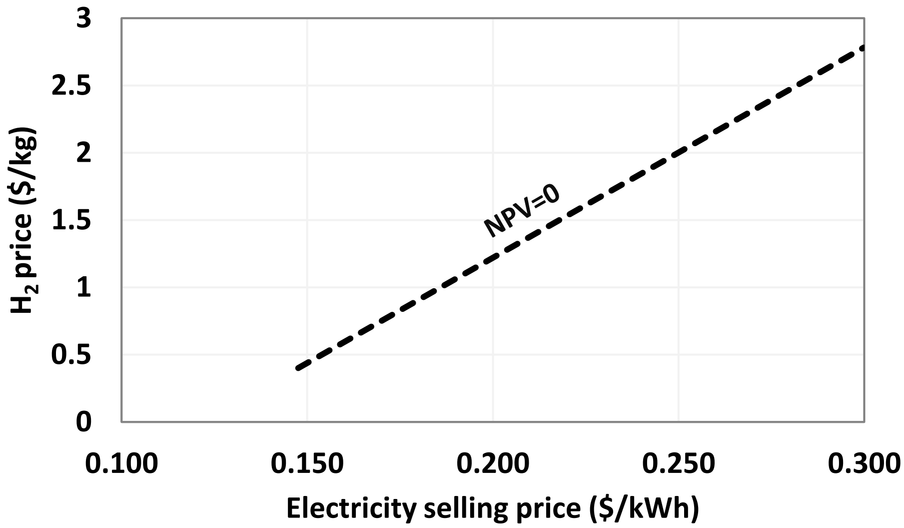

Figure 6. The electricity selling price target at given hydrogen price to gain a net present value equal to zero.

2.2 Economic analysis for combined sectors (Fertilizer and energy)

The nitrogen economy can be based on a portfolio of products, addressing demands in both the energy and fertilizer sectors. The different products can be sold at a combined competitive price depending on market fluctuation. For example in a case where the electricity price is low, while the demand for fertilizers is high, selling fertilizers at higher prices can help to compensate the market needs for low electricity price and vice versa. To demonstrate this, an example scenario was simulated where 72% of the ammonia is directed to fuel synthesis (based on the amount of fuel needed to supply 250MW electricity), 18% to urea production and the remaining 10% of ammonia was sold as is. Currently the prices of ammonia are in the range of 0.386-0.771 $/kg and for urea the range is 0.346-0.795 $/kg [52]. Figure 7 shows the electricity selling price for NPV=0 at different selling prices of ammonia and urea, assuming the price ranges above remain valid in the near future.

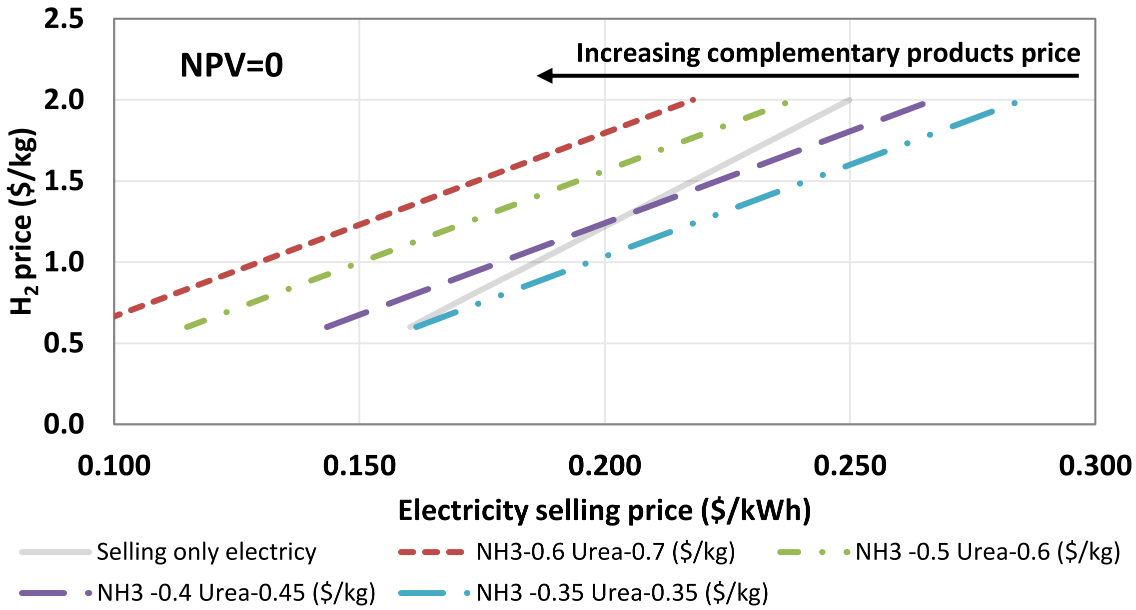

Figure 7. The electricity selling price target at given hydrogen price to gain a net present value (NPV) equal to zero, while selling complementary products (ammonia and urea) at various prices. The case for selling only electricity without complementary products is marked in a continuous line, equal to the line presented in Figure 6.

In cases where ammonia and urea are sold at relatively high market prices, the electricity selling price can be decreased to below 0.15 $/kWh and still be economically feasible (NPV>0). For the project to be economically feasible, the electricity price must be increased to compensate for lower selling prices of ammonia and urea. This example demonstrates that addressing both fertilizer and energy sectors is economically more flexible.

3. Conclusions

The economic feasibility of a nitrogen economy where nitrogen-based fuels act as hydrogen carriers was investigated for the first time in the energy and fertilizer sectors. A levelized cost of energy storage index (LCOES) was defined and used to evaluate and compare suggested storage technologies. The analysis shows that even today a model nitrogen-based fuel based on urea and ammonium hydroxide can be competitive with other suggested large-scale alternative storage technologies such as batteries and renewable synthetic carbon-based fuels (methanol). The critical factor that influences the expansion of the nitrogen economy into the energy sector is the price of hydrogen. In the future when cost effective technology for producing hydrogen will be ready, nitrogen-based fuels will be economically competitive with current mature technologies such as PHS, CAES and peaking power plants. An advantageous economic flexibility can be achieved by expanding the nitrogen economy to both fertilizer and energy sectors, thereby balancing the price of electricity and fertilizer products. In summary, nitrogen based fuels offer a storage solution that can provide clean and economically feasible power, thus fertilizing our energy portfolio in the future.

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