CHEMISTRY

Catalyst-free, highly selective synthesis of ammonia from nitrogen and water by a plasma electrolytic system

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There is a growing need for scalable ammonia synthesis at ambient conditions that relies on renewable sources of energy and feedstocks to replace the Haber-Bosch process. Electrically driven approaches are an ideal strategy for the reduction of nitrogen to ammonia but, to date, have suffered from low selectivity associated with the catalyst. Here, we present a hybrid electrolytic system characterized by a gaseous plasma electrode that facilitates the study of ammonia formation in the absence of any material surface. We find record-high faradaic efficiency (up to 100%) for ammonia from nitrogen and water at atmospheric pressure and temperature with this system. Ammonia measurements under varying reaction conditions in combination with scavengers reveal that the unprecedented selectivity is achieved by solvated electrons produced at the plasma-water interface, which react favorably with protons to produce the key hydrogen radical intermediate. Our results demonstrate that limitations in selectivity can be circumvented by using catalyst-free solvated electron chemistry. In the absence of adsorption steps, the importance of controlling proton concentration and transport is also revealed.

INTRODUCTION

The artificial fixation of nitrogen (N₂) has an enormous energy, environmental, and societal impact, the most important of which is the synthesis of ammonia (NH₃) for fertilizers that helps support nearly half of the world’s population (1). Industrially, NH₃ is currently produced via the Haber-Bosch (H-B) process by reacting N₂ with hydrogen (H₂) over an iron-based catalyst at high pressure (150 to 300 atm) and high temperature (400° to 500°C) (2). This heterogeneous reaction scheme consumes more energy and contributes more greenhouse gas emissions than any other process associated with the top large-volume chemicals manufactured worldwide (3). A critical reason is that the source of H₂ for H-B is fossil fuels, and either coal or natural gas must be catalytically converted in multiple steps before NH₃ synthesis takes place. Because of the low single-pass conversion efficiency (15%) and high temperatures and high pressures, plants that implement H-B are large and centralized to be economical, making them difficult to integrate with renewable sources of H₂ such as electrolysis (4).

Strategies for large-scale NH₃ synthesis at ambient conditions that use renewable sources, such as water or H₂ from electrolysis, are being explored and include photochemical (5) and electrochemical (6) processes. The major drawback with these approaches has been poor selectivity (<1%) for the desired NH₃ product (7) largely related to the catalyst. Photochemical reduction suffers from weak adsorption of N₂ on the surface of and oxidation of the reaction products by the holes in semiconductor catalysts (8). Electrochemical reduction has been characterized by large overpotentials that are required for the relatively stable N₂ to associatively or dissociatively adsorb on a metal catalyst and energetically satisfy multiple intermediates involved in the complex reaction mechanism (9, 10). Moreover, the electrocatalysts with the lowest overpotentials are metals that favor the adsorption of hydrogen species (H₂, H⁺, etc.) over N₂, making it difficult to suppress the hydrogen evolution reaction (HER), which ultimately compromises NH₃ formation (11).

Plasma-based processes are capable of activating N₂ without a catalyst by generating highly energetic electrons; nitrogen fixation to convert N₂ and oxygen (O₂) to nitrates (NO₃⁻) occurs naturally in the atmosphere from lightning (12) and was industrially developed before H-B by forming an electric arc in air known as the Birkeland-Eyde process (13). More recently, plasmas have been combined with solid catalysts to enhance the heterogeneous reaction of N₂ and H₂ and enable NH₃ synthesis at atmospheric pressure and low temperature (14). The synthesis of NH₃ from water has also been reported (15). While these studies are promising, particularly the latter to avoid a dependence on fossil fuels (16), selective reduction of N₂ to NH₃ from renewable sources remains elusive.

Here, we report a hybrid electrolytic approach using a gaseous plasma electrode to study NH₃ formation at ambient temperature and pressure from N₂ and water free of any catalytic material surface. Distinct from other plasma-based processes such as lightning and the Birkeland-Eyde process, the conditions are controlled by removing air via a gas purge and reacting solvated electrons with water containing acid to selectively produce NH₃. Solvated electrons, one of the most powerful reducing agents known, are injected into water from the plasma that is formed by electrical breakdown of an N₂ gas flow in contact with the liquid surface (17). The feasibility of solvated electrons reducing N₂ to NH₃ has been previously demonstrated using boron-doped diamond films but required ultraviolet radiation to generate the solvated electrons, and the surface termination influenced NH₃ formation (18). By using only electricity and forming the solvated electrons at a gas-liquid interface, we have discovered that high selectivity (up to 100%) and large production rate (0.44 mg/hour) are possible. Measurements of NH₃ at varying currents and pH and in the presence of scavengers for potential reaction intermediates provide insight that a key step in our process is the reduction of protons (H⁺) to hydrogen radicals (H·) by solvated electrons. Moreover, we find that by removing kinetic barriers for adsorption to a surface, NH₃ formation depends primarily on the concentration and transport of H⁺. These results elucidate
how solvated electron chemistry can be harnessed to circumvent limitations in selectivity associated with the catalyst for \( \text{NH}_3 \) production from renewable energy sources.

**RESULTS**

**NH\(_3\) formation in a plasma electrolytic system**

The synthesis of \( \text{NH}_3 \) from \( \text{N}_2 \) and water was carried out in a plasma electrolytic system schematically depicted in Fig. 1A. The setup bears similarity to electrochemical approaches except that the metal cathode was replaced by a plasma formed in a gas gap between a stainless steel nozzle and the solution surface. Details of this general approach have been reported elsewhere (19). Here, to study \( \text{NH}_3 \) formation, both argon (Ar) and \( \text{N}_2 \) were investigated as the plasma supply and purge gas. We performed all the experiments with a platinum (Pt) electrode immersed in the solution, which operated as the anode. The solution contained sulfuric acid (H\(_2\)SO\(_4\)) in deionized water (18.2 megohm) to both supply protons (H\(^+\)) for \( \text{N}_2 \) reduction and trap the as-synthesized \( \text{NH}_3 \).

We initially performed a series of control experiments to verify \( \text{NH}_3 \) formation under the same amount of time and current of 45 min and 6 mA, respectively. Figure 1B shows the average mass of \( \text{NH}_3 \) produced for the following configurations: (i) \( \text{N}_2 \) both flowing into the cathode tube where the plasma is normally generated and bubbled through the solution to purge, but no electrical power applied (i.e., no plasma generated); (ii) Ar as both the supply gas in the plasma and the purge gas; (iii) Ar as the supply gas in the plasma and \( \text{N}_2 \) as the purge gas; and (iv) \( \text{N}_2 \) as both the supply gas in the plasma and the purge gas. The complete set of data for all trials is shown in table S1A.

![Fig. 1. Catalyst-free, electrolytic \( \text{NH}_3 \) production from \( \text{N}_2 \) and water using a plasma electrolytic system.](http://advances.sciencemag.org/)

(A) Schematic of the plasma electrolytic system operated by a dc power supply and galvanostatically controlled using a resistor (R) in series. The direction of electron flow (e\(^-\)) is indicated. (B) Total \( \text{NH}_3 \) produced after 45 min at 6 mA and pH 3.5 for various gas configurations and controls. (C) Potentially important species contained in the plasma, such as vibrationally excited \( \text{N}_2 \) \([\text{N}_2(v)]\), and in the water, such as solvated electrons \([\text{e}^-(\text{aq})]\), and their involvement in reactions, such as the generation of hydrogen radicals \((\text{H}^+\)) that lead to \( \text{NH}_3 \) formation. The overall reactions for \( \text{N}_2 \) reduction to \( \text{NH}_3 \) and \( \text{H}_2 \) evolution (under acidic conditions) at the cathode are shown.
electrolysis, as demonstrated in previous studies (20). In comparison, NH$_3$ was produced (statistically nonzero; table S1B) when N$_2$ was either the purge or the plasma supply gas, confirming that it was not coming from other sources including background contamination. The NH$_3$ yield was significantly larger with N$_2$ in the plasma compared with Ar in the plasma (table S1B).

A potential reaction mechanism for NH$_3$ synthesis by solvated electron chemistry was proposed by Christianson et al. (21) based on the reduction of protons to hydrogen radicals (H·), H$^+$ + e$^-$(aq) $\rightarrow$ H·, followed by sequential addition of H· to N$_2$. This relatively simple picture is generally consistent with the associative pathway that has also been proposed for N$_2$ reduction in biological and electrochemical systems (7). As shown in Fig. 1C, analogous to electrochemical synthesis of NH$_3$, the HER is a major competing reaction, reducing selectivity, and occurs via either the second-order recombination of solvated electrons, 2e$^-$(aq) + 2H$_2$O $\rightarrow$ H$_2$ + 2OH$^-$, or hydrogen radicals, 2H· $\rightarrow$ H$_2$, with the latter predominant under acidic conditions. We note that the first and rate-limiting step of this previously proposed mechanism for NH$_3$ formation, which forms the reaction intermediate N$_2$H·, is characterized by sluggish kinetics, and it is likely that the HER will dominate in this scenario. For this reason, while this mechanism may be relevant for our experiments with Ar in the plasma and N$_2$ bubbled, the relatively high NH$_3$ yield with N$_2$ in the plasma suggests a different pathway for NH$_3$ formation.

There are two aspects to our system that are distinct from that reported by Christianson et al. (see Fig. 1C). The first is that when N$_2$ is supplied in the plasma, an excess of N$_2$ is provided to the plasma-water interface. The solubility of N$_2$ in water at atmospheric pressure and room temperature (25°C) is relatively low (6.8 × 10$^{-4}$ M) and, in the case of an Ar plasma, will be even further depleted as N$_2$ that is bubbled is converted to NH$_3$. However, we estimate that the interfacial solvated electron concentration is ~0.5 mM at a current of 6 mA, and it is unlikely that the N$_2$ concentration at the interface could ever be high enough to overcome the much faster HER and explain the observed higher NH$_3$ yield. The second difference in our system is that N$_2$ in the plasma could lead to gas-phase excitation or dissociation of N$_2$. We point out that at atmospheric pressure, the electron energies in a plasma are dampened by collisions and the most likely mode of excitation is vibrational, which has the lowest energy threshold. In catalytic conversion of N$_2$ and H$_2$ to NH$_3$, the importance of vibrationally excited N$_2$ in lowering the activation barrier for the initial dissociative adsorption step is well known (14). The role of such excited species in plasma-water interfacial chemistry has not been reported, but we suggest, based on our results, that it is possible that vibrationally excited N$_2$ reacts in a water vapor layer to form an intermediate that then dissolves at sufficiently high concentrations with favorable kinetics toward solvated electrons or H atoms to enhance NH$_3$ formation.

**NH$_3$ yield and efficiency**

NH$_3$ yield and efficiency in the plasma electrolytic system were examined by measuring the amount of NH$_3$ synthesized after different processing times and at different steady-state operating currents. Figure 2A shows the average mass of NH$_3$ obtained as a function of time at a current of 6 mA and a pH of 3.5. The complete set of data for all trials is shown in table S2A. A linear increase in NH$_3$ produced with time would indicate a constant production rate, but we find that the rate changes, decreasing after 10 min. The efficiency was estimated by comparing the measured NH$_3$ mass at each time point to the amount of NH$_3$ calculated from Faraday’s law assuming a three-electron reaction (see the Supplementary Materials for details).

We note that while the set point for the current through the hybrid electrolytic system was kept constant, there were small fluctuations over the duration of the experiments arising from plasma instabilities, particularly when the plasma was ignited (fig. S1). Over the experimental period, these fluctuations did not cause substantial deviations from the average current because they occurred on very short time scales on the order of seconds. Nonetheless, to ensure that the faradaic amount of NH$_3$ calculated was precise, the temporal current, $I(t)$, was monitored and integrated to obtain the total charge, $Q = \int I(t)dt$. As a function of process time, the average faradaic efficiency is found to decrease from ~60% at 5 min to a statistically indistinguishable value of ~30% at 30 min and 45 min (table S2B), consistent with the observed changes in the NH$_3$ production rate. A longer time trial of 5 hours was also conducted, and the faradaic efficiency was only slightly lower than at 45 min (24.9% compared with 32.2%), confirming that the observed trends are maintained (table S2A).

Figure 2B shows the average mass of NH$_3$ produced as a function of current after 45 min and at pH 3.5. The complete set of data for...
measurements showed no discernible peak corresponding to H2 up from background at any time during plasma operation (fig. S2). GC measurement of 6 ppm H2, and at 2 mA after 30 and 45 min equivalent to 33 ppm, respectively (table S3C). We note that the generation of H2 in our reactor over time is not necessarily inconsistent with our faradaic efficiency estimations. In contrast to the NH3 measurements, which reflect how much is accumulated over time, the GC measures how much H2 is produced at an exact time and, assuming that the rest of the current goes toward NH3 production, provides only an instantaneous faradaic efficiency (see the Supplementary Materials for details). To obtain a comparable cumulative faradaic efficiency, we measured H2 at other times and integrated the instantaneous faradaic efficiencies by assuming two-step functions to obtain an upper and a lower bound (fig. S3). This analysis showed faradaic efficiencies after 45 min of 95.1 to 100% at 1 mA and 77.9 to 95.9% at 2 mA, which agree well with the faradaic efficiencies independently obtained from NH3 measurements (see table S3A).

**NH3 stability and trapping**

While a notable amount of NH3 was produced in a single-compartment cell setup, we addressed the potential decomposition of NH3 by comparing it with a split H-cell geometry where the plasma cathode was operated in one compartment, the Pt anode was contained in the other, and the solutions in the two compartments were separated by a glass frit that allowed ionic contact but prevented mixing (fig. S4). If NH3 is decomposed by oxidation at the anode in the single cell, then the measured amount of NH3 would be lower than what is actually produced at the cathode and the split cell would show a higher yield. Figure 3A compares the average masses of NH3 produced in a single and split cell at 6 mA and pH 3.5 after different processing times. The complete set of data for all trials is shown in table S4A. The NH3 yields were found to be statistically identical, indicating that NH3 is not decomposed at the anode (table S4B). This is consistent with a previous report that proposed NH3 decomposition occurs through reaction with hydroxide ions (OH-) and only becomes considerable in basic solutions (22). Another possible loss mechanism for NH3 is simply vaporization because of its relatively low solubility. We studied the effectiveness of NH3 trapping by varying the pH of our solution in the single cell and connecting the gas effluent from the cell to a second vessel containing a strongly acidic H2SO4 bath (pH 2) to ensure complete capture. Figure 3B shows the average mass of NH3 measured in the main reaction cell and the second trap vessel at different pH. The complete set of data for all trials is shown in table S5A. The results confirm that for pH ≤ 5.5, no detectable amount of NH3 is lost from the reaction cell. The lack of any NH3 collected in the trap under acidic conditions also shows that the NH3 measured in our electrolytic process is not formed in the gas phase, for example, by reaction in the plasma...
between N\textsubscript{2} and H\textsubscript{2} produced from the HER or water vapor, but is formed in the solution. This was corroborated by RGA measurements that showed no detectable amount of NH\textsubscript{3} in the exhaust gas (fig. S2). We also observe that the NH\textsubscript{3} yield and faradaic efficiency significantly increase with decreasing pH (table S5B). This is consistent with the important role that H\textsuperscript{+} plays and the contribution of the competing HER pathways (see Fig. 1C). Decreasing pH should lead to an increase in the proton (H\textsuperscript{+}) concentration and enhance the rate of H\textsuperscript{+} reacting with solvated electrons via mass action to produce H\textsuperscript{·} relative to the second-order recombination of solvated electrons (see Fig. 1C). The former reaction step leads to either NH\textsubscript{3} by sequential addition to some nitrogen-containing intermediate, or H\textsubscript{2}, through the second-order recombination of H\textsuperscript{·}, while the latter reaction step results in H\textsubscript{2}. The pH trends for NH\textsubscript{3} yield and faradaic efficiency support this picture of the solvated electrons reacting favorably with H\textsuperscript{+}, as the pH is decreased, and also show that the second-order recombination of H\textsuperscript{·} does not become important even at the lowest pH tested, pH 2, where the H\textsuperscript{+} and then the H\textsuperscript{·} concentration could be high. This reaffirms that a nitrogen-containing intermediate is at sufficiently high concentrations in our process to react quickly with any available H\textsuperscript{·} and form NH\textsubscript{3}. We note that the dependence of NH\textsubscript{3} formation on H\textsuperscript{+} is independent of its trapping since all the NH\textsubscript{3} formed is effectively captured in the reaction cell at pH \leq 5.5.

**NO\textsubscript{x} scavenging and measurement**

The crucial role of solvated electrons and H\textsuperscript{·} in plasma electrolytic synthesis of NH\textsubscript{3} was verified by scavenger experiments. The high reactivity of these species allows a controlled impurity or scavenger to be added to the solution, which rapidly reacts to prevent their formation or convert them, potentially impeding their subsequent reaction. This approach is well known in radiation chemistry to elucidate reaction pathways involving solvated electron formation and their reaction by-products (23). Relevant to our study, scavengers have also been shown to reduce the concentration of solvated electrons generated by a plasma (17). We initially studied nitrate (NO\textsubscript{3}\textsuperscript{−}), which has a high reactivity for presolvated electrons (24), the precursor to solvated electrons, and solvated electrons with a measured rate constant for plasma-injected solvated electrons, \(k = 7.0 \pm 2.6 \times 10^{9}\) M\textsuperscript{-1} s\textsuperscript{-1} (17), and would be expected to rapidly lower the solvated electron concentration, as depicted in Fig. 4A. Figure 4B shows that the NH\textsubscript{3} yield is slightly reduced by the addition of 10 mM NO\textsubscript{3}\textsuperscript{−} and more substantially reduced (~50% reduction), but not completely suppressed, at 1 M. The complete set of data for all trials is shown in table S6A. We also studied nitrite (NO\textsubscript{2}\textsuperscript{−}), which has been found to have a similar reactivity as NO\textsubscript{3}\textsuperscript{−} for plasma-injected solvated electrons, \(k = 5.2 \pm 2.6 \times 10^{9}\) M\textsuperscript{-1} s\textsuperscript{-1}, but reacts close to 500 times faster with H\textsuperscript{·} (25) (see Fig. 4A). At the same concentrations as NO\textsubscript{3}\textsuperscript{−}, NO\textsubscript{2}\textsuperscript{−} more effectively reduced NH\textsubscript{3} production, with almost complete suppression at 1 M (see Fig. 4B and table S6B). We believe that both NO\textsubscript{3}\textsuperscript{−} and NO\textsubscript{2}\textsuperscript{−} do not completely suppress NH\textsubscript{3} formation at 10 mM because the scavenger concentration is actually much lower at the plasma-water interface, and the reactions involving the scavenger become mass transport limited. Previous measurements of the solvated electron concentration at the plasma-water interface by optical absorbance indicate that the scavenger bulk concentration must be higher than ~0.1 M to completely attenuate the absorption signal (17). The NO\textsubscript{2}\textsuperscript{−} may be more effective at reducing NH\textsubscript{3} formation at this bulk concentration because of its enhanced reactivity with H\textsuperscript{·}. At 1 M bulk concentrations, the interfacial scavenger concentrations are sufficiently high to completely quench the solvated electrons and, in the case of NO\textsubscript{3}\textsuperscript{−}, stop NH\textsubscript{3} formation. The unexpected continued formation of NH\textsubscript{3} in the case of NO\textsubscript{3}\textsuperscript{−}, even at these high concentrations, suggests a more complicated picture involving the formation of a new reducing radical species such as NO\textsubscript{2}\textsuperscript{−} (26) in our system and a different reaction pathway independent of solvated electrons. Nonetheless, the scavenger experiments, particularly NO\textsubscript{2}\textsuperscript{−}, substantiate that the formation of NH\textsubscript{3} occurs through solvated electron chemistry and that one of the key intermediates is H\textsuperscript{·}.

Although the single-compartment cell was closed and purged with Ar or N\textsubscript{2} to remove background ambient air, the oxidation process at the Pt anode in our system evolves O\textsubscript{2} gas, which could serve as an unintended impurity during the experiments in several ways. The presence of O\textsubscript{2} in the plasma could lead to reactions with gas-phase electrons and reduce their flux to the solution surface, thus decreasing the concentration of solvated electrons produced (27). In addition, O\textsubscript{2} could react with N\textsubscript{2} in the plasma to produce NO\textsubscript{x} in the gas phase, as historically demonstrated by the Birkeland-Eyde process (13), and its subsequent dissolution forms NO\textsubscript{2}\textsuperscript{−} and NO\textsubscript{3}\textsuperscript{−} in the solution (28), which would affect solvated electron chemistry via the aforesaid scavenging reactions (see Fig. 4A). The relative similarity of NH\textsubscript{3} yields in the split and single cells shows that the former is not an issue. To address the latter, we measured the NO\textsubscript{x} generated in the solution for our plasma electrolytic system. Figure 4 (C and D) shows the NO\textsubscript{x} concentration after different processing times at 6 mA and as a function of current after 45 min, respectively. The complete set of data for all trials is shown in table S7A. The NO\textsubscript{x} concentrations were found not to be large enough to scavenge and quench the solvated electrons (see Fig. 4B). We verified that the NO\textsubscript{x} formation was from O\textsubscript{2} gas evolution at the Pt anode by also carrying out these measurements in the split cell, which showed no detectable amount of NO\textsubscript{x}. This was further corroborated by comparing the measured NO\textsubscript{x} with an expected amount from the faradaic yield of O\textsubscript{2} and assuming that all of it reacts with N\textsubscript{2} (in the plasma) to form either NO\textsubscript{2} or NO\textsubscript{3} (fig. S5).

**DISCUSSION**

The two key results that emerge from our study are the high, 100% selectivity toward NH\textsubscript{3} formation at low currents (1 and 2 mA) and the marked decrease in selectivity as the current is increased to 3 mA and beyond. Given that O\textsubscript{2} gas evolution and subsequent NO\textsubscript{x} formation are not sizeable, it is not likely that scavenging of solvated electrons and/or H\textsuperscript{·} is responsible for the current-dependent decrease in NH\textsubscript{3} production. Alternatively, we propose that there is a combination of factors related to the solvated electron, H\textsuperscript{+}, and H\textsuperscript{·}-concentrations, which collectively have been found to play a critical role in NH\textsubscript{3} formation in our system, and their spatiotemporal evolution. Initially, before the plasma is ignited and reactions begin to occur, the solution concentrations of solvated electrons and H\textsuperscript{+} are zero, and the concentration of H\textsuperscript{·} at the plasma-water interface is the same as its bulk concentration. After the plasma is ignited, the solvated electron concentration immediately increases as plasma electrons are injected into the solution, and H\textsuperscript{+} is depleted and H\textsuperscript{·} is generated as a result of the reduction of H\textsuperscript{+} by solvated electrons. All of this occurs primarily in an interfacial region where the solvated electrons are formed and react, and the interfacial H\textsuperscript{·} concentration...
becomes disparate from (lower than) its bulk concentration. As the steady-state current is increased, the production rate of solvated electrons concomitantly increases, depleting the interfacial concentration of H⁺ even faster. At sufficiently high currents, the H⁺ may be depleted, slowing down or stopping NH₃ formation. While H⁺ may be present in the bulk from the initial acid and water oxidation at the Pt anode \(2H_2O(l) \rightarrow O_2(g) + 4H^+ + 4e^-\), mass transport limitations could prevent the bulk H⁺ from reaching the plasma-water interface. The high concentrations of solvated electrons and the low concentrations of H⁺ would result in higher rates of HER by both decreasing the reaction rate of the H⁺ reduction and increasing the reaction rate of the second-order recombination of solvated electrons. Thus, at higher currents, the HER becomes more important and reduces the selectivity toward NH₃ formation. We note that the decrease in NH₃ production rate and faradaic efficiency with time also supports a similar picture with H⁺ being depleted at the plasma-water interface and transport-limited (Fig. 2A). A similar interplay between reaction and transport in a plasma electrolytic system has been observed for the reduction of silver ions to silver nanoparticles (29). There, the actual concentration of silver ions needed to achieve 100% faradaic efficiency was found to be 10 times higher than predicted by reaction modeling because of transport limitations. Transport issues may also be present in other electrolytic approaches to NH₃ production but are relatively less important because of the kinetic limitations related to adsorption on the catalytic surface. Our findings show that by removing the adsorption step, transport limitations become a challenge but can be overcome to enable high selectivity.

While determination of the detailed reaction mechanism and transport parameters is subject to future studies, we have shown that the plasma electrolytic system allows the study of NH₃ formation without the need for a catalyst and is capable of highly efficient production. Table 1 compares the overall performance of our system with recently reported results for similar aqueous (containing water) electrically driven demonstrations at ambient conditions. We note that only studies that used a non-nitrogen control gas are included, and the highest faradaic efficiency in each study is highlighted. The approach described in this study is found to have the highest faradaic efficiency while maintaining high production rate, over an order of magnitude higher than other electrochemical methods at similar reaction geometric areas. Our system is characterized by a power consumption of 2270 kWh/kg at 2 mA for 45 min based on a
plasma voltage of ~500 V (table S8). The high energy consumption is a result of the electrical power required to produce sufficiently large electric fields in the plasma to generate and sustain electrons. Only a very small fraction of the energy is dissipated as heat, which is why these plasmas are referred to as nonthermal (30). In support, we measured the temperature profile of the solution surface during a process run at 6 mA and found a maximum temperature of 65°C after 45 min (fig. S6).

The power consumption of our plasma electrolytic system is considerably larger than that of H-B, which requires about 9 to 13 kWh/kg NH₃ using natural gas, coal, or fuel oil as feedstocks (31). Electrochemical synthesis of NH₃ has the potential to be competitive with H-B if the faradaic efficiency could be improved, but catalyst selectivity for NH₃ production over H₂ remains a challenge. Thus, the development and integration of a successful electrocatalyst into a full-cell device is the intense focus of current research. A relevant recent study provides a point of comparison for full-electrochemical cell operation: At 65°C, 1.6 V, and 4.5 A/cm² NH₃ production, the faradaic efficiency is 0.044% for an energy consumption of ~17,000 kWh/kg (32). Notably, higher faradaic efficiencies have been reported in half-cell experiments (see Table 1). Simulations suggest that an electrochemical NH₃ cell has the potential to be competitive with H-B if a catalyst can be developed to have >50% faradaic efficiency (33). Similar to electrochemical approaches, the plasma electrolytic process does not require high pressures or temperatures and can operate at a small scale but does not require a catalyst. Considering the overall cost of NH₃ that is associated with production, capital, shipping, and storage costs, our technology could be economically attractive by enabling smaller-scale distributed networks. Future studies should be aimed at lowering the energy consumption by enhancing electron generation in plasmas by, for example, modifying the electrode geometry or exploring other electrode materials (34). Even with the power requirements reported here, it is possible for this system to be integrated with renewable energy, which is continually decreasing in cost. Similar plasma systems have already been integrated with solar power for portable applications (35). With further exploration and optimization, the approach presented here could become a potentially promising technology for green, economical NH₃ production.

In summary, we demonstrate that a hybrid plasma electrolytic system can serve as a tool to study NH₃ formation without a catalytic material surface and achieve high faradaic efficiencies (up to 100%) at ambient temperature and pressure for NH₃ production from N₂ and water. Experiments conducted at different pH values and with scavengers show that solvated electrons play a key role in the reaction chemistry, particularly the reduction of H⁺, and NH₃ formation occurs through a mechanism involving H. Our analysis reveals that in the absence of adsorption barriers, the study and optimization of transport are required to further improve performance. In addition, a comparison of this technology with other similar electrocatalytic ammonia generation alternatives suggests that it may be a promising approach for distributed, renewable NH₃ production.

### MATERIALS AND METHODS

#### NH₃ synthesis from N₂ and water in a plasma electrolytic system

The synthesis of NH₃ from N₂ and water was carried out in a quartz reaction cell sealed with a polytetrafluoroethylene (PTFE) lid. The PTFE lid contained feedthroughs for the electrodes that consisted of a stainless steel capillary tube (outer diameter, 1.59 mm; inner diameter, 0.508 mm; and length, 10 cm; Restek Inc.) held 1 mm above the electrolyte solution surface and a Pt foil (purity, 99.9%; thickness, 0.0254 mm; Alfa Aesar) immersed in the electrolyte solution. A plasma was ignited in the gas gap between the tube and solution surface in a flow of either Ar (airgas, 99.5%) or N₂ (airgas, 99.99%+), using a negative high-voltage power supply (RR15-10R, Gamma High Voltage Research) that was ballasted (0.25 to 1 megohm). The plasma served as the cathode and the Pt foil as the anode. Two additional feedthroughs were used to bubble the solutions before each experiment and exhaust the gas. The H-shaped split cell was similar except that the plasma cathode and Pt anode were in separate compartments, each with its own PTFE lid and feedthroughs for bubbling and exhaust, connected by a glass frit. The electrolyte solution was a mixture of 18.2 megohm water and sulfuric acid (purity, 99.999%; Sigma-Aldrich), typically at pH 3.5. The solution was bubbled with either Ar or N₂ for 30 min before igniting the plasma to ensure the removal of any dissolved gases and to purge the headspace of the vessel.

The voltage and current were measured by a previously reported electrical circuit (19). Briefly, the voltage was measured between the capillary tube and the Pt anode by using a digital multimeter, and the current was obtained from the voltage drop across a resistor in series between the Pt anode and the power supply. The current was measured in real time using LabVIEW. Temperature measurements of the solution surface as a function of position and time during a process run were performed using an FLIR i3 infrared camera with the PTFE lid removed to allow optical access. An emissivity, ε, of 0.6 was assumed, and the accuracy of the temperatures was verified by a thermometer to be ±2°C.

#### Measurement of NH₃ produced

The production of NH₃ in the plasma electrolytic system was measured by the o-phthalaldehyde method (36). First, 2 ml of the processed solution was removed and refrigerated in an N₂-purged, sealed vial until analysis. Ten-microliter aliquots were then pipetted into a 96-well analysis tray, and 90 μl of an assay solution containing buffer solution and active reagents (Quantifluo DNH3200, BioAssay Systems) was added. After a 15-min incubation period with no light exposure, the concentration of NH₃ was determined from fluorescence measurements at an excitation wavelength of 360 nm and emission wavelength of 450 nm using a Molecular Devices Spectramax M2 microplate reader. Calibration of the method was carried out with

<table>
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<tr>
<th>Reference</th>
<th>Production rate (mg/hour)</th>
<th>Demonstration size (geometric area, catalyst loading)</th>
<th>Faradaic efficiency (%)</th>
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<td>(38)</td>
<td>0.021</td>
<td>1 cm², 1 mg/cm²</td>
<td>8</td>
</tr>
<tr>
<td>(32)</td>
<td>0.0047</td>
<td>6.25 cm², 3.5 mg/cm²</td>
<td>2</td>
</tr>
<tr>
<td>(39)</td>
<td>0.000063</td>
<td>0.25 cm², 146 μg/cm²</td>
<td>60</td>
</tr>
<tr>
<td>(40)</td>
<td>0.00016</td>
<td>1 cm², 0.33 mg/cm²</td>
<td>4</td>
</tr>
<tr>
<td>This study</td>
<td>0.44</td>
<td>1 mm², catalyst free</td>
<td>100</td>
</tr>
</tbody>
</table>
four known concentrations of aqueous ammonium hydroxide solutions as standards: 0, 0.25, 0.50, and 0.75 mM (Fig. S7). The fluorescence intensity had a lower detection limit of 12 µM NH₃ and was found to increase linearly with NH₃ concentration.

Measurement of H₂ gas produced
The production of H₂ in the plasma electrolytic system was measured using a Shimadzu GC-2014 gas chromatograph with a thermal conductivity detector and a Restek ShinCarbon ST 80/100 mesh 2 m by 2 mm column. Ar was used as the carrier gas to allow identification of the N₂ from the reactor and to enhance measurement sensitivity for H₂. The gas analysis was performed by connecting the reactor exhaust directly into a six-way valve, filling a 100-sensitivity for H₂. The gas analysis was performed by connecting the exhaust gas mixtures of H₂ and N₂ controlled by two separate digital mass flow controllers. The reactor exhaust was also simultaneously analyzed using a Stanford Research Systems RGA100 atmospheric pressure sampling mass spectrometer.

Measurement of NOₓ produced
The production of NOₓ in the plasma electrolytic system was measured by the Griess method (37) with reagents from Sigma-Aldrich (23479-1KT-F). First, 2 ml of the process solution was removed and refrigerated, similar to the NH₃ measurements. Ten-microliter aliquots were then pipetted into a 96-well tray, and 70 µl of buffer along with 10 µl of nitrate reductase and 10 µl of the provided Griess coenzymes were added. After a 2-hour incubation period, 50 µl of Griess reagent A was added and incubated for 5 min before addition of 50 µl of Griess reagent B and incubation for an additional 10 min. The absorbance was then measured at 540 nm using a Molecular Devices Spectramax M2 microplate reader to determine the total moles of NOₓ, and the concentration was obtained from the initial 10-µl volume. Calibration of the method was carried out with four known molar quantities of sodium nitrate at 0, 2, 4, and 8 mmol in a 10-µl volume (Fig. S8).

Statistical analysis
All data are represented as the mean of a dataset ± SE, which was calculated from the variance in the raw data within two SDs of the mean (approximately 95% confidence interval). Statistical differences between datasets were determined using a two-sample t test. To determine whether a dataset was nonzero, a one-sample t test was used. All t tests were performed using the Minitab 2017 Statistical Software. The results of all of the t tests and the sample size for each dataset are tabulated in the Supplementary Materials. For all statistical tests, a threshold value of α = 0.05 was chosen, and a P value at or less than 0.05 indicated significance.

Supplementary Materials
Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/5/1/eaat5778/DC1

SUPPLEMENTARY MATERIALS
Figure S1. Representative current waveforms measured in the plasma electrolytic system during NH₃ synthesis.

Figure S2. RGA measurements of mass/charge ratio (m/z) 2 and 17, corresponding to H₂ and NH₃ partial pressure, at 2 mA in a plasma electrolytic reactor by analyzing exhaust gas from cell as a function of time.

Figure S3. H₂ production in the plasma electrolytic system.

Figure S4. Schematic of the hybrid plasma electrolytic system in a split H-cell geometry.

Figure S5. Comparison of NOₓ produced with that predicted from O₂ gas evolution in plasma electrolytic system.

Figure S6. Heating of solution in the plasma electrolytic system.

Figure S7. Summary of one-sample and two-sample t tests carried out on datasets in Table S1A. Table S2A. Summary of NH₃ produced and faradaic efficiencies by plasma electrolytic synthesis after different processing times.

Figure S8. Summary of one-sample and two-sample t tests carried out on datasets in Table S2A.

REFERENCES AND NOTES


Catalyst-free, highly selective synthesis of ammonia from nitrogen and water by a plasma electrolytic system
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