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ALASKA'S RENEWABLES-SOURCE FUEL ENERGY STORAGE PILOT PLANT: TOWARD COMMUNITY ENERGY INDEPENDENCE VIA SOLID STATE AMMONIA SYNTHESIS (SSAS)

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ABSTRACT

Alaska village survival is threatened by the high cost of imported fuels for heating, electricity generation, and vehicles. During Winter 2007-8, the price per gallon of heating oil and diesel generation fuel exceeded $8 in many villages. Many villagers were forced to move to Anchorage or Fairbanks. Although indigenous renewable energy (RE) resources may be adequate to supply a community's total annual energy needs, the innate intermittent and seasonal output of the renewables – except geothermal, where available, which may be considered "baseload" -- requires large-scale, low-cost energy storage to provide an annually-firm energy supply. Anhydrous ammonia, NH_3, is the most attractive, carbon-free fuel for this purpose at Alaska village scale, because of its 17.8% mass hydrogen content and its high energy density as a low-pressure liquid, suitable for storage in inexpensive mild steel tanks. NH_3 may be synthesized directly from renewable-source electricity, water, and atmospheric nitrogen (N_2) via solid state ammonia synthesis (SSAS), a new process to be pioneered in Alaska.

INTRODUCTION

Alaska's 720,000 people live in over 200 "energy islands" with no electricity grid connection to each other or North America. Smaller communities have no road connection to each other, the rest of Alaska, or the continent. Most energy is imported: diesel for electricity generation and heat; gasoline for transportation. All Alaskans might obtain an annually-firm supply of most of their energy, for all purposes, by converting Alaska's diverse, stranded, renewable energy (RE) resources to liquid anhydrous ammonia (NH3) fuel, transporting and storing it at low cost in common steel propane tanks, recovering the RE via stationary combined-heat-and-power (CHP) plants, in internal combustion engine (ICE) and combustion turbine (CT) gensets, and via fuel cells, and as transportation fuel. Alaskans could achieve a significant degree of community energy independence, and perhaps export their abundant, stranded renewables as "green" liquid NH3 fuel. Solid state ammonia synthesis (SSAS) appears promising.

The State of Alaska, via the new Emerging Energy Technology Fund, will grant ~ $750,000 for a two-year project for design, build, and Alaska deployment of a transportable, proof-of-concept, kW-scale, pilot plant to demonstrate a novel anhydrous ammonia (NH3) fuel synthesis process for low-cost, annual-scale storage of renewable energy (RE) electricity. Energy is recovered from the stored NH3 fuel via CHP gensets with ICE or CT prime movers, or via direct ammonia fuel cells (DAFC), and via space heating appliances and transportation fuel. NH3 fuel may provide an alternative to electricity for transmission, annual-scale firming storage, and energy supply integration. For example, the Southeast Intertie (electricity transmission via land lines and submarine cables) long desired throughout Southeast, was declared "uneconomic" in the 2012 Southeast Alaska Integrated Resource Plan. [1]

Converting stranded, curtailed, or spilled RE-source electricity, at the sources, to NH3 fuel, allows harvest, transmission, and storage of this stranded RE, for a degree of community energy independence. All energy supplies may be thus conserved; costs may be thus stabilized, not necessarily reduced. A kW-scale SSAS-PP must be designed, built, and tested to discover and demonstrate at multi-SSAS-element-reactor pilot scale whether SSAS has the potential to more efficiently, reliably, and economically synthesize NH3 from electric energy, water vapor, and N2 than conventional NH3 synthesis via water electrolysis and Haber-Bosch (H-B) synthesis. This small-scale project of < 1 kWe input will discover and demonstrate whether SSAS may be technically and economically superior to EHB, and offers a path to partial energy independence for isolated Alaska communities – many of which enjoy multiple indigenous RE resources.

Solid State Ammonia Synthesis (SSAS) technique, which might provide a technically and economically attractive path to village energy sustainability via annually-firm energy storage in the same type of mild steel surface NH_3 tanks used for propane (LPG) storage.

SSAS converts electric energy, water, and atmospheric nitrogen to NH_3 at high efficiency; indigenous renewable-source electricity is the key driver and resource. The stored NH_3 may easily be reformed to hydrogen fuel, with the nitrogen (N_2) byproduct returned to Earth's atmosphere. Or, the NH_3 fuel may be combusted directly in modified internal combustion engines (ICE's), combustion turbines (CT's), and space heaters at high efficiency. Or, it may be converted to electricity in direct-ammonia fuel cells. Figure 9 shows an NH_3 fueled ICE on long-term test.

For example, the 37 MWh of energy in 1 ton of hydrogen would be stored in about 6.5 tons of NH_3, which would require approximately a 10,000 liter steel tank, which would cost about $25 – 50K installed in an Alaska village. No gaseous hydrogen (GH2) would be stored, avoiding low-energy-density, high-pressure GH2 storage with the associated hydrogen embrittlement potential for steel components.

Ammonia as a hydrogen storage medium may be a promising complement to gaseous or liquid hydrogen storage, especially at the large energy quantities required for an annually-firm RE supply. A successful Alaska demonstration, preceded by the requisite SSAS research and development, could pave the way to large-scale hydrogen storage, transmission, and delivery, as NH_3, in many North America and world markets. In the USA Corn Belt, the NH_3 pipelines and storage tanks are already in place.

NOMENCLATURE

Anhydrous ammonia, NH_3 ,solid state ammonia synthesis (SSAS), fuel, energy storage, renewable-source, renewable energy (RE)

ALASKA: ENERGY ECONOMY, VILLAGES, LEGISLATION, EMERGING ENERGY TECHNOLOGY

Alaska has no electricity (grid) connection to other North America electric energy systems. The "railbelt", Anchorage and Fairbanks and the communities along the Alaska Railroad connecting them, are an isolated electricity transmission "grid", Alaska's largest energy "island". This, and all other Alaska villages, towns, and cities, are energy islands. Except for hydro generation prevailing in Southeast Alaska (SE), electricity generation, heating, and transportation fuels are primarily imported petroleum products. Indigenous firewood space heating is common in some communities. Several coal-fired generating plants serve the railbelt grid. A few communities supply a small fraction of their electricity from wind generation or other renewables; Kotzebue is perhaps the best example. The Renewable Energy Alaska Project (REAP; non-profit) expertly encourages increasing renewable energy production from all resources.

Power Cost Equalization (PCE) is the program designed to (1) extend power assistance to rural Alaska as a response to the development of other power around the state and (2) make power more affordable to rural Alaskans: " Because power costs in many rural communities are approaching the $1.00 [per kilowatt-hour] range … many rural families would simply not be able to afford to buy the electricity needed for even the basic services that we take for granted." In FY 07, the State of Alaska, via its Alaska Energy Authority (AEA), distributed $25.4 million among 78,500 people in 183 villages and small towns, via the PCE program. FY08 cost is higher. The State would like to reduce this program's cost.

Each Alaska community wishing energy independence via indigenous renewable energy resources must:

1. Assess its "internal" energy economy (initially excluding the "external" energy required to support the community, which is not supplied by the local economy – primarily fuel for aircraft and barges). This energy audit should yield community total annual energy consumption from all energy sources.

2. Assess its available, indigenous, renewable energy resources to find:

a. How much RE is available;

b. What total annual community energy demand would cost to harvest (generate) from the several RE sources;

c. How much gross energy storage is required to provide firm energy year-round, for all energy needs, from these RE resources.

3. Determine costs for converting its energy-consuming equipment, from the electric generating plant to boat, snowmachine, and ATV engines, to operate on NH_3 fuel.

4. Decide where to site its NH_3 storage tank or tank farm, preferably at a distance downwind of the community, so that any large accidental NH_3 leak would not endanger inhabitants.

In 2010 the 26th Alaska legislature enacted and funded SB220, which established the Emerging Energy Technology Fund (EETF), a pool of ~ $8.5M for grants for sixteen innovative energy demonstration projects within the State of Alaska. Alaska Applied Sciences, Inc. (AASI) has been selected for a $750K EETF grant, principal funding in a $1M project to build a solid state ammonia synthesis (SSAS) proof-of-concept pilot plant (SSAS-PP).

SOLID STATE AMMONIA SYNTHESIS PILOT PLANT (SSAS-PP)

Figs. 13, 14, SSAS-PP. Renewable-source electricity is converted to NH_3 in an SSAS reactor, stored as liquid fuel, regenerated in an NH_3 fueled genset for return to the local electricity grid. The system is thoroughly instrumented for SCADA system report via internet to remote data collection and analysis at the Alaska Center for Energy and Power (ACEP), University of Alaska, Fairbanks (UAF). [2] This SSAS-PP demonstration system is a complete, instrumented, self-contained, containerized (insulated CONEX), transportable, NH3 synthesis, storage, and regeneration system. It is capable of closed-loop NH3 synthesis, storage, and regeneration from RE-source electricity, water, and air. The two-year design, fabrication, and test project should begin in early 2013.

Methodology: Design, build, test, and deploy in Alaska a complete SSAS-PP, operating in closed-loop NH3 fuel production from RE-source electricity, with on-board NH3 fuel storage and CHP regeneration of the NH3 fuel for feedback to the RE-source electricity grid. The on-board SCADA system will collect real time and logged performance data. ACEP will monitor and validate the SCADA data and help analyze and publish it.

This pilot-scale demonstration of how renewable electricity generation from diverse local sources may supply a major share, or all, of a village or small community “energy island” annual energy consumption – of electricity and of heating and vehicle fuels -- with annual-scale firming via energy storage as NH3 fuel. The average annual “village” cost of energy will depend on:

- The cost per kWh of renewable-source generation at the village, assuming renewable sources are available and energetic, for high capacity factor generation;
- The amortized capital cost of conversion and annual-scale-firming storage components, plus O&M costs / kWh.

The total annual average cost of energy (COE) at the village may or may not be lower than recent market prices for fossil fuel, but this COE will be predictable, after O&M cost is determined by experience, because fuel cost is zero. This pilot-scale system capacity of about 0.5 kWe input, producing about 1.5 kg of NH_3 fuel per day, will be about 1% of the scale needed for a typical Alaska village of 200 people.

A custom-built ammonia-fueled ICE genset is available for the SSAS-PP, similar to that in Fig. 9. Further R&D and Demonstration would need to be done to confidently and economically modify ICE’s, including those now operating in Alaska community electricity generation service, for multi-fuel (diesel or NH_3) service. In 2010 Sturman Industries demonstrated a test camless all-electronic internal combustion engine (ICE) operating very efficiently on 100% NH3 liquid fuel injection, in compression ignition, without significant NOx formation. [3] This would be the critical component and technology of efficient ICE gensets, although other techniques for operating ICE’s on NH_3 fuel have been demonstrated. In a CHP installation, over 90% of the NH_3 fuel energy could be recovered.

SSAS now needs to be demonstrated in a scale-model reactor composed of about 5-20 PCC tubes, with gas management, packaging, and electric interface that will be necessary for commercial-scale (10 – 1,000 kW modules, scalable to any size) SSAS systems. Satisfactory performance and durability testing on the first reactor advances SSAS to proof-of-concept technology readiness level (TRL) 5-6.

The goal of this EETF project is demonstrating potential scaleup to achieve commercial success at $200K per metric ton (Mt) anhydrous ammonia (NH_3) per day capital cost, 7.5 kWh / kg NH3 conversion (75% efficiency (HHV)).

Objectives of this EETF project, building the SSAS-PP:

1. Discover and demonstrate, at proof-of-concept pilot plant scale, whether SSAS has the potential to produce RE-electricity-source NH3 fuel at significantly lower cost per kg NH3, at a given kWhe input cost, than EHB (electrolysis plus Haber-Bosch) synthesis.
2. Demonstrate SSAS in a complete, self-contained, containerized, transportable plug-and-play system capable of round-trip NH3 synthesis, NH3 fuel storage, and CHP regeneration of electric energy to feedback into the electricity grid.
3. Begin the process of commercialization of SSAS for widespread deployment in Alaska, if market-driven economic modeling, such as that proposed in Action Initiative #3, Southeast Alaska Renewable Energy Cluster Industry Working Group, demonstrates a market for RE-SSAS.
4. Produce basic SSAS component and system performance data, by which to qualify for further product R&D and Development funding, from both public and private sources.

SSAS-PP Key technology elements are:

1. PCC tubes: discover and demonstrate energy conversion efficiency, per tube terminal voltage and current, durability, and cost, beginning with the “small” prototype tubes in this project
2. SSAS reactor: demonstrate multiple-PCC-tube assembly, with mechanical tube mounting and sealing, gas management, and electric input energy distribution
3. SSAS reactor electric drive: PCC tubes are low-voltage, high-current devices, presenting an impedance matching problem for the power electronics and power conditioning necessary to operate SSAS reactors from an alternating current generator or grid input energy supply.

The following are proven, but key technology elements of little technical risk for the SSAS-PP:

1. SCADA system: off-shelf hardware and software, for custom system design
2. ICE genset: at least one candidate is available.

BULK ENERGY STORAGE SCHEMES

Figure 8 compares the several schemes and technologies currently considered as “electricity” storage, with gaseous hydrogen (GH2) and liquid NH3 , which appear “off the chart”. No “electricity” storage option can affordably store enough energy to “firm” RE, at annual scale, other than geothermal which may be considered “baseload” supply, but have important applications in electricity transmission and distribution stability, power quality, and for the nascent “smart grid”. GH2 and NH3 are promising for GW-scale transmission and annual-scale firming of diverse, stranded renewables.

BENEFITS OF RE STORAGE AS NH_3 FUEL

1. Community energy supply, from diverse, indigenous RE resources, may be inexpensively stored to provide a firm, dispatchable, year-round energy supply for all purposes: electricity and space heat via CHP generation, space heating, transportation.

2. Surplus stranded renewable energy, such as Southeast Alaska hydro which is now “spilled” at some plants, can be monetized by conversion to liquid NH_3 for export and sale as C-emissions-free fuel, for heating, for vehicles, boats, construction machinery, and for CHP on-site electricity generation. This might apply to off-peak wind and other renewables: Fire Island (Anchorage area) wind, for example. This helps service renewable energy generation plant debt.

3. Monetizing surplus stranded renewable energy would lower the retail energy price for the generating facility customers, and for the NH_3 fuel consumers.

4. Community income flow to outside fuel suppliers will be greatly reduced, and potentially eliminated.

5. Community jobs will be created to construct and maintain the new RE systems.

6. In case electric utility system demand exceeds hydro supply, ratepayer cost might be reduced from that of diesel generation by instead using NH_3 fuel produced from Alaska surplus and stranded renewable resources.

These benefits should apply to “energy island” communities worldwide; we intend to demonstrate these benefits in Alaska.

NH_3 PRODUCTION

Fig 5 is the conventional electrolysis followed by Haber-Bosch reactor (EHB) system. The Haber-Bosch process has prevailed for over a hundred years. Hydrogen must be supplied from electrolysis of water by electricity from RE, or other sources. Worldwide ammonia consumption is ~ 130 million tons per year; almost all is produced from hydrogen made from natural gas (methane, CH_4 , via steam methane reforming (SMR) with the CO_2 waste product released to Earth’s atmosphere).

NH_3 SYNTHESIS VIA ELECTRICITY FROM RENEWABLE ENERGY RESOURCES

Figures 6, 7. Solid State Ammonia Synthesis (SSAS) is an invention patented by NHThree LLC, which converts electricity, water, and nitrogen directly to ammonia in SSAS reactors without producing hydrogen as an intermediate feedstock. [4] The electrolyzers are eliminated; the ASU remains. SSAS is a lab-scale device, not yet commercialized, offering potentially lower capital costs and higher conversion efficiency for renewable-source electricity to NH_3, in a simpler system than Haber-Bosch.

SSAS appears more suited to remote, Alaska energy “island” villages. In most Alaska villages, fresh water supply is adequate for NH_3, synthesis feedstock. Atmospheric nitrogen, N2, must probably be supplied by an on-site, electrically-driven air separation unit (ASU): a significant piece of capital equipment probably operating at low capacity factor (CF). ASU is a mature technology.

NH3 TRANSMISSION AND STORAGE

Except for geothermal, RE sources are unfortunately time-varying in output, at time scales of seconds to seasons. The RE generation assets thus operate at an inherently-low capacity factor (CF) of typically 30-40%, inflicting this low CF on all downstream system components and preventing delivery of annually-firm energy to consumers. Several studies show that NH_3 may be a promising strategy and technology for gathering, transmission, firming storage, and distribution of diverse, GW-scale, stranded renewables.

Cost of energy storage as NH3 : Figures 2, 3, 4, 10. In the Lower 48 States, large “atmospheric” refrigerated tanks can store energy for < \$100 / MWh capital cost. Pressurized carbon steel “bullet” tanks are available up to 200 tons, at about twice the cost. Such large tanks, transported to and installed in Alaska villages, might more than double this cost. Perhaps not many Alaska communities would need storage as large at “atmospheric tanks. Figure 2 shows costs for smaller, pressurized liquid storage. Total energy storage cost would include capital and O&M costs and energy conversion losses for renewable-source electricity to NH3 fuel, and energy recovery from the fuel.

Properties of NH_3:

- 17.8% mass hydrogen content; 1 ton contains ~ 6.5 MWh as hydrogen
- A carbon-free fuel; a carbon-free energy carrier if made from non-carbon-emitting energy sources or processes;
- A pumpable liquid at ambient temperatures at 150 psi;
- Can be readily reformed to produce hydrogen (~85% efficiency);
- Low pressure, low-cost storage and transport in trucks and pipelines;
- Not flammable except under extreme conditions of high compression and high ignition energy typically found only in specially-designed ICE's and CT's;
- Non-corrosive, non-embrittling to steel, although copper, brass, and bronze fittings must not be used;
- Liquid NH_3 has about half the volumetric energy content of gasoline: Table 1;
- Safety: ammonia is regulated as an inhalation hazard. Transport is regulated by the US DOT; no exotic equipment or vessel is required. Storage is regulated by the EPA and state agencies. Ammonia is delivered routinely to the end user in a variety of ways, including pipeline, barge, train, and tanker truck. At the end user's location, ammonia is typically stored in 250 psi-rated carbon steel tanks, which are much like propane tanks. Although ammonia is toxic in high concentration, its offensive odor improves leak detection safety.

Iowa State University has hosted six annual Ammonia Fuel Conferences, which include NH_3 as an RE transmission and storage medium, as well as a transportation and distributed generation fuel. [5]

NH_3 contains no carbon; has physical properties similar to propane; liquefies at ambient temperatures at about 10 bar or at -33 degrees C at 1 atmosphere. Liquid ammonia has over 50% more volumetric energy than liquid hydrogen; more than twice the volumetric energy of hydrogen gas at 700 bar. It is the second-largest-volume industrial chemical in global trade: ~130 MMT / year, mostly for N-fertilizer. USA consumes ~12 MMT / year, with a good safety record. NH_3 is classified as an "inhalation hazard".

NH_3 is nearly 18% hydrogen by weight and has slightly over half the energy density of gasoline by volume. All of ammonia's energy is derived from its hydrogen content; it can be easily reformed to hydrogen and nitrogen, with N_2 returned to its source, Earth's atmosphere. NH_3 has the highest hydrogen content by volume of any liquid fuel, including gasoline, liquefied natural gas (LNG), liquefied petroleum gas (LPG, propane), ethanol, and even liquid hydrogen. Liquid anhydrous ammonia, NH_3, has more atoms of hydrogen per liter than liquid hydrogen. This ability of NH_3 to store hydrogen very compactly at ambient temperature and moderate pressure is a key advantage for NH_3 over GH2.

Like hydrogen, ammonia can burn directly in spark-ignited internal combustion engines and may also be fed directly to medium temperature solid oxide, proton-conducting ceramic, and molten-salt direct-ammonia fuel cells. Ammonia combusts according to:

$$4\,NH_3 + 3O_2 \rightarrow 2N_2 + 6H_2O$$

with only nitrogen and water vapor as combustion products. Like hydrogen, ammonia is lighter than air and is not a greenhouse gas.

The electrolysis-plus-H-B (EHB) synthesis process shown in Fig. 5 has too much system complexity and capital cost operating at low capacity factor (CF), with the estimated cost of wind-source NH_3 at the plant gate > \$ 1,000 / tonne, which is not competitive with domestic or imported fossil-source NH_3. Consequently, SSAS, shown in Figs 6, 7 was developed to reduce the cost of RE-source NH_3. However, SSAS has not yet been demonstrated at commercial scale. The SSAS pilot plant (SSAS-PP) will explore pre-commercialization. Figs 11, 12 show the key technology component in lab test.

Beyond Alaska village scale, annual firming of the output of the proposed Susitna Watana hydroelectric plant proposed for ~ 150 km north of Anchorage, AK will require ~ 300,000 MWh energy storage, at estimated capital costs of:

As "electricity" in Vanadium Redox Battery (VRB)	\$ 100B
As GH2 in salt caverns	\$ 100M
As NH_3 in "atmospheric" surface tanks	\$ 90M

CONCLUSION

Alaska's high energy prices, isolation from the continental electricity grid, and abundant indigenous RE in many communities presents a good opportunity to explore the technical and economic feasibility of anhydrous ammonia, NH_3, as a hydrogen-rich energy storage medium by which to supply firm energy, at annual scale, to achieve partial or total independence from imported fossil fuels for the Alaska community's "internal" energy economy.

A successful Alaska demonstration, preceded by the requisite SSAS research and development, could pave the way to large-scale hydrogen storage, transmission, and delivery, as NH_3, in many North America and world markets. In the USA Corn Belt, the NH_3 pipelines and storage tanks are already in place.

ACKNOWLEDGMENT

We thank Dr. John H. Holbrook, AmmPower LLC, for his contribution to the invention of SSAS and for co-authoring several research papers on RE systems including SSAS. [2]

	Liquid Anhydrous Ammonia	Liquid Hydrogen	10 Ksi Hydrogen Gas	Gasoline
Percent H2 by mass	18	100	100	16
Energy Density—Gravimetric (MJ/kg)	21	110	110	42
Energy Density—Volumetric (MJ/L)	14.0	7.6	6.5	34.0

Table 1. Energy content comparisons of ammonia with hydrogen and gasoline, without adjustment for the energy required for compression and liquefaction of hydrogen or ammonia.

Figure 1. Alaska's 200 villages are "energy islands", unconnected by road or utility lines. Largest "island" is the Anchorage – Fairbanks – Kenai "railbelt". Many communities have diverse RE resources, variable at seconds to seasons, requiring low-cost storage for an annually-firm energy supply.

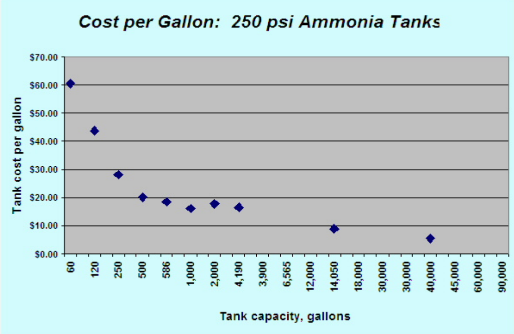

Figure 2. Village-scale mild steel (carbon steel) storage tanks, FOB California. Transport to, and installation in, Alaska villages could more than double the cost.

Figure 3. Energy storage: (top) Agricultural fertilizer liquid NH_3 "nurse tank": capacity 1,450 gallons @ 265 psi = 620 kg hydrogen each. Capital cost ~ $9.5K each. (bottom) Gaseous hydrogen tube trailer: capacity 5,800 gallons @ 3,200 psi = 350 kg hydrogen. Capital cost ~ $750K

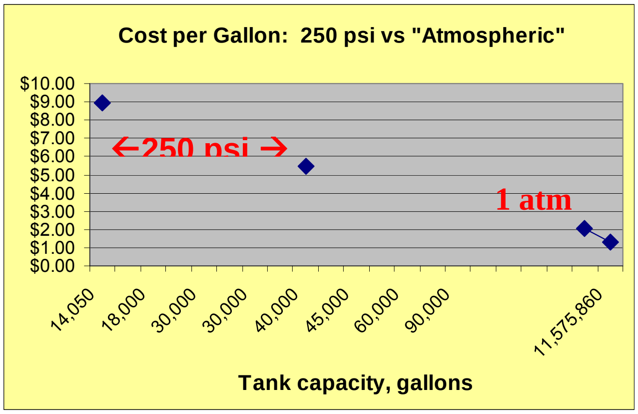

Figure 4. "Atmospheric" refrigerated tanks at -33 C and 1 atmosphere are optimum for GWh-scale ammonia energy storage. Both size ranges are liquid storage. See Fig. 10.

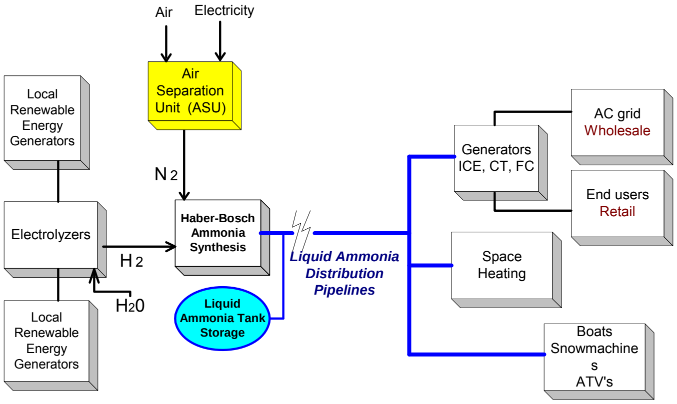

Figure 5. Electrolysis plus Haber-Bosch (EHB) ammonia synthesis from electric energy requires electrolyzers and an ASU, at any production scale. Haber-Bosch NH_3 synthesis has dominated production for a century, producing almost all world NH_3 annual consumption of ~ 130 million tons from natural gas via steam methane reforming (SMR) of methane, with waste CO2 released to Earth's atmosphere. RE-source hydrogen eliminates waste CO2 .

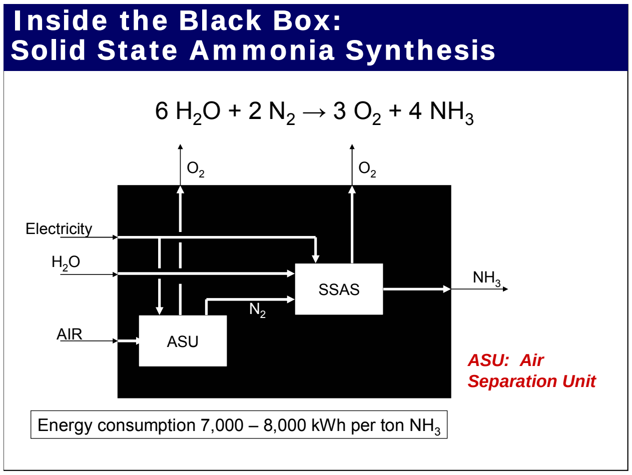

Figure 6. SSAS ammonia synthesis eliminates electrolysis, but requires an ASU. RE-source electricity eliminates the CO_2 waste product.

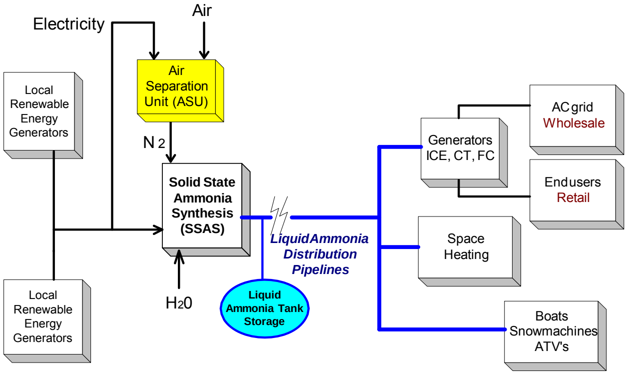

Figure 7. SSAS ammonia synthesis eliminates electrolyzers, but requires an air separation unit (ASU). RE-source electricity eliminates the CO_2 waste.

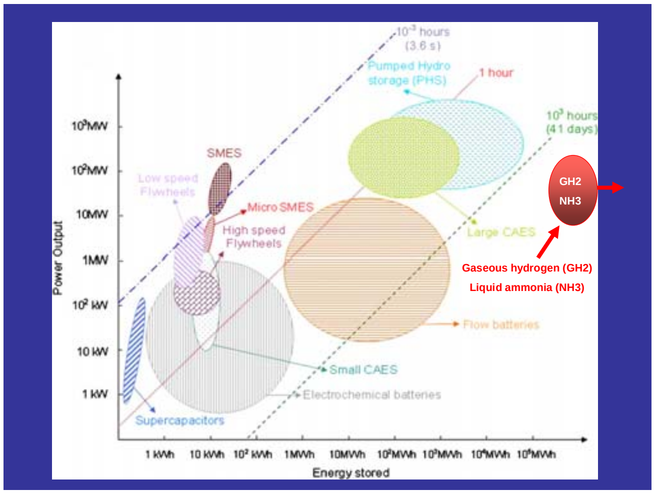

Figure 8. Bulk energy storage schemes and technology comparison.

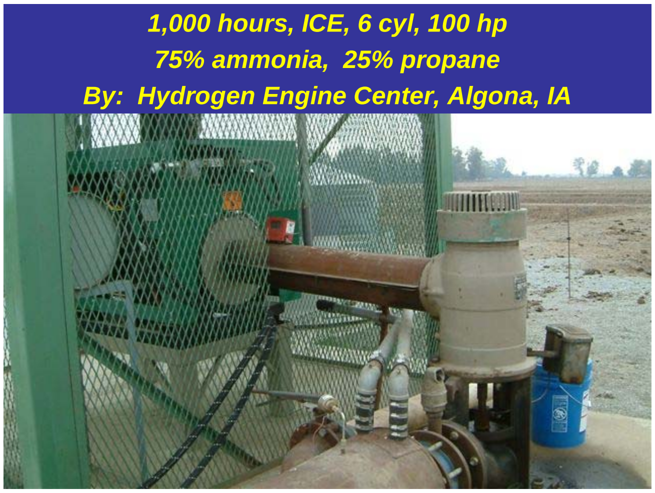

Figure 9. Ammonia-fueled internal combustion engine (ICE) operating an irrigation pump in Central Valley, California, on long-term test. 30:1 compression ratio; ~ 50% total efficiency. This ICE, or larger versions, could drive Alaska village electric generators. This ICE is not in production.

Figure 10. Liquid anhydrous ammonia (NH_3) storage tanks. Foreground: 10 bar, ~ 100 ton, carbon steel “bullet” tank, appropriate for Alaska village storage. Rear: 1 atm, ~ 30,000 ton, -33 C refrigerated, double-wall steel tank, appropriate for large Alaska communities and for firming seasonal hydro plants.

Figure 11. Proton conducting ceramic (PCC) tube section (center) installed between alumina fixture tube sections for solid state ammonia synthesis (SSAS) testing.

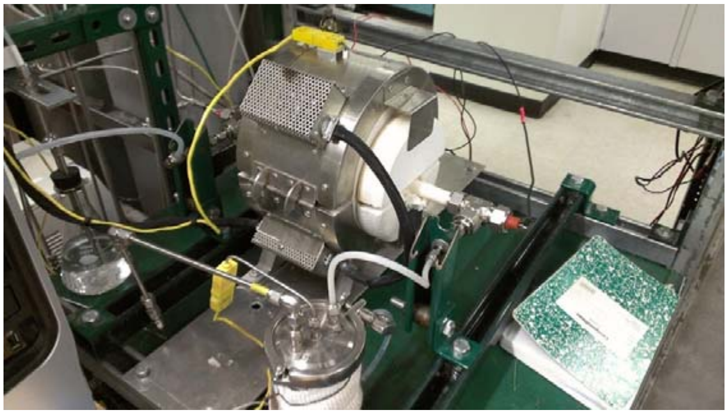

Figure 12. Proton conducting ceramic (PCC) tube section in alumina fixture in heated chamber for solid state ammonia synthesis (SSAS) testing.

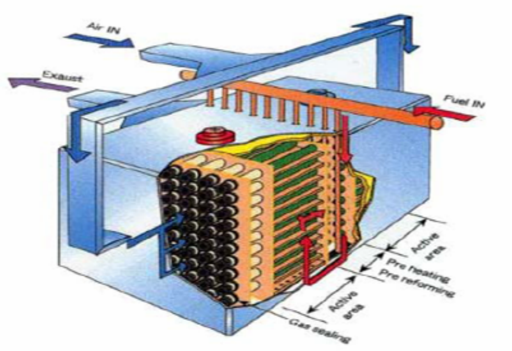

Figure 13. A multi-PCC-tube SSAS reactor would resemble a solid oxide fuel cell (SOFC) in architecture.

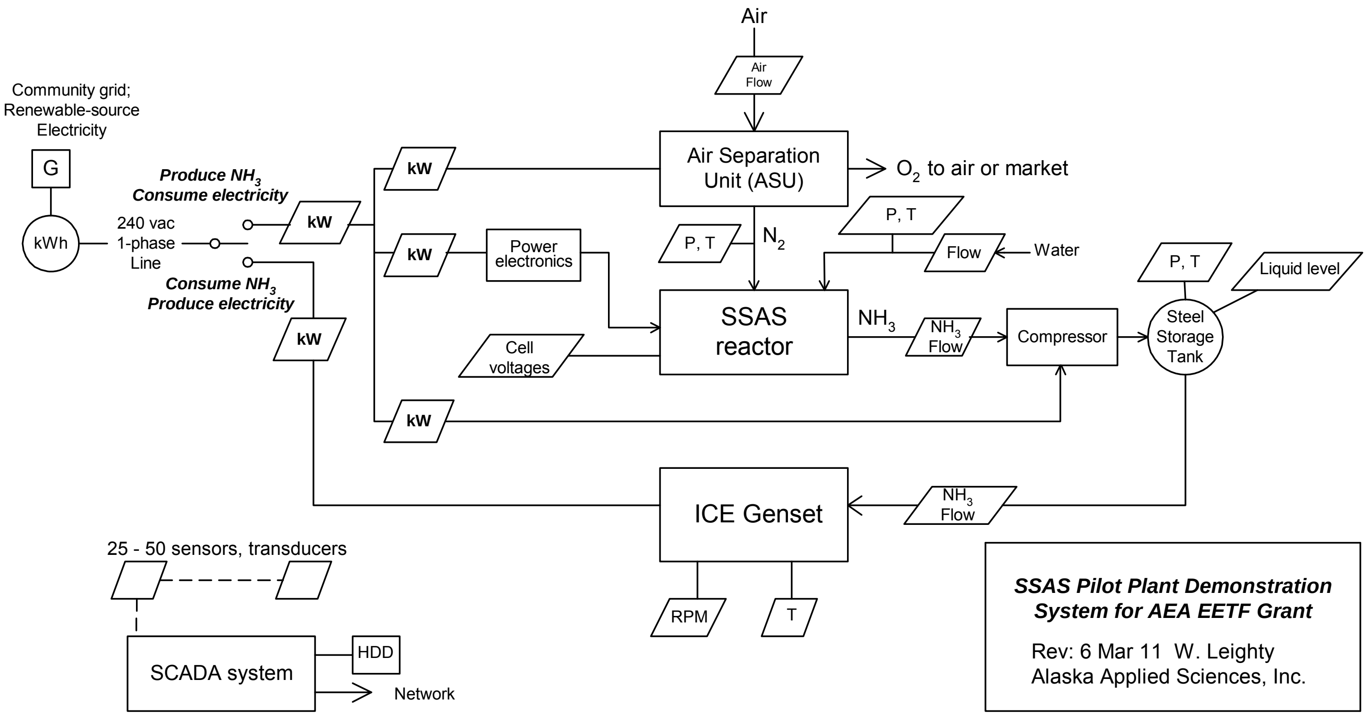

Figure 14. Proposed SSAS proof-of-concept pilot plant (SSAS-PP) demonstration system: a complete, instrumented, self-contained, containerized (insulated CONEX), transportable NH3 synthesis, storage, and regeneration system. Capable of closed-loop NH3 synthesis, storage, and regeneration from RE-source electricity, water, and air.

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[4] US Patent 7,811,442 was granted 12 Oct 10, assigned to NHThree LLC (Richland, WA)

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