Ammonia Fuel
Opportunities, Markets, Issues

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The Prize – 21st Century

(With Apologies to Daniel Yergin)

A zero carbon fuel

That can be used for transportation and power generation

That is scalable from global chemical to global energy proportions

That is an inherently clean fuel with regard to traditional pollutants and CO_2

That has a century long history of large scale handling and use

That is competitive in energy pricing to current fuels

That holds promise for low or no carbon production (through CCS on standard technology or advanced technology for renewables or nuclear)

That *appears to be* within easy reach through optimization of production, use and safety regulations

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What We Know

- **Ammonia average price over last 20 years is $300 per tonne. Equivalent to $1.75 gal gasoline and $14 per MMBTU LNG. Power at $0.11 per kwh (@45% efficiency)**
- **Ammonia can be produced from zero carbon energy (hydro, nuclear, wind) and with *significant* CCS at lowest cost of capture for any hydrocarbon process**
- **Ammonia diesel engines are proven and essentially equivalent in cost (either with diesel blending, precracking or advanced engines)**
- **Ammonia turbines with precracking to produce hydrogen for component of the fuel are efficient and flexible**
- **In general, these technologies have considerable headroom and are primarily in need of engineering optimization and field prototyping for commercialization**

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Low Carbon Ammonia (And Front End For CCS)

- **Ammonia plants emit pure (sequestration-ready) CO_2. Approximately 2/3 is pure. With current technology, the rest is flue gas from the reformer.**
- **There are active markets to purchase CO_2 for enhanced oil recovery.**
- **Ammonia plants built close to EOR fields can sell their waste CO_2 to be sequestered in oil fields after use. EOR technologies exist for complete CO2 sequestration at low incremental cost. (co-injection with N2)**
- **This co-product value can reduce production cost for eventual fuel use.**
- **These operations will also supply a great deal of experience, technology and infrastructure for carbon capture and for CO_2 transportation and sequestration.**

- **This will serve as a bridge while "green ammonia" technologies from renewables, hydro and nuclear energy are optimized for a decarbonized ammonia energy system for power and for liquid fuel for transportation.**

Zero Carbon Ammonia

As a Basis for Affordable, World Scale Zero Carbon Energy

- **Decarbonize the giant gas reserves. Initially, pure CO2 injection for miscible EORce. Separate injection points of CO2 flue gas for immiscible pressure maintenance.**
- **Injection continues into reservoir following oil production and into adjacent reservoirs.**
- **Renewable energy (wind, solar, hydro, geothermal) and nuclear to produce ammonia from water and air.**
- **Electrolysis to H2 and Haber Bosch ammonia in development at prototype stage – potentially $400 per tonne on technologies in development.**
- **Solid State Ammonia Synthesis (SSAS) also in the same range.**

- **Fundamental point. Ammonia is the simplest molecule that stores hydrogen in a liquid form at near ambient conditions.**

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Power Generation - NH3 Diesel Engines

- One of the most promising early applications for ammonia as a fuel is large stationary diesel gen sets. **(nominally 40-45% efficient for power, 75% for CHP). Sturman engines as prototype.**
- There are over 200 GW of medium to large diesel engines that run on a continuous basis producing electricity. These installations often feature a dozen or more engines installed in a kind of 'modular power plant'.
- These modular power plants can be installed very quickly, scaled up or added as necessary, and redeployed when not needed or if the economic conditions change.

- Gas Turbines. Crack some of the NH3 to produce arbitrary amount of H2 for co-feed with NH3 (tunable fuel, exhaust heat recovery). SPG
- Fuel Cells. Ideal fuel for SOFCs. Ideal hydrogen storage and delivery for PEMFCs and FCVs
- Space heating, Process heat (similar to LPG). Ideal for CHP from gensets.

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Starting Points For Transportation

- **There are several entrepreneurs and institutions that are advancing the technology of engines for ammonia fuel.**
- **Toyota is developing a technology and patent portfolio for ammonia engines including onboard cracker for tunable addition of hydrogen.**
  https://www.collectiveip.com/companies/toyota-motors/patents?fin=Norihiko+Nakamura&q=ammonia+engine
- **Jay Schmuecker has developed a system to manufacture ammonia from solar and a tractor to run on the ammonia.**
  https://nh3fuel.files.wordpress.com/2014/10/nh3fa-2014-jay-schmuecker.pdf
  http://solarhydrogensystem.com/new/wp-content/uploads/2015/04/schmuecker-launch-brochure-web.pdf
- **Sturman Industries is developing ammonia engines based on advanced concepts in valves, camless engines and injection strategies.**
  https://www.youtube.com/watch?v=aojUI74qHfc
- **The Iowa Energy Center is developing engine technologies for use in agricultural industry.**
  http://www.iowaenergycenter.org/search/?cx=003074495176662961374%3Apisxjengoxu&cof=FORID%3A11&ie=UTF-8&q=energy+ammonia+engine&sa=Search&sa=Search
- **Greg Vezina has developed ammonia vehicles on standard platforms. From all appearances, these are well developed prototypes.**
  https://www.youtube.com/watch?feature=player_embedded&v=Bs3HSChSh_E
  (Hydrofuel, http://nh3fuel.com/)

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Global Sources - Overview

- Alaska North Slope
- US Southwest/Midwest/Fracking in general
- Middle East / North Africa (lowest cost ammonia currently, lots of headroom)
- Canada Hydroelectric (10's of GW of low cost power on contract)
- Iceland (practically unlimited geothermal at ~3 cents/kwh)
- Big Wind (depends on low capex electrolysis tech, allows local grid stabilization)
- Off Peak Nuclear (depends on low capex electrolysis tech, allows local grid stabilization)

Global Markets - Overview

- Alaska (displace diesel across the state, supply Anchorage, alternate export market for Alaska gas)
- Hawaii (displace diesel, resid and gasoline across the islands; CHP and distributed generation)
- Northeast/MidAtlantic (energy security, grid stability, alternative to gas)
- Midwest (energy security, grid stability, displace fuel oil/LPG, fertilizer)
- Caribbean (displace diesel, resid and gasoline across the islands)
- Japan (alternative to expensive LNG and coal, replacing nuclear)
- Indonesia (displace diesel, resid and gasoline across the islands)
- China (clean cities, rural access, much easier than gas)
- Europe (energy security, CHP, DG, fertilizer/fuel)
- Africa, South America (ammonia diesel gen, clean cities, rural access)

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Neighborhood Energy Station

- A typical high volume gasoline station can easily dispense 1.5 MM gallons of multiple grades of gasoline/diesel in a year. This case examines a 'neighborhood' ammonia energy station of approximately the same scale that could provide power and heat to the neighborhood (or condo or office building) in an urban environment. This station would house a diesel genset/CHP unit running on ammonia. The prototype for this is the MHI MegaNinja gas genset (delivered on 40' trailer, 1.5 MW generator operating at 42.5% efficiency, designed for combined heat/power taking efficiency up to 75% for medium pressure steam/space and water heating and adsorptive air conditioning.)

- The general complexity of these stations would be less than a gasoline station (single grade, dispensed almost entirely to the generators instead of retail interface with hundreds of transactions to untrained public per day). Tank volume, general regulatory requirements and fuel delivery logistics would be similar.

- The average weekly volume would be about 35,000 gallons. We can 'design' for 40,000 gal/week peak usage. A typical tank size for ammonia distributors is 30,000 gallons. So, with one 30,000 gal tank (installed underground for safety, security and ease of temp/pressure maintenance), we could operate with three a week deliveries from 11,500 gal tank trucks (typical size ammonia trucks). I'm sure the logistics can/will be optimized beyond that, but this will do for illustration.

- Very rough project costs would be about $1.2 MM for ammonia MegaNinja, $0.1 MM for underground tank, connections and land. Roughly $1.5-$2 MM.

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Neighborhood Energy Station

- Upside revenue potential for similar projects in other regions of the world. Examples:
- Island economies that must generate their power from fuel oil (Hawaii, Caribbean, Indonesia). Fuel oil is $30-$40 per mmbtu. It is dirty and must be located away from populations (and especially resorts). That also makes it very difficult to capture and utilize the 1/3 of the btu's from CHP that clean ammonia engines can provide. These units can provide clean power at less than half the cost and, on top of that, very efficient heat and air conditioning (absorptive chilling).
- Medium scale distribution/retail (frozen/refrigerated foods), light industry and agriculture utilizing refrigeration, medium pressure steam or drying (e.g., crops) that place high value on the associated heat)
- Regions that place high value on pure water (exhaust from ammonia Sturman engine is water and nitrogen. Pure water can be captured at the cost of condensing the water.) Combustion of 1.75 MM gallons of ammonia generates about 1.7 MM gallons of water.
- They will be very attractive to sites willing and able to pay large premiums for locally controlled, uninterruptible power (financial/business centers, server farms, hospitals, military/government installations, large research facilities/research universities)
- Regions that are imposing a cost on CO2 emissions can reduce or eliminate those costs. Clean Power Plan.
- Grid ancillary services. Load following, Peak power, Voltage/frequency regulation, Locational value, Black start

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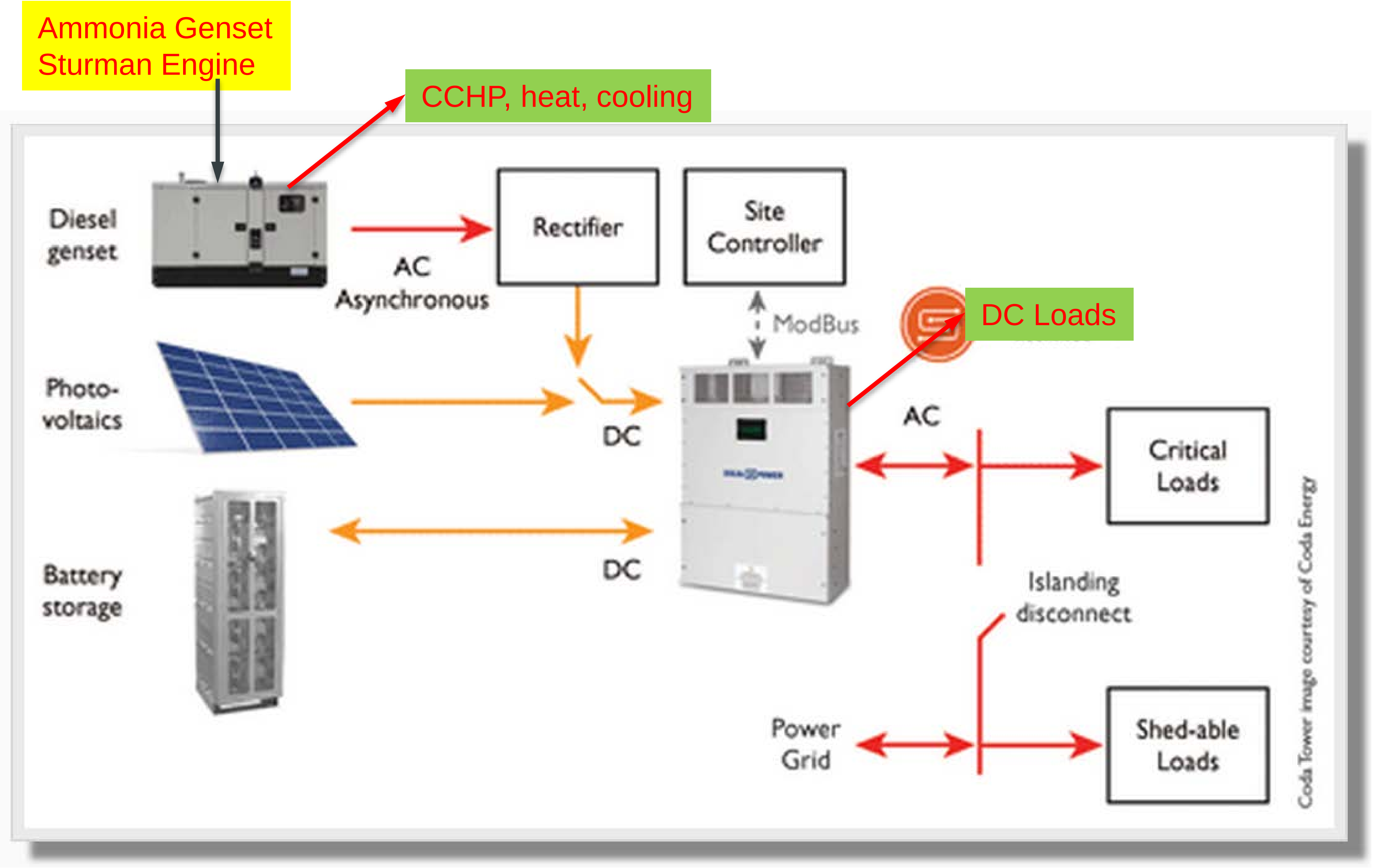
Neighborhood Energy Station – Ideal Power



http://www.idealpower.com/hybrid.aspx

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Utility Level Storage to Stabilize Grid

<u>Utility Storage Market Drivers:</u>

- Wind and Solar Integration
- Energy Arbitrage
- Frequency Regulation & Ancillary Services
- Infrastructure Upgrade Deferral
- Locational Capacity

Different battery technologies will supply this market

120kW – 500kW
Bonneville Power Authority, WA

Ideal Power is forming alliances with leading battery suppliers

LG Chem

AQUION ENERGY

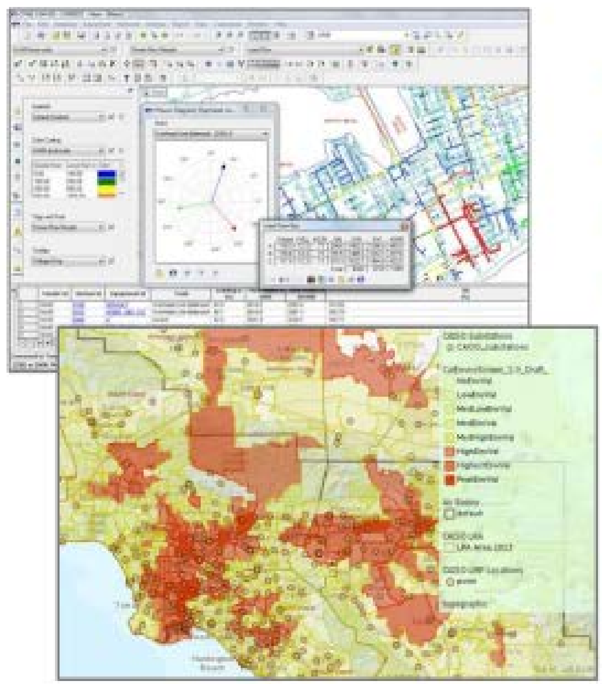
eos ENERGY STORAGE

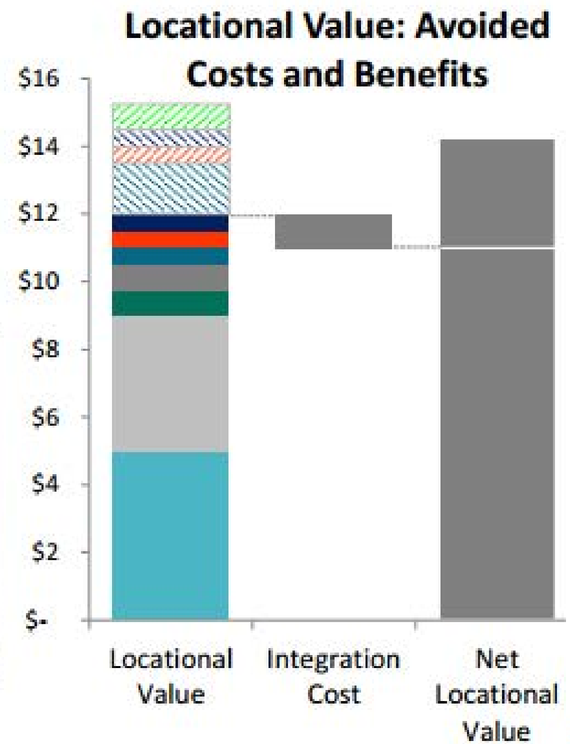
powin ENERGY

IDEAL POWER

Ammonia Energy Station can be installed at highest locational value
Highest leverage to stabilize grid, relieve congestion and defer infrastructure investment

For Each DPA & Substations/Feeders → **Annual Dist. Planning & Integration Capacity Analyses** → **Biennial DRP Locational Value Analysis**





http://resnick.caltech.edu/docs/MTS_V2.pdf

Neighborhood Energy Station

- With a set up like Ideal Power, this configuration can

- Easily accommodate renewable solar or wind by cutting back genset (with immediate local load following).
- Pass through solar/wind or ammonia power and ancillary services to the grid. 24/7 availability of peaking power (125% of genset rating typical), frequency regulation, voltage support, black start.
- Provide predictable, addressable standby reserve available on 5 minute call-up (with right incentives and minimally sophisticated 'smart grid' controls) (much cheaper and much more flexible than spinning reserve CCGT that is only used as gas prices are rising above $40/mmbtu)
- Provide distributed and potentially very substantial regional fuel reserve for mid-winter, late summer, regional security (much cheaper (pseudo-'free') than natural gas storage and much more flexible). 30,000 gallon underground tank of ammonia provides about 180 MWh of electricity (42%) and 400 MMBTU of CHP heat (30%), About 5 days of continuous operation.

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How Does This All Get Started?

- Market demonstration at 1-10 MW scale (diesel gen, refit, new optimized, blends) Sturman engines, Fleming Ammonia, others
- Evaluation of these systems for zero carbon power across the value chain by experts and system modelers
- Engage regulators and power industry
- Engage ammonia producers/investors
  - New build guaranteed offtake (some fraction of production)
  - Eventually, utility plants with guaranteed returns for fuel take or pay (with perhaps shared profits for joint sales into market after satisfaction of energy market contractual requirements)
  - Market, regulatory, technology demo support from self selected producers
  - Plant technology/engineering firms (KBR, Uhde, MHI, etc) that will benefit from increased building
- Low cost, high CO2 value areas for low carbon, low cost fuels
- Accelerate demo/commercialization of power to NH3 technologies
  - Compile list of potentially interested investors, green funding, etc for incipient technologies for investments in the range of $5-$20 MM for FEED, critical demoes or initial deployment in regions for low cost "stranded" power (i.e., Canada, Iceland, Hawaii)
  - Competition for proposals for ammonia from power, perhaps with funding from such entities
- Project development with engaged stakeholders

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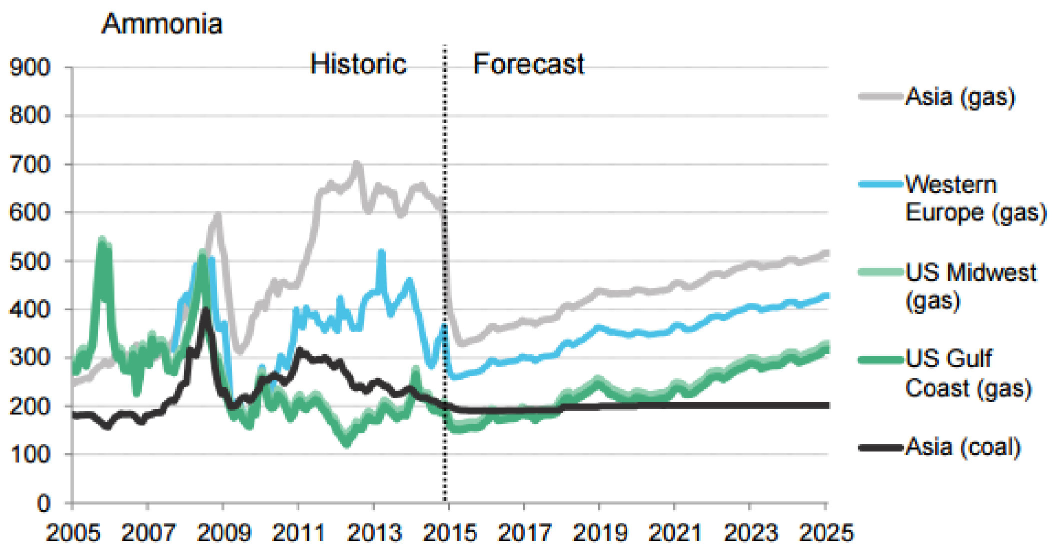
Backup Slides

Indicative Economics - Overview

- New world scale plant, 1 mm tonnes/year @ $1200 per tonne of annual capacity. 10% annual capital charge about $120/tonne
- Approx. 30 mmbtu of gas required per tonne of ammonia (e.g., $4/mmbtu gas, about $120/tonne of ammonia)



http://www.ourenergypolicy.org/wp-content/uploads/2015/04/BNEF_ChemicalsWhitePaper_2015-01-20-final1.pdf

Compare to Battery Storage

- **Much lower cost, 30,000 gal underground tank (similar to gas station) stores about 180 MWh and 400 MMBTU CHP heat. About $100,000 capital cost.**
- **Much longer life (genset versus batteries)**
- **Gensets require more maintenance**
- **Zero carbon ‘recharge’ from ammonia delivery (does not use local excess power to manage local peaks/valleys). Accesses lowest cost excess power in region.**

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Compare to Nat Gas Genset

- No need for gas supply
- No new pipelines required (multi hundred million $ projects, 5 year projects from negotiation thru gas flow, political/public opposition)
- Purchase fuel from multiple sources rather than prices set by pipeline operations
- Reduced exposure to price volatility
- Not subject to pipeline/compressor failure
- Very low cost local storage of energy (days of operation without refill) compared to expensive cavern storage backed up by LNG
- No CO_2 emissions
- Low/No NOX

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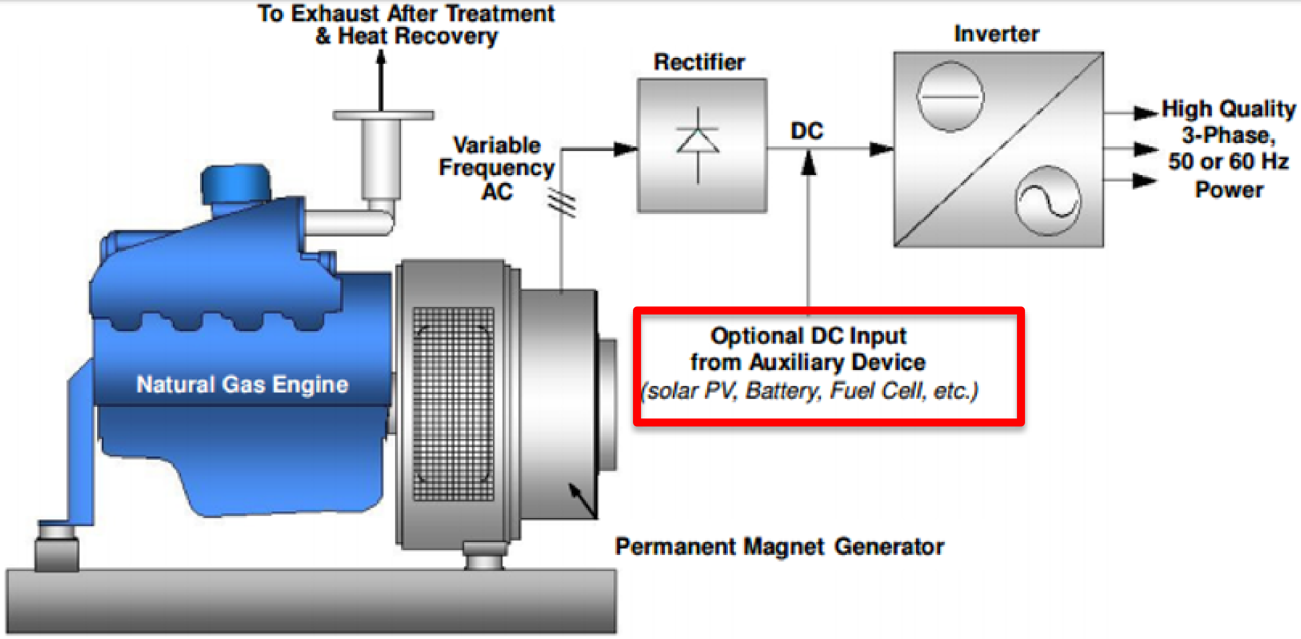
Because the system can now operate at variable rpm, it maintains a high torque regardless of the output, thus maintaining near full-load efficiency throughout its operating range. Additionally, more output can be derived from the same engine if it can be operated to the higher rpm, that is, beyond the typical synchronous speed of 1800 rpm. Another advantage is that the same machine can be applied to the 50 Hertz market, without de-rating or design changes.



Engine/Generator Output

RPM	Volts	Freq (hz)	KW
1000	98	135	39
2200	207	297	93
3000	258	405	130

Power Conversion

Delivered kW

Volts	Freq (hz)	KW
480	60	37
480	60	88
480	60	123

FIGURE 1. CONCEPTUAL DESIGN OF INVERTER-BASED ENGINE GENERATOR

http://bpe-ne.com/wp-content/uploads/2012/07/top10-reasons-to-choose-inverter-based-engine-chp.pdf

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Ammonia Fuel Cost	Ammonia Cost ($/tonne)	$/mmbtu (@21.3 mmbtu per tonne)	Efficiency of conversion to power	kwh per tonne of ammonia	kwh per gallon of ammonia	$/kwh for fuel cost		Total Capital	Annual Operating Profit (no cap charge)	Payback, years
	$ 300	$ 14.08	45.0%	2812.5	6.53	$ 0.107		$ 2,250,000	$ 503,758	4.47

Cap Charge	Capex for dieselgen ($/kw)	% premium utilization per year	premium kwh per year per installed kw capacity	Annual capital charge as % capex	Annual capital charge (per kw)	capital charge per premium kwh dispatched				
	$ 1,500	60.0%	5256	12.5%	$ 188	$ 0.036				

Scale of Installation and costs	Scale (kw installed)	premium kwh dispatched	annual tonnes of ammonia for premium ops	Annual fuel expenditure for premium ops, $	Annual Capex Charge, $	annual gallons of ammonia	ammonia use during full dispatch (gal per hour)	Days of operation from full 50,000 gal tank	number of 11500 gal tanker truck deliveries per year	Annual maintenance and labor @ $0.02 per kwh
	1500	7,884,000	2803	$ 840,960	$ 281,250	1208179	230	9.1	105	$ 157,680

Revenue Streams	Recoverable heat per tonne of ammonia (40% of 21.3 MMBTU)	Total recoverable heat, mmbtu	Sales heat price, $/mmbtu	Annual heat revenue		Sales power price, premium on demand, $ per kwh	Annual power revenue (from % utilization)		Total annual revenue Premium operation	Premium Revenue - fuel cost - cap charge - labor & maintenance
	8.5	23827.2	$ 4.00	$ 95,309		$ 0.15	$ 1,182,600		$ 1,277,909	$ (1,981)

Opportunistic operations	Sales power price, opportunistic, $/kwh	Opportunistic sales (% dispatch outside premium window)	Opportunistic dispatch (hrs/yr)	Opportunistic dispatch (kwh/yr)	Annual tonnes ammonia for opportunistic	Opportunistic fuel/maintenance cost	Opportunistic revenue (power+heat)	Opportunistic revenue - fuel/maintenance	Total annual revenue (w/ opportunistic)	Total Revenue - fuel cost - cap charge - labor & maintenance
	$ 0.20	50%	1752	2,628,000	934	$ 332,880	$ 557,370	$ 224,490	$ 1,835,278	$ 222,508

Capital (MM $)	Capacity (1000 tpa)	Cost of Capital	Length of loan, years	Sustaining capital MM per year	CAPEX charge annual MM	Cash cost ex ch4 per tonne	Ch4 mmbtu per tonne NH3	Gas cost $ per mmbtu			**IRR**
1100	1200	4.0%	20	$ 10.00	($70.94)	$ 45.00	32	$3.00			**12.3%**
Gas cost per year MM$	Cash cost per year MM	NH3 sales price $ per tonne	Revenue (MM $)	Cash Margin MM$	Profit, cash - cap charge MM$			Pure CO2, 1000 tpa	CO2 sales price, $ per tonne	CO2 revenues, MM$	Profit with CO2
$ 115	$ 169	$ 300	$ 360	$ 191	$ 120			1500	20	$ 30	$ 150

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Some Initial Scenarios For Discussion

Hawaii distillate, resid and coal import (125 T BTU)

MODEL RESULTS

USER INPUTS ALLOWED IN GREEN CELLS	ALL VALUES EQUIV 1 MT NH3	ALL VALUES CORRESPOND TO CASE PARAMETERS
REQUIRED INPUT or CALCULATE Tonnes NH3 for your scenario in D4	1.00	5.86E+06
OPTIONAL USER-DEFINED VARIABLE. ENTER VARIABLE NAME IN THIS CELL. ENTER (1 T NH3 BASIS) IN C5. ITERATE D4 TO ACHIEVE DESIRED QUANTITY IN D5		0.00
MMBTU (or 1000 CF gas equiv) contained in NH3	21.32	124,987,434
MMBTU gas required for NH3	32.0	187,616,000
TCF natural gas required for NH3	2.94E-08	0.172
Tonnes water produced from NH3	1.58E+00	9,263,540
# Global ammonia industry	6.67E-09	0.039
# of World Scale NH3 Plants	1.25E-06	7.33
Number of 60,000 cbm vessels	2.44E-05	143
Number of 80 tonne railcar deliveries	0.0125	73,288
# of 1 MM TPA NH3 pipeline	1.00E-06	5.9
MWh from 45% efficient power plants	2.81E+00	16,475,030
# of 10 MW plants that can be run for 1 year, 45%	3.21E-05	188.0
Equivalent # of 6 mtpa LNG train (BTU basis)	6.87E-08	0.40
Tonnes LNG equivalent	0.41	2,403,830
Metric Tonnes coal equiv	1.04	6,097,520
Tonnes oil equivalent (TOE)	0.500	2,931,500
Tonnes resid equiv	0.530	3,107,390
Gal LPG equiv	234	1,371,942,000
Gal Gasoline equiv	172	1,008,436,000
Gal Ethanol equiv	253	1,483,339,000
Price NH3	$350	
Total NH3 cost $		2,052,050,000
Fuel cost for power, $/kwh from NH3	$ 0.125	
Price NATURAL GAS	$30.00	
Total Natural Gas cost $		$ 3,746,457,000
Fuel cost for power for power, $/kwh from gas	$ 0.228	
Price GASOLINE	$4.00	
Total Gasoline cost $		$ 4,033,744,000
Fuel cost for power, $/kwh from gasoline	$ 0.313	
Price LPG	$4.00	
Total LPG cost $		$ 5,487,768,000
Fuel cost for power, $/kwh from LPG	$ 0.334	
Price DIESEL	$4.00	
Total Diesel cost $		$ 3,658,512,000
Fuel cost for power, $/kwh from diesel	$ 0.284	
Price COAL	$50	
Total Coal cost $		$ 304,876,000
Fuel cost for power, $/kwh from coal	$ 0.024	
Price ETHANOL	$5.00	
Total Ethanol cost $		$ 7,416,695,000
Fuel cost for power, $/kwh from ethanol	$ 0.452	
MegaTonnes CO2 saved with NH3 with harvest vs GAS	5.50E-07	3

COST, THERMO AND CO2 MATRIX

AMMONIA	NATURAL GAS	GASOLINE	LPG	DIESEL	COAL	ETHANOL	METHANOL	DME
INPUT Price of NH3 delivered to site, $ per tonne	INPUT Price of gas delivered to site, $ / mmbtu	INPUT Price of gasoline delivered to site, $ / gal	INPUT Price of LPG delivered to site, $ / gal	INPUT Price of diesel delivered to site, $ / gal	INPUT Price of coal delivered to site, $ / tonne	INPUT Price of ethanol delivered to site, $ / gal	INPUT Price of methanol delivered to site, $ / tonne	INPUT Price of DME delivered to site, $ / tonne
$350	$30.00	$4.00	$4.00	$4.00	$50	$5.00	$200	$290
Tonnes NH3 for 21.3 MMBTU	MMBTU gas for 21.3 MMBTU	Gal gasoline for 21.3 MMBTU	Gal LPG for 21.3 MMBTU	Gal diesel for 21.3 MMBTU	Tonnes coal for 21.3 MMBTU	Gal ethanol for 21.3 MMBTU	Tonnes methanol for 21.3 MMBTU	Tonnes DME for 21.3 MMBTU
1.0	21.3	172	234	156	1.0	253	0.982	0.71
NH3 Fuel Cost (for 21.3 mmbtu) - This Scenario	Gas Fuel Cost (for 21.3 mmbtu) - This Scenario	Gasoline Fuel Cost (for 21.3 mmbtu) - This Scenario	LPG Fuel Cost (for 21.3 mmbtu) - This Scenario	Diesel Fuel Cost (for 21.3 mmbtu) - This Scenario	Coal Fuel Cost (for 21.3 mmbtu) - This Scenario	Ethanol Fuel Cost (for 21.3 mmbtu) - This Scenario	Methanol Fuel Cost (for 21.3 mmbtu) - This Scenario	DME Fuel Cost (for 21.3 mmbtu) - This Scenario
$350	$639	$688	$936	$624	$52	$1,265	$196	$206
kwh from 21.3 mmbtu at 45% efficiency (gas/nh3 like)	kwh from 21.3 mmbtu at 45% efficiency (gas/nh3 like)	kwh from 21.3 mmbtu at 35% efficiency (coal like)	kwh from 21.3 mmbtu at 45% efficiency (gas/nh3 like)	kwh from 21.3 mmbtu at 35% efficiency (coal like)	kwh from 21.3 mmbtu at 35% efficiency (coal like)	kwh from 21.3 mmbtu at 45% efficiency (gas/nh3 like)	kwh from 21.3 mmbtu at 45% efficiency (gas/nh3	kwh from 21.3 mmbtu at 45% efficiency (gas/nh3
2800	2800	2200	2800	2200	2200	2800	2800	2800
Fuel cost for power, $/kwh from NH3	Fuel cost for power for power, $/kwh from gas	Fuel cost for power, $/kwh from gasoline	Fuel cost for power, $/kwh from LPG	Fuel cost for power, $/kwh from diesel	Fuel cost for power, $/kwh from coal	Fuel cost for power, $/kwh from coal	Fuel cost for power, $/kwh from methanol	Fuel cost for power, $/kwh from DME
$0.125	$0.228	$0.313	$0.334	$0.284	$0.024	$0.452	$0.070	$0.074

AMMONIA, NO CCS	AMMONIA w/ HARVEST	NATURAL GAS	GASOLINE	LPG	DIESEL	COAL	ETHANOL	METHANOL	DME
T CO2 per 21.3 mmbtu,only production, no CCS	T CO2 per 21.3 mmbtu,only production, CO2 harvest	T CO2 per 21.3 mmbtu, NOT COUNTING LIFECYCLE	T CO2 per 21.3 mmbtu, NOT COUNTING LIFECYCLE	T CO2 per 21.3 mmbtu, NOT COUNTING LIFECYCLE	T CO2 per 21.3 mmbtu, NOT COUNTING LIFECYCLE	T CO2 per 21.3 mmbtu, NOT COUNTING LIFECYCLE	T CO2 per 21.3 mmbtu, NOT COUNTING LIFECYCLE	T CO2 per 21.3 mmbtu, NOT COUNTING LIFECYCLE	T CO2 per 21.3 mmbtu, NOT COUNTING LIFECYCLE
1.93	0.68	1.23	1.65	1.48	1.68	2.42	0.33	1.80	1.80

CASE NOTES

HAWAII distillate, resid and coal import (125 T BTU)

Gas price - $40 per mmbtu

Power - $350 per mwh (about 80% from coal, resid and fuel oil)

This could be displaced by 6 mmt nh3 (about 7.5 ammonia plants)

About 150 cargo ship deliveries per year.3

Fuel cost for ammonia per year - $2.0 bb. Fuel cost for power ('free' heat from CHP) - **$125 per MWH.**

Fuel cost for gas per year - $3.7 bb. Fuel cost for power ('free' heat from CHP) - $228 per MWH.

Fuel cost for diesel per year - $3.6 bb. Fuel cost for power ('free' heat from CHP) - **$284per MWH.**

Fuel cost for coal per year - $0.3 bb. Fuel cost for power ('free' heat from CHP) - $30 per MWH.

Fuel price not the whole story.

Ammonia much easier to distribute and store than coal or gas.

Ammonia much cleaner to burn and use than coal, resid or fuel oil.

Ammonia can be deployed for power gen at 40%+ efficiency at scales between 250 kw and 50 M. At a capex of $600- $800 per kw. With turn on/off in a few minutes. Coal and gas cannot.

Small scale, clean combustion (500 kw – 200 MW) greatly facilitates CHP (heating, absorptive AC, hot water). Raising efficiency to 70-80% and displacing other heating fuels (perhaps 50% additional to electricity.

Ammonia at $250 - $350 per tonne is available from $2-$4 gas around the world for this entire market once the demand is established. That existing demand for fuel oil, LPG, LNG has established much higher prices.

Hawaii resid/distillate

Most of Hawaii's electricity is generated from heavy hydrocarbons. This is expensive (HI power more than 3X cost of mainland) and environmentally destructive, 35-40 cents/kwh). Hawaii is working very hard to reduce hydrocarbon reliance (small scale LNG, renewables energy efficiency).

There is great scope for this since power is so expensive. But the cheapest way is through ammonia.

Displacing all of HI resid, fuel oil and coal about equivalent to 6 MMTPA NH3 (about 7 plants or 140 cargo ship deliveries.) Ammonia at $350/tonne has a fuel cost of 13 cents / kwh (not counting credit for CHP from ammonia diesel gen sets).

Think also – Caribbean, Indonesia, Greece, Philippines

NEIGHBORHOOD ENERGY STATION (LIKE A GAS STATION) Dispensing 1.75 MM Gals Per Year Of Ammonia

MODEL RESULTS

USER INPUTS ALLOWED IN GREEN CELLS	ALL VALUES EQUIV 1 MT NH3	ALL VALUES CORRESPOND TO CASE PARAMETERS
REQUIRED INPUT or CALCULATE Tonnes NH3 for your scenario in D4	1.00	4,060
OPTIONAL USER-DEFINED VARIABLE. ENTER VARIABLE NAME IN THIS CELL. ENTER (1 T NH3 BASIS) IN C5. ITERATE D4 TO ACHIEVE DESIRED QUANTITY IN D5		0.00
MMBTU (or 1000 CF gas equiv) contained in NH3	21.32	86,558
MMBTU gas required for NH3	32.0	129,930
TCF natural gas required for NH3	2.94E-08	0.000
Tonnes water produced from NH3	1.58E+00	6,415
# Global ammonia industry	6.67E-09	0.000
# of World Scale NH3 Plants	1.25E-06	0.01
Number of 60,000 cbm vessels	2.44E-05	0
Number of 80 tonne railcar deliveries	0.0125	51
# of 1 MM TPA NH3 pipeline	1.00E-06	0.0
MWh from 45% efficient power plants	2.81E+00	11,410
# of 10 MW plants that can be run for 1 year, 45%	3.21E-05	0.1
Equivalent # of 6 mtpa LNG train (BTU basis)	6.87E-08	0.00
Tonnes LNG equivalent	0.41	1,665
Metric Tonnes coal equiv	1.04	4,223
Tonnes oil equivalent (TOE)	0.500	2,030
Tonnes resid equiv	0.530	2,152
Gal LPG equiv	234	950,116
Gal Gasoline equiv	172	698,376
Gal Ethanol equiv	253	1,027,262
Gal Ethanol equiv	253	1,027,262
Price NH3	$350	
Total NH3 cost $		1,421,114
Fuel cost for power, $/kwh from NH3	$ 0.125	
Price NATURAL GAS	$15.00	
Total Natural Gas cost $		$ 1,297,274
Fuel cost for power for power, $/kwh from gas	$ 0.114	
Price GASOLINE	$3.00	
Total Gasoline cost $		$ 2,095,128
Fuel cost for power, $/kwh from gasoline	$ 0.235	
Price LPG	$2.00	
Total LPG cost $		$ 1,900,232
Fuel cost for power, $/kwh from LPG	$ 0.167	
Price DIESEL	$3.80	
Total Diesel cost $		$ 2,406,961
Fuel cost for power, $/kwh from diesel	$ 0.269	
Price COAL	$50	
Total Coal cost $		$ 211,137
Fuel cost for power, $/kwh from coal	$ 0.024	
Price ETHANOL	$3.00	
Total Ethanol cost $		$ 3,081,787
Fuel cost for power, $/kwh from ethanol	$ 0.271	
MegaTonnes CO2 saved with NH3 with harvest vs GAS	5.50E-07	0

COST, THERMO AND CO2 MATRIX

AMMONIA	NATURAL GAS	GASOLINE	LPG	DIESEL	COAL	ETHANOL	METHANOL	DME
INPUT Price of NH3 delivered to site, $ per tonne	INPUT Price of gas delivered to site, $ / mmbtu	INPUT Price of gasoline delivered to site, $ / gal	INPUT Price of LPG delivered to site, $ / gal	INPUT Price of diesel delivered to site, $ / gal	INPUT Price of coal delivered to site, $ / tonne	INPUT Price of ethanol delivered to site, $ / gal	INPUT Price of methanol delivered to site, $ / tonne	INPUT Price of DME delivered to site, $ / tonne
$350	$15.00	$3.00	$2.00	$3.80	$50	$3.00	$200	$290
0	MMBTU gas for 21.3 MMBTU	Gal gasoline for 21.3 MMBTU	Gal LPG for 21.3 MMBTU	Gal diesel for 21.3 MMBTU	Tonnes coal for 21.3 MMBTU	Gal ethanol for 21.3 MMBTU	Tonnes methanol for 21.3 MMBTU	Tonnes DME for 21.3 MMBTU
1.0	21.3	172	234	156	1.0	253	0.982	0.71
NH3 Fuel Cost (for 21.3 mmbtu) - This Scenario	Gas Fuel Cost (for 21.3 mmbtu) - This Scenario	Gasoline Fuel Cost (for 21.3 mmbtu) - This Scenario	LPG Fuel Cost (for 21.3 mmbtu) - This Scenario	Diesel Fuel Cost (for 21.3 mmbtu) - This Scenario	Coal Fuel Cost (for 21.3 mmbtu) - This Scenario	Ethanol Fuel Cost (for 21.3 mmbtu) - This Scenario	Methanol Fuel Cost (for 21.3 mmbtu) - This Scenario	DME Fuel Cost (for 21.3 mmbtu) - This Scenario
$350	$320	$516	$468	$593	$52	$759	$196	$206
kwh from 21.3 mmbtu at 45% efficiency (gas/nh3 like)	kwh from 21.3 mmbtu at 45% efficiency (gas/nh3 like)	kwh from 21.3 mmbtu at 35% efficiency (coal like)	kwh from 21.3 mmbtu at 45% efficiency (gas/nh3 like)	kwh from 21.3 mmbtu at 35% efficiency (coal like)	kwh from 21.3 mmbtu at 35% efficiency (coal like)	kwh from 21.3 mmbtu at 45% efficiency (gas/nh3 like)	kwh from 21.3 mmbtu at 45% efficiency (gas/nh3	kwh from 21.3 mmbtu at 45% efficiency (gas/nh3
2800	2800	2200	2800	2200	2200	2800	2800	2800
Fuel cost for power, $/kwh from NH3	Fuel cost for power for power, $/kwh from gas	Fuel cost for power, $/kwh from gasoline	Fuel cost for power, $/kwh from LPG	Fuel cost for power, $/kwh from diesel	Fuel cost for power, $/kwh from coal	Fuel cost for power, $/kwh from coal	Fuel cost for power, $/kwh from methanol	Fuel cost for power, $/kwh from DME
$0.125	$0.114	$0.235	$0.167	$0.269	$0.024	$0.271	$0.070	$0.074

AMMONIA, NO CCS	AMMONIA w/ HARVEST	NATURAL GAS	GASOLINE	LPG	DIESEL	COAL	ETHANOL	METHANOL	DME
T CO2 per 21.3 mmbtu,only production, no CCS	T CO2 per 21.3 mmbtu,only production, CO2 harvest	T CO2 per 21.3 mmbtu, NOT COUNTING LIFECYCLE	T CO2 per 21.3 mmbtu, NOT COUNTING LIFECYCLE	T CO2 per 21.3 mmbtu, NOT COUNTING LIFECYCLE	T CO2 per 21.3 mmbtu, NOT COUNTING LIFECYCLE	T CO2 per 21.3 mmbtu, NOT COUNTING LIFECYCLE	T CO2 per 21.3 mmbtu, NOT COUNTING LIFECYCLE	T CO2 per 21.3 mmbtu, NOT COUNTING LIFECYCLE	T CO2 per 21.3 mmbtu, NOT COUNTING LIFECYCLE
1.93	0.68	1.23	1.65	1.48	1.68	2.42	0.33	1.80	1.80

CASE NOTES

Local Energy Station Dispensing 1.75 Mm Gals Per Year Of Ammonia

A typical high volume gasoline station can easily dispense 1.5 MM gallons of multiple grades of gasoline/diesel in a year. This case examines a 'neighborhood' ammonia energy station of approximately the same scale that could provide power and heat to the neighborhood (or condo or office building) in an urban environment. This station would house a diesel genset/CHP unit running on ammonia. The prototype for this is the MHI MegaNinja gas-driven genset (delivered on 40' trailer, 1.5 MW generator operating at 42.5% efficiency, designed for combined heat/power taking efficiency up to 75% for medium pressure steam/space and water heating and adsorptive air conditioning.)

The general complexity of these stations would be less than a gasoline station (single grade, dispensed almost entirely to the generators instead of retail interface with hundreds of transactions to untrained public per day). But tank volume, general regulatory requirements and fuel delivery logistics would be similar.

The average weekly volume would be about 35,000 gallons. We can 'design' for 40,000 gal/week peak usage. A typical tank size for

The average weekly volume would be about 35,000 gallons. We can 'design' for 40,000 gal/week peak usage. A typical tank size for ammonia distributors is 30,000 gallons. So, with one 30,000 gal tank (installed underground for safety, security and ease of temp/pressure maintenance), we could operate with three a week deliveries from 11,500 gal tank trucks (typical size ammonia trucks). I'm sure the logistics can/will be optimized beyond that, but this will do for illustration.

Very rough project costs would be about $1.2 MM for ammonia MegaNinja, $0.1 MM for underground tank, connections and land. Roughly $1.5-$2 MM.

With these delivery assumptions (1.75 MM gal ammonia/year), a 1.5 MW Meganinja can be supplied 85% of the time (.13/.15). The unit would be available 100% of the time (minus maintenance) and could be run at the cost of more frequent ammonia deliveries. We can model this as

A CHP unit that is integrated into the local electrical grid, sells excess power into the grid and buys power from the grid when power is offered at below cost/value of local power and heat supply. For example, buying low cost base load power at night from utility based on TOD pricing and operating during the day to ease peak power demand on the utility's peakers)

Runs 85% of the time routinely (providing 1.5 MW for 7450 hrs for 11,200,000 kwh and 26,000 mmbtu of CHP heat (calculated as 30% of the mmbtu's in the 1.75 mm gal of ammonia)). We will assume conservatively that 15,000 mmbtu of that heat would be effectively used or sold.

At $300/tonne, 1.75 mm tonnes of ammonia costs $1.2 MM

If we assume New England/Middle Atlantic urban environments, then $0.14 per kwh and $14 per MMBTU are conservative prices for residential customers (especially conservative in the winter). Sales (or avoided costs of gas/power purchases) of the power and CHP heat from 85% operation at these prices would yield $1.57 MM for power and $0.21 MM for heat for a total of $1.78 MM.

At $300/tonne ammonia, the fuel cost for power (even rejecting all the CHP heat) is $0.107 per kwh. So, for the additional 15% of the year that kwh are valued at higher than $0.11 per kwh, the generator can be operated for additional profit. For example, in New England/Middle Atlantic region, retail electricity prices are uniformly above $0.16 per kwh. So, if we are running a 1500 kw unit for 15% of a year (1300 hrs), we are selling 2,000,000 kwh at a margin of $0.05 (bringing in $100,000 extra revenue).

Overview on very rough numbers running the business blind (i.e, selling at average prices, managing CHP heat and extra power sales loosely)
Fuel cost at $300/tonne - $1,200,000
Revenues from 85% base operations (contracted at conservative prices) - $1,780,000
Opportunistic sales of power for other 15% of generating capacity – $100,000
Operating margin of $680,000 to cover capex/opex/profit.

Upside potential on these revenues.

Capacity payments from PJM RPM (market to pay for guaranteed capacity in PJM grid). In New York, this is about $200 per MW (paid whether the unit is running or not). This is $73,000 per year.

Potential payments from reliability premiums from the grid (this power is much more reliable than grid provided power (no risk from gas deliverability, downed power lines, frozen equipment, price spikes from hot summer afternoons, etc).

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The average weekly volume would be about 35,000 gallons. We can 'design' for 40,000 gal/week peak usage. A typical tank size for ammonia distributors is 30,000 gallons. So, with one 30,000 gal tank (installed underground for safety, security and ease of temp/pressure maintenance), we could operate with three a week deliveries from 11,500 gal tank trucks (typical size ammonia trucks). I'm sure the logistics can/will be optimized beyond that, but this will do for illustration.

MidWest LPG Demand

1/8 of midwest propane demand and IL annual purchase of NH3 (1 MM tonnes)

MODEL RESULTS

USER INPUTS ALLOWED IN GREEN CELLS	ALL VALUES EQUIV 1 MT NH3	ALL VALUES CORRESPOND TO CASE PARAMETERS
REQUIRED INPUT or CALCULATE Tonnes NH3 for your scenario in D4	1.00	1,000,000
OPTIONAL USER-DEFINED VARIABLE. ENTER VARIABLE NAME IN THIS CELL. ENTER (1 T NH3 BASIS) IN C5. ITERATE D4 TO ACHIEVE DESIRED QUANTITY IN D5		0.00
MMBTU (or 1000 CF gas equiv) contained in NH3	21.32	21,318,000
MMBTU gas required for NH3	32.0	32,000,000
TCF natural gas required for NH3	2.94E-08	0.029
Tonnes water produced from NH3	1.58E+00	1,580,000
# Global ammonia industry	6.67E-09	0.007
# of World Scale NH3 Plants	1.25E-06	1.25
Number of 60,000 cbm vessels	2.44E-05	24
Number of 80 tonne railcar deliveries	0.0125	12,500
# of 1 MM TPA NH3 pipeline	1.00E-06	1.0
MWh from 45% efficient power plants	2.81E+00	2,810,000
# of 10 MW plants that can be run for 1 year, 45%	3.21E-05	32.1
Equivalent # of 6 mtpa LNG train (BTU basis)	6.67E-08	0.07
Tonnes LNG equivalent	0.41	410,000
Metric Tonnes coal equiv	1.04	1,040,000
Tonnes oil equivalent (TOE)	0.500	500,000
Tonnes resid equiv	0.530	530,000
Gal LPG equiv	234	234,000,000
Gal Gasoline equiv	172	172,000,000
Gal Ethanol equiv	253	253,000,000
Price NH3	$350	
Total NH3 cost $		350,000,000
Fuel cost for power, $/kwh from NH3	$ 0.125	
Price NATURAL GAS	$12.00	
Total Natural Gas cost $		$ 255,600,000
Fuel cost for power for power, $/kwh from gas	$ 0.091	
Price GASOLINE	$4.00	
Total Gasoline cost $		$ 688,000,000
Fuel cost for power, $/kwh from gasoline	$ 0.313	
Price LPG	$3.50	
Total LPG cost $		$ 819,000,000
Fuel cost for power, $/kwh from LPG	$ 0.293	
Price DIESEL	$4.00	
Total Diesel cost $		$ 624,000,000
Fuel cost for power, $/kwh from diesel	$ 0.284	
Price COAL	$100	
Total Coal cost $		$ 104,000,000
Fuel cost for power, $/kwh from coal	$ 0.047	
Price ETHANOL	$4.00	
Total Ethanol cost $		$ 1,012,000,000
Fuel cost for power, $/kwh from ethanol	$ 0.361	
MegaTonnes CO2 saved with NH3 with harvest vs GAS	5.50E-07	1

COST, THERMO AND CO2 MATRIX

AMMONIA	NATURAL GAS	GASOLINE	LPG	DIESEL	COAL	ETHANOL	METHANOL	DME
INPUT Price of NH3 delivered to site, $ per tonne	INPUT Price of gas delivered to site, $ / mmbtu	INPUT Price of gasoline delivered to site, $ / gal	INPUT Price of LPG delivered to site, $ / gal	INPUT Price of diesel delivered to site, $ / gal	INPUT Price of coal delivered to site, $ / tonne	INPUT Price of ethanol delivered to site, $ / gal	INPUT Price of methanol delivered to site, $ / tonne	INPUT Price of DME delivered to site, $ / tonne
$350	$12.00	$4.00	$3.50	$4.00	$100	$4.00	$300	$420
Tonnes NH3 for 21.3 MMBTU	MMBTU gas for 21.3 MMBTU	Gal gasoline for 21.3 MMBTU	Gal LPG for 21.3 MMBTU	Gal diesel for 21.3 MMBTU	Tonnes coal for 21.3 MMBTU	Gal ethanol for 21.3 MMBTU	Tonnes methanol for 21.3 MMBTU	Tonnes DME for 21.3 MMBTU
1.0	21.3	172	234	156	1.0	253	0.982	0.71
NH3 Fuel Cost (for 21.3 mmbtu) - This Scenario	Gas Fuel Cost (for 21.3 mmbtu) - This Scenario	Gasoline Fuel Cost (for 21.3 mmbtu) - This Scenario	LPG Fuel Cost (for 21.3 mmbtu) - This Scenario	Diesel Fuel Cost (for 21.3 mmbtu) - This Scenario	Coal Fuel Cost (for 21.3 mmbtu) - This Scenario	Ethanol Fuel Cost (for 21.3 mmbtu) - This Scenario	Methanol Fuel Cost (for 21.3 mmbtu) - This Scenario	DME Fuel Cost (for 21.3 mmbtu) - This Scenario
$350	$256	$688	$819	$624	$104	$1,012	$294	$298
kwh from 21.3 mmbtu at 45% efficiency (gas/nh3 like)	kwh from 21.3 mmbtu at 45% efficiency (gas/nh3 like)	kwh from 21.3 mmbtu at 35% efficiency (coal like)	kwh from 21.3 mmbtu at 45% efficiency (gas/nh3 like)	kwh from 21.3 mmbtu at 35% efficiency (coal like)	kwh from 21.3 mmbtu at 35% efficiency (coal like)	kwh from 21.3 mmbtu at 45% efficiency (gas/nh3 like)	kwh from 21.3 mmbtu at 45% efficiency (gas/nh3	kwh from 21.3 mmbtu at 45% efficiency (gas/nh3
2800	2800	2200	2800	2200	2200	2800	2800	2800
Fuel cost for power, $/kwh from NH3	Fuel cost for power for power, $/kwh from gas	Fuel cost for power, $/kwh from gasoline	Fuel cost for power, $/kwh from LPG	Fuel cost for power, $/kwh from diesel	Fuel cost for power, $/kwh from coal	Fuel cost for power, $/kwh from coal	Fuel cost for power, $/kwh from methanol	Fuel cost for power, $/kwh from DME
$0.125	$0.091	$0.313	$0.293	$0.284	$0.047	$0.361	$0.105	$0.107

AMMONIA, NO CCS	AMMONIA w/ HARVEST	NATURAL GAS	GASOLINE	LPG	DIESEL	COAL	ETHANOL	METHANOL	DME
T CO2 per 21.3 mmbtu,only production, no CCS	T CO2 per 21.3 mmbtu,only production, CO2 harvest	T CO2 per 21.3 mmbtu, NOT COUNTING LIFECYCLE	T CO2 per 21.3 mmbtu, NOT COUNTING LIFECYCLE	T CO2 per 21.3 mmbtu, NOT COUNTING LIFECYCLE	T CO2 per 21.3 mmbtu, NOT COUNTING LIFECYCLE	T CO2 per 21.3 mmbtu, NOT COUNTING LIFECYCLE	T CO2 per 21.3 mmbtu, NOT COUNTING LIFECYCLE	T CO2 per 21.3 mmbtu, NOT COUNTING LIFECYCLE	T CO2 per 21.3 mmbtu, NOT COUNTING LIFECYCLE
1.93	0.68	1.23	1.65	1.48	1.68	2.42	0.33	1.80	1.80

CASE NOTES

Midwest Fertilizer, Heat and Electricity

The Midwestern states ran dangerously low of LPG for heat and farm use this winter with emergency measures required. Even with growing availability of propane from shale oil and gas, the infrastructure for delivery and storage of propane was strained by high demand for drying extra wet crops followed by record cold.

Prices rose to $4-5 per gallon (normally around $2). And a lot of people got really cold and mad.

I've modelled ammonia equivalent to 12.5% of Midwest propane demand (also equivalent to Illinois demand for ammonia fertilizer). If 12.5% of LPG demand were stored at ammonia facilities at the end of harvesting and the start of winter (when these facilities are operating low because they are most full before and during planting season), this could be a substantial cushion for managing the costs and risks of LPG shortages. This is equivalent to 230 MM gal LPG (replaced by 1 MM tonnes ammonia). The total cost of that ammonia at $350/tonne is $350 MM. The cost of the equivalent BTUs of LPG at $2/gal is $468 MM and at $4/gal is $936 MM. There clearly is large financial incentive even without the consideration of risk management.

If Sturman engine 1.0 MW units (40' trailers with Sturman fitted control systems) were sited on farms and neighborhoods, they would produce well-conditioned power for local use and utility offtake at 45% efficiency. The units are also ideally suited for CHP (total efficiency up to 75% or so) which can be used for district heating and, very importantly, crop drying.

One other huge advantage is countercyclical infrastructure use. The ammonia infrastructure is weighted toward winter and spring (for planting) and the LPG infrastructure is weighted toward summer and fall (for crop drying and winter heating). The ammonia producers will be happy to have profitable smoothing of their storage and distribution.

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Prices rose to $4-5 per gallon (normally around $2). And a lot of people got really cold and mad.

1/8 of MidWest LPG demand is 1 MM TPA NH3. Even at $500 per tonne, ammonia BTUs are 20% cheaper than $4/gal LPG.

If ammonia diesel gens were sited on farms and neighborhoods, they would produce well-conditioned power for local use and utility offtake at 45% efficiency. The units are also ideally suited for CHP (total efficiency up to 75% or so) which can be used for district heating and, very importantly, crop drying.

One other huge advantage is countercyclical infrastructure use. The ammonia infrastructure is weighted toward winter and spring (for planting) and the LPG infrastructure is weighted toward summer and fall (for crop drying and winter heating). The ammonia producers might be happy to have profitable smoothing of their storage and distribution.

CLEAN AIR TASK FORCE