Natural Gas Locomotives

A Case Study in Railroad Technology and Economics

Management Essentials for the Railroad Industry
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Why Are We Discussing Them?

Progressive Railroading, September 28, 2012

“CN to test natural gas-powered locomotives”

Wall Street Journal, March 6, 2013

“Railroad [BNSF] Tests Switch to Gas”

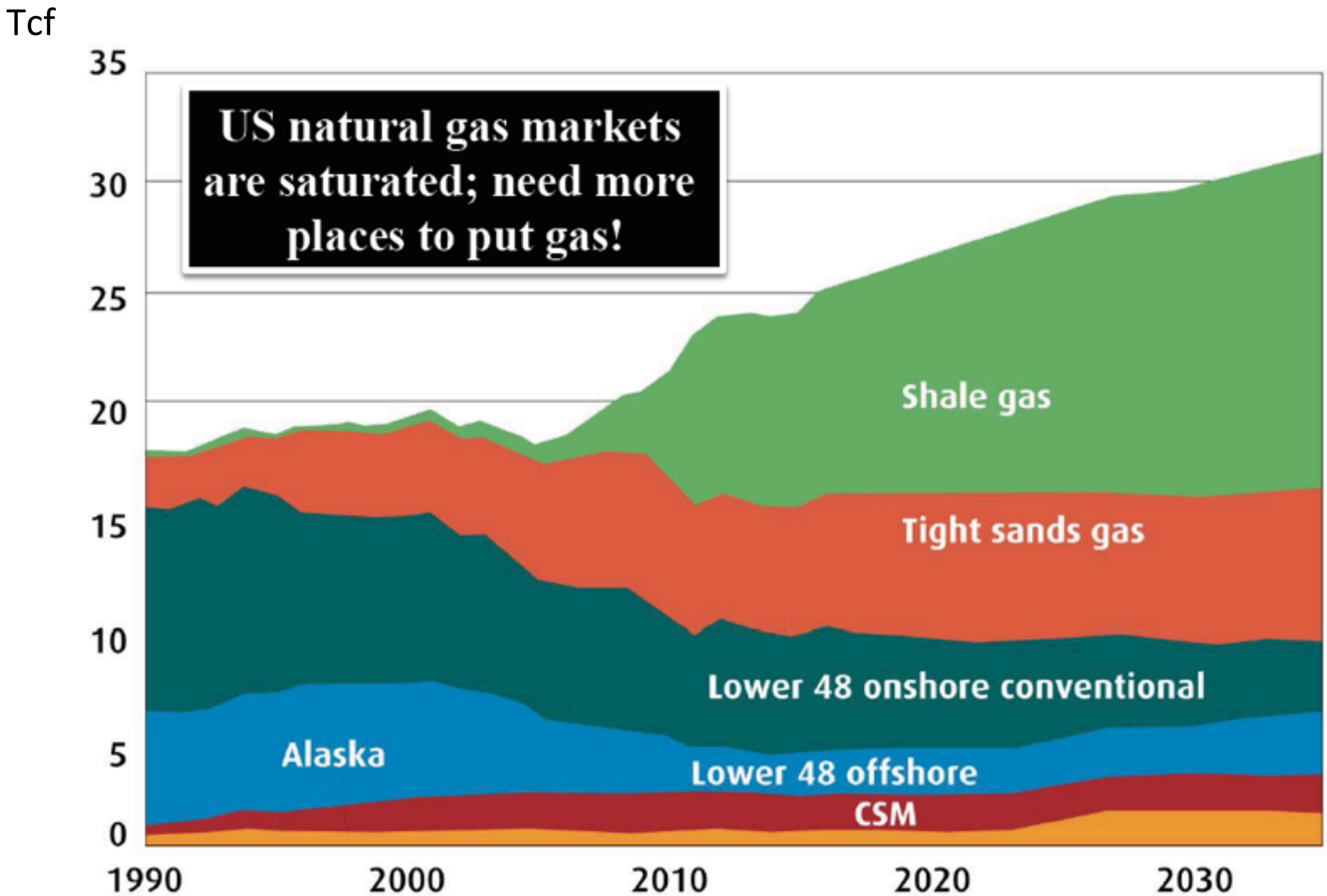
Financial Times, April 14, 2013

“US rail operators divided over LNG future”

Trains Magazine, June 2013

“Bigger than the switch from steam: Using natural gas as fuel means big up-front costs, but huge savings for railroads”

US Gas Production to 2035



Source: EIA, AEO 2013 Reference Case

Topics

- Properties of natural gas (methane) and related hydrocarbons
- Liquefied natural gas (LNG) vs. compressed natural gas (CNG)
- Availability and use of natural gas in the US
- How to haul LNG and CNG on trains – tender cars vs. belly tanks
- Locomotive engine issues – dual-fuel vs. spark ignited
- Equipping locomotives – road units vs. switchers
- Fueling station issues
- Natural gas locomotive demonstration programs
- Natural gas buses
- Safety and perceptions of safety
- Environmental attributes
- Order-of-magnitude costs for locomotives, tenders, and fueling stations
- Economics of natural gas vs. diesel fuel
- Related concepts to avoid
- Summary

Properties of Natural Gas

- NG primarily consists of methane, CH_4
- Methane is a colorless, odorless, tasteless, non-toxic gas
- An odorant (mercaptan) is often added as a safety measure so it can be detected
- Methane is lighter than air at room temperature and standard pressure (1 atm); it disperses
- Methane is flammable only over a narrow range of concentrations (5 to 15%) in air; it won't burn if the mixture is too lean or too rich
- $CH_4 + 2\ O_2 \rightarrow CO_2 + 2\ H_2O$
- Boiling point of methane is -161^{o} C; below that it is a cryogenic liquid known as LNG
- Liquid methane does not burn

Hydrocarbons Related to Methane

- **Methane (CH_4)** is the simplest molecule in the alkane family, whose members have the formula: C_nH_{2n+2}
- Natural Gas Liquids (NGL) – a/k/a Liquefied Petroleum Gas (LPG) – consist of **ethane (C_2H_6), propane (C_3H_8)**, and **butane (C_4H_{10})** and are derivatives of raw natural gas, extracted during gas refining; are liquid under pressure; at atmospheric pressure are gases heavier than air and do not disperse.
- Gasoline is a mixture of alkanes from **pentane (C_5H_{12})** up to about **decane ($C_{10}H_{22}$)**.
- Kerosene contains alkanes from about n=10 to n=16.
- Alkanes with higher values of n are found in diesel fuel, fuel oil, motor oils, crude oil, petroleum jelly, paraffin wax, and, for the highest values of n, asphalt.

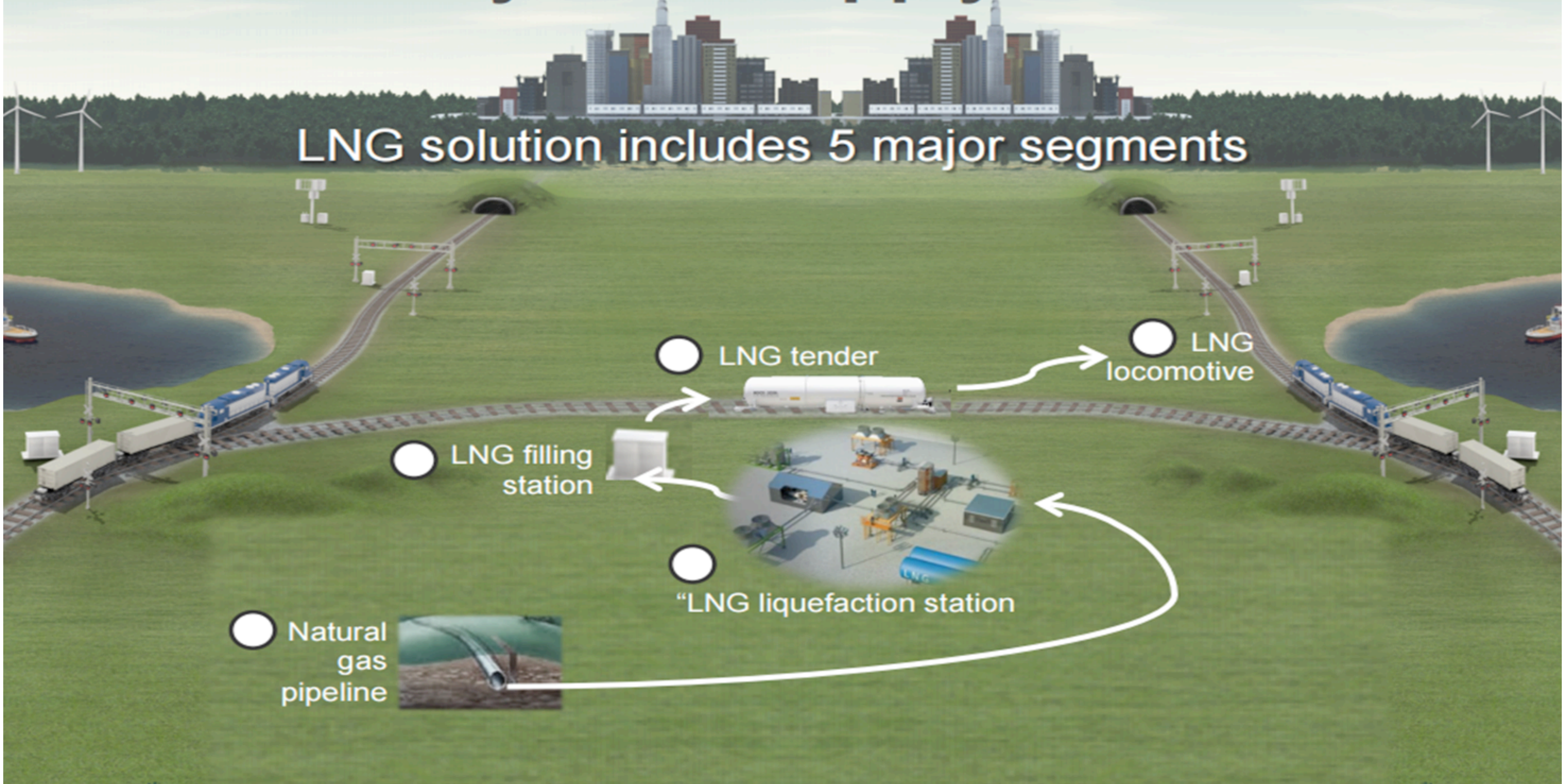
Availability and Use of Natural Gas in the US

- 200+ years supply of natural gas in the US
- 150,000 natural gas vehicles in the US and 5 million worldwide
- 50% of the households in the US use natural gas for heating and cooking
- In 2012, the US consumed approximately 25.46 trillion cubic feet (Tcf) of natural gas:
  - Electric power generation: 9.14 Tcf (36%)
  - Industrial: 7.10 Tcf (28%)
  - Residential: 4.18 Tcf (16%)
  - Commercial: 2.90 Tcf (11%)
  - NG lease and plant fuel consumption: 1.39 Tcf (5%)
  - Pipeline and distribution: 0.71 Tcf (3%)
  - Vehicle fuel: 0.03 Tcf (<1%)

Liquefied Natural Gas (LNG) vs. Compressed Natural Gas (CNG) vs. Diesel

	CNG (2400 psig)	LNG (1 atm)	Diesel (1 atm)
Energy content, BTU/gal (“energy density”)	19,760	76,300	138,400
Diesel gallon equivalents (DGE)	7	1.8	1

Rail industry LNG supply chain



How to Haul LNG and CNG on a Train

- Tank cars as tenders – preferred for road locomotives
  - LNG – Typically 20,000 gallon DOT-113 cryogenic (i.e., heavily insulated) tank car with center sill; carries equivalent of 11,800 gal of diesel fuel. Two options for moving the NG to the locomotive:
    - On-board heat exchanger to gasify the LNG to a pressure of 100 psig for transmission to the locomotive
    - Cryogenic pump to move LNG at 3600 psig to the locomotive
  - CNG – Heavy duty flat car with center sill, carrying 90 ft^3 steel cylinders; 17 cylinders would carry 1530 ft^3 of CNG at 2400 psig, equivalent to 2380 gal of diesel fuel.
- Belly tanks – preferred for switching locomotives
  - Can carry LNG or CNG in lesser amounts
- Intermodal flat cars with ISO containers carrying LNG

Locomotive Engine Issues

Railroad locomotives have two different types of engines:

- **Four-stroke cycle engines**, manufactured by General Electric and Caterpillar
- **Two-stroke cycle engines**, manufactured by Progress Rail (formerly Electro-Motive Diesel), a division of Caterpillar

There are different approaches to having these two types of engines run on natural gas.

Locomotive Engine Issues (cont'd)

Four principal types of natural gas-fueled diesel engines:

- **Low-pressure** (100 psig), **early-cycle direct injection** of NG into the cylinders, **pilot injection of diesel fuel** for ignition; 2-stroke cycle engines *
- **Low-pressure** (100 psig), **early-cycle direct injection** of NG into the cylinders, **spark ignition**; 4-stroke cycle engines
- **Low-pressure** (100 psig) injection of NG into the inlet air before it reaches the cylinder; **pilot injection of diesel fuel** for ignition; 4-stroke cycle engines *
- **High-pressure** (3600 psig), **late-cycle direct injection** of LNG into the cylinders, **pilot injection of diesel fuel** for ignition; 2 or 4-stroke cycle engines *

* Engines with pilot injection of diesel fuel can also run on straight diesel fuel

Locomotive Engine Issues (cont'd)

- To prevent pre-ignition of NG ("knocking") in the cylinders, there are two approaches:
  - Derate the engine by reducing the compression ratio – accomplished with new pistons and/or cylinder heads
  - Cool the inlet air into the cylinders
- Some NG engines for use in gas field pumping stations are purposely derated so they can burn "field gas" containing heavier hydrocarbons.
- Engine oil of NG locos has fewer contaminants, reducing wear of piston rings, liners, and valves, but special lube oil is needed; cuts consumption of repair parts and reduces costs.
- Suppliers of engine spare parts are not pleased.

Locomotive Engine Issues (cont'd)

- Dual-fuel conversion kits include:
  - Natural gas injectors, either for gaseous NG or for LNG
  - New cylinder heads to accommodate the injectors in two-stroke cycle engines
  - For four-stroke cycle engines, NG is inserted into the inlet air stream
  - New pistons with an altered shape to provide better "swirl" for complete combustion
  - Electronic controller for the fuel injectors
  - Modified coolant cycle piping and radiators
  - Conversion kits are available for spark-ignited as well as compression-ignited engines
- Two-stroke cycle engines easier to convert than four-stroke cycle engines – they have more space around the cylinder heads for injector installation

Equipping Locomotives – Road Units vs. Switchers

- The more low-cost NG that a locomotive burns, rather than high-cost diesel fuel, the more attractive the use of natural gas becomes.
- Road locomotives consume a great amount of fuel, and the economic case for converting them to natural gas is strong.
- If utilization rates of road locomotives can be increased, it improves the economic case for converting them to natural gas.
- Switcher locomotives do not consume much fuel, so the economic case for running them on NG is not strong.
- NG switcher locomotives, though, can help railroads meet strict air quality standards in urban areas.

Fueling Station Issues

- For demonstration programs, a fueling station needs storage tanks and pumps for trucked-in LNG.
- For large-scale programs, LNG liquefaction plants with storage tanks would be built where NG pipelines are in close proximity to rail lines.
- Such liquefaction/fueling stations are expensive and only a limited number would be built on high-density corridors (and not everywhere there currently is a diesel fueling station).
- For CNG fueling stations, a compressor with CNG pressurized storage tanks is needed.

Fueling Station Issues (cont'd)

- Tender cars loaded at a fueling station can be swapped out with empty tender cars on arriving trains; no waiting while tender cars are filled.
- Because railroaders have no knowledge of how to deal with NG and LNG, it is best to have fueling stations built and operated by firms that produce industrial gases and cryogenic liquids, e.g. Air Products & Chemicals, Air Liquide, BOC, Koch Industries, Linde, Shell.
- LNG is nearly pure methane; heavier hydrocarbons separate off during the liquefaction process and can be used to fuel the liquefaction plant.

NG Loco Demo Program
Burlington Northern Railroad 1982 - 1987

NG Loco Demo Program
Burlington Northern Railroad 1982 - 1987 (cont'd)

- This was a proof-of-concept program; loco and tender operated in revenue service between Minneapolis and Superior, WI 1985 through 1987. Project partners were Northern States Power, Northern Natural Resources, and Northern Natural Gas.
- EMD early-cycle low-pressure gas conversion kit (made for field engines) was applied to an EMD 567 engine in an EMD GP-9 locomotive; involved addition of a cam shaft to actuate the NG injectors; a new cam shaft would be needed to alter timing of injection. The engine was derated.
- A highway CNG trailer was mounted on a conventional flat car; fed one locomotive. FRA required the trailer hitch on the flat car to be rigid, not collapsible.
- Success led to next program with larger locos, electronic fuel injection (EFI), and LNG tenders.

NG Loco Demo Program
Burlington Northern Railroad 1988 - 1995

NG Loco Demo Program
Burlington Northern Railroad 1988 - 1995 (cont'd)

- Two SD40-2 locomotives with EMD 645 engines were converted to run on NG with low-pressure early-cycle injection kits from Energy Conversions, Inc. (ECI). These were the first diesel locomotives anywhere with EFI; made it easy to change injection timing.
- Achieved full rated horsepower with an innovative heat transfer system: it moved warmed ethylene glycol from engine to tender car to gasify the LNG so the NG could move to the engine as a gas at 100 psi; the cooled ethylene glycol was then moved back to the engine aftercooler where it was used to cool the inlet air entering the cylinders, thus preventing engine "knock."
- Engine ran on diesel fuel when idling and notches 1 & 2; NG injection initiated at notch 3, and, by notch 8, 95% of the energy was provided by NG and 5% by diesel fuel.

NG Loco Demo Program
Burlington Northern Railroad 1988 – 1995 (cont'd)

- A tender car (DOT-113 cryogenic tank car) fed two locomotives simultaneously and held sufficient LNG for a complete 1800 mile round-trip from fueling station to coal mine to power plant or port and return.
- Tender cars had a center sill to withstand buff and draft forces and had frame-braced trucks for stability (a BN decision).
- TTC tested LNG tender car insulation for BN, and analyzed in-train stresses on the LNG tender car using the TOES model.
- Locomotives were equipped with health-monitoring system and data radios for real-time on-board monitoring.
- Locomotives underwent 500 hours of stationary testing before over-the-road service began.
- Revenue service first on local trains on Olympic Peninsula in Washington, then on unit coal trains for four years (1991-1995) between Wyoming and northern Minnesota and Wisconsin.

NG Loco Demo Program
Burlington Northern Railroad 1988 - 1995 (cont'd)

- Locomotives were equipped with methane gas detectors; they would shut off the gas at the tender and on the loco, and the loco would automatically switch to diesel fuel.
- Gas lines between tenders and locos had air-operated, spring-loaded-return safety shut-off valves.
- Tender cars and fueling station (at Staples, MN where LNG was trucked in) supplied by Air Products & Chemicals, Inc.; BN spent about $10 million on the overall project.
- Was given AAR's "Outstanding Technical Achievement Award for 1992."
- Locomotive crews and maintainers, union officials, communities, and Congressmen became advocates.

NG Loco Demo Program
Union Pacific and Santa Fe/BNSF in LA Basin
1993 - 2013

NG Loco Demo Program
Union Pacific and Santa Fe/BNSF in LA Basin
1993 - 2013 (cont'd)

- Four Morrison-Knudsen 1200G switcher locomotives equipped with Caterpillar 3516G spark-ignited gas engines; two leased to UP and two to ATSF, went into service in 1995.
- Diesel version of Cat 3516 engine rated at 2000 HP; gas version at 1200 HP.
- LNG carried in belly tanks; gasified on-board for direct injection into cylinders; LNG was trucked in to fueling station.
- Program demonstrated reduced emissions in the LA Basin; locos retired after 20 years of service.
- Because they did not consume much fuel, there was an issue of boiling off and venting of methane.

NG Loco Demo Program
Union Pacific 1992 - 1995

NG Loco Demo Program
Union Pacific 1992 - 1995 (cont'd)

- UP undertook a program with GE and EMD to look into high-pressure (3600 psig) late-cycle injection of LNG into engine cylinders with pilot injection of diesel fuel.
- Photo shows a GE C41-8W locomotive and a tender (DOT-113 tank car) equipped with cryogenic pumps.
- LNG carried at 3600 psi from tender car to locomotive to engine cylinders.
- Limited stationary testing at the two locomotive builders (5 hours at GE), and the locomotives never entered revenue service.

NG Loco Demo Program
Napa Valley Wine Train 1999 - present

NG Loco Demo Program
Napa Valley Wine Train 1999 - present (cont'd)

- Alco FPA-4 with EMD 645 12-cylinder engine; originally equipped in 1999 with ECI dual-fuel conversion kit, 60% NG and 40% diesel.

- Further conversion to 100% NG in 2003.

- CNG is carried in on-board tanks.

- In continuous operation ever since.

NG Loco Demo Program
Brazil 2010 - present

NG Loco Demo Program
Brazil 2010 - present (cont'd)

- Three GE Dash-9 locomotives with 7FDL16–EFI engines converted in 2010-2011 with ECI dual-fuel kits to inject NG into inlet air; NG replaces 50% of diesel fuel.

- Engines derated from 4400 HP to 4000 HP.

- Operate on Vitoria-Minas Railroad (EFVM), in southeast Brazil – an iron ore heavy haul line.

- Tender car in photo is a prototype; conventional cryogenic tank cars have since been built.

NG Loco Demo Program
Russia 1990 - 1994

NG Loco Demo Program

Russia 1990 – 1994 (cont'd)

- Locomotive was manufactured at Luhanskteplovoz in Luhansk, Ukraine, working with the All-Soviet (now All-Russian) Railroad Research Institute in Shcherbinka (Moscow), Russia.
- Engine was a 3000 HP two-stroke cycle opposed-piston Fairbanks Morse engine, manufactured in Kolomna, Russia, with an FM dual-fuel gas conversion kit.
- Tender car had two 4-foot diameter LNG cylinders stacked vertically within a carbody that had an internal walkway; contained 17 metric tons of LNG for a range of 500 miles for 2 locomotives; pneumatic gas sensors; LNG gasified on-board.
- No over-the-road testing.

NG Loco Demo Program
Russia 1990 - 2002+

Рис. 1. *Маневровый газотепловоз ТЭМ18Г-002 на Экспериментальном кольце ВНИИЖТ (г. Щербинка)*

NG Loco Demo Program
Russia 1990-2002+ (cont'd)

- Switcher locomotive manufactured at Luhansk, Ukraine, and tested at the Railroad Research Institute at Shcherbinka, near Moscow.
- Engine was a 1200 HP, 6 cylinder four-stroke cycle dual-fuel engine manufactured by Kolomna and similar to an Alco 251 engine.
- CNG contained in belly tanks, enough for three days of operation.
- Planned for service in Moscow area.

NG Loco Demo Program Canadian National 2012 -

NG Loco Demo Program
Canadian National 2012 - (cont'd)

- CN program initially used the same technology as the BN NG locomotive demo program of 20 years earlier (i.e., EMD SD40-2 locomotives, ECI dual-fuel low-pressure injection conversion kits, revised coolant cycle).
- Was in revenue service between Edmonton and Fort McMurray, Alberta, until autumn of 2013
- Top photo shows tender car borrowed from the UP. Future tender cars will be intermodal well cars with ISO containers holding LNG; one tender car will fuel two locomotives.
- CN took delivery of two EMD SD70-M locos with High-Pressure Direct Injection (HPDI) engines modified by Westport and a well-car tender in autumn 2014.

NG Loco Demo Program

BNSF 2013 -

DOT-113 Tender

Well-car Tender

NG Loco Demo Program
BNSF 2013 - (cont'd)

- BNSF is working with both GE and EMD on dual-fuel natural gas locomotives.
- Two EMD SD70ACe locomotives have undergone testing at TTC in Pueblo with a refurbished DOT-113 tender car from the 1990s demonstration program, and, with FRA permission, are in over-the-road local service out of Barstow, CA.
- Two GE ES44AC locomotives with another refurbished DOT-113 tender car are underwent emissions testing at SwRI in San Antonio, TX before heading to Barstow.
- BNSF has also built four well-car tenders with smaller tanks
- Ultimately plan to use the LNG locomotives on corridors that have high burn rates.

NG Loco Demo Program

CSX 2013 -

NG Loco Demo Program
CSX 2013 - (cont'd)

- CSX worked with GE on a NextFuel NG retrofit kit for dual-fuel (LNG and diesel) capability. Estimating up to 80% gas substitution, and potential reduction of fuel cost by 50%.
- Also working out technical and regulatory details with tender-car vendors, fuel suppliers, and FRA.
- Testing began early 2015.
- GE ad: "This is going to be something that is going to change the industry like going from steam to diesel."

NG Loco Demo Program
Florida East Coast 2014 -

NG Loco Demo Program
Florida East Coast 2014 - (cont'd)

- FEC took delivery in 2014 of 4 GE ES44C4s with NextFuel LNG kits installed (like the CSX units).
- Testing took place between Jacksonville and New Smyrna Beach, FL.
- LNG initially trucked in from Georgia, but plans are to build LNG terminal in Jacksonville, capable of producing 300,000 gallons daily.

NG Loco Demo Program
Norfolk Southern 2013 -

NG Loco Demo Program
Norfolk Southern 2013- (cont'd)

- NS converted an EMD GP38-2 locomotive with a 645E engine into a 100% CNG-powered locomotive at its Juniata, PA shop.
- Used a spark-ignition conversion kit supplied by Energy Conversions, Inc. (ECI). A spark plug was fit in a "pre-chamber" in place of the diesel injector in each cylinder.
- The project includes a slug which doubles as a tender. The slug has eight steel CNG tanks that together hold 1,000 DGEs – diesel gallon equivalents

NG Loco Demo Program
Union Pacific 2013 -

- UP is "working closely with loco and engine manufacturers, cryogenic fuel-tank suppliers and natural gas/LNG suppliers."
- "Safe, reliable and cost-effective locomotive engines that could be fueled by LNG have not yet been developed."
- "Locomotive engine performance, including fuel efficiency and emissions, has not been thoroughly evaluated."
- "A locomotive still needs to be modified and a tender still needs to be set up."
- "UP is planning to test LNG as a fuel source for locomotives in early 2015."
- Has reclaimed its tender cars lent to the CN.

NG Loco Demo Program
Canadian Pacific 2014 -

- Apparently converting two SD40-2s to run on CNG at St. Paul, MN shops
- Remaining tight-lipped about other aspects of its program

NG Loco Demo Program
Russia 2014 –

NG Loco Demo Program
Russia 2014 – (cont'd)

- Switcher locomotive manufactured at Bryansk, and tested in the Sverdlovsk region
- TEM19 locomotive has on-board LNG tank.
- Was designed by the Russian Institute of Research, Design, and Technical Studies

Natural Gas Buses

Natural Gas Buses (cont'd)

- Many thousands of CNG buses are now in service in the US.
- CNG is carried in tanks on roofs under the metal shields.
- Many of the buses are built by New Flyer Industries, Inc. of Winnipeg, Manitoba, and have Cummins Westport CNG spark-ignited engines.
- CNG buses are refueled daily or more frequently.

Early Natural Gas Bus in Chongquing, China

Safety of Natural Gas

- Natural gas is quite safe; we use it to cook our food and heat our homes.
- Methane is flammable only over a narrow range of concentrations (5 to 15%) in air if there is an ignition source; if unconstrained, it will burn; if in a constrained space, it will explode.
- There are no specific FRA safety regulations at present regarding the use of NG as a locomotive fuel. The pending Grow America Act would have FRA issue safety regulations for NG locomotives.
- FRA requires that hazardous materials being hauled in commerce be placed at least a car length behind the loco; no such requirement exists for loco fuels.

Safety of Natural Gas (cont'd)

- Nevertheless, FRA is concerned with all safety matters, and wants gas detectors on locos and tenders to detect leaks and valves to shut down the flow of NG if there is a leak. FRA also reportedly concerned about use of intermodal well cars with ISO containers as tender cars.
- In 1990, BN Railroad contracted with Los Alamos National Laboratory for a "Safety Analysis of Alternative Locomotive Fuels".
- As expected, the analysis showed that diesel fuel was the safest locomotive fuel, followed by LNG, CNG, and methanol, with LPG (propane) being the most hazardous.

Perceptions of Safety

- Most people have heard of houses that have exploded due to leaking natural gas.
- People confuse NG (methane) with LPG (a/k/a NGL – propane and butane).
- Memories persist of LNG from ruptured tank running into sewers in Cleveland in 1944, followed by fires and 150 deaths.
- To address adverse perceptions of safety of NG, education and training of train crews, maintenance shop personnel, fueling station staff, communities, and first responders is absolutely necessary.
- Probably best to not use LNG fuel tenders on passenger trains.

Environmental Attributes

- NG emits 27% less CO_2 than diesel fuel per unit of energy consumed.
- There is no sulfur in NG; no oxides of sulfur (SO_x) are produced when burning NG.
  - Most of the sulfur has been removed for diesel fuel now being delivered to railroads.
- Heat of combustion is less with NG than with diesel fuel; therefore less oxides of nitrogen (NO_x) are produced.
- Methane itself is a greenhouse gas (GHG); complete combustion is important and leakage must be prevented.

Order-of-Magnitude Costs for LNG Locomotives and Tenders

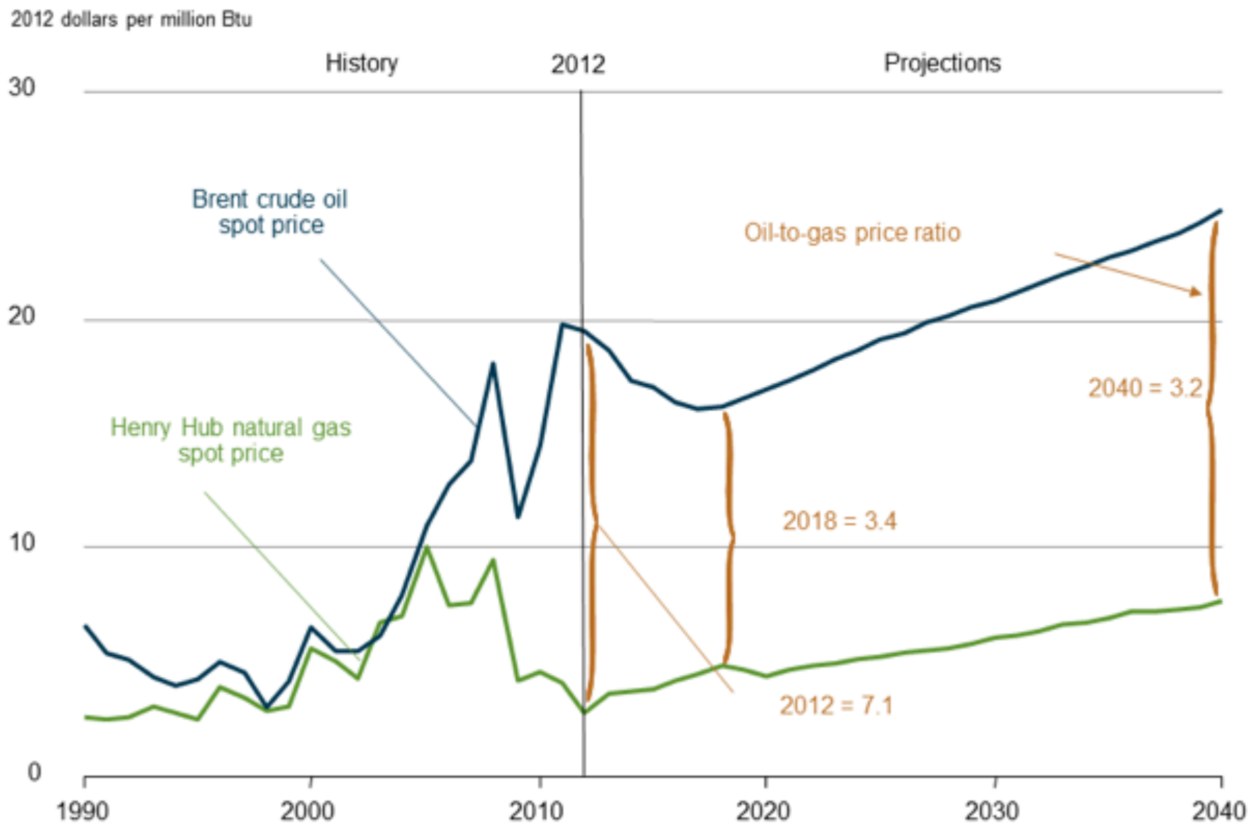
- Installed LNG dual-fuel conversion kits cost on the order of $500,000.
- LNG tender cars cost on the order of $1 million.
- Therefore, approximate cost for two converted locomotives plus tender car is $2 million.
- New locos with spark-ignited engines carry a premium of about $1 million.
- Costs need to be confirmed by talking with vendors; larger orders will reduce costs.

Order-of-Magnitude Costs for LNG Fueling Stations

- LNG fueling stations with tanks to hold trucked-in LNG cost on the order of millions of dollars.
- Combined LNG liquefaction plant and fueling station costs on the order of hundreds of millions of dollars.
- Energy to run LNG liquefaction plant can come from heavier hydrocarbons that separate off during the methane liquefaction process.
- Companies that build and operate LNG liquefaction plants could be willing to do that and charge railroads fully allocated cost of liquefying pipeline NG.
- Costs need to be confirmed by talking with vendors.

Economics of Natural Gas vs. Diesel Fuel

Figure IF3-1. Comparison of spot prices for Brent crude oil and Henry Hub natural gas, 1990-2040

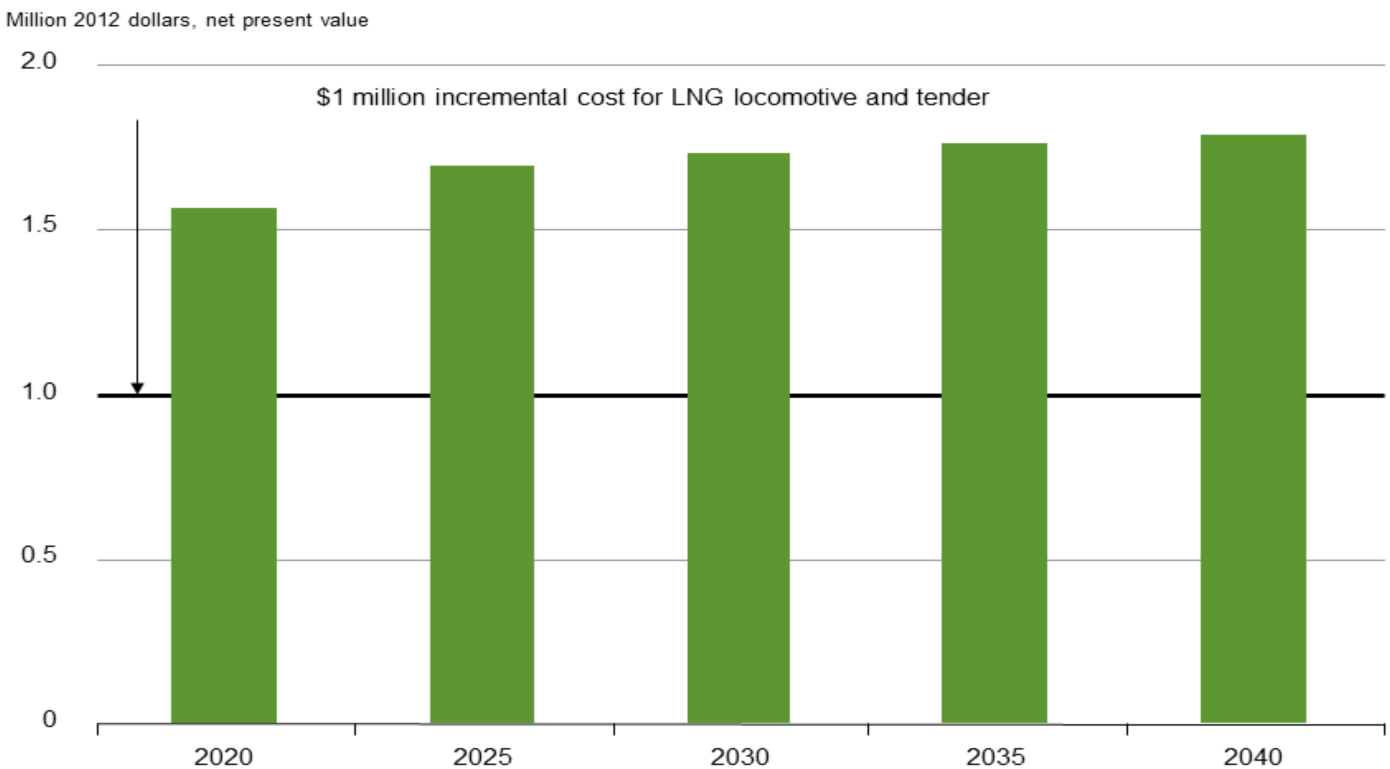


"Given the difference between LNG and diesel fuel prices, railroads that switch locomotive fuels could accrue significant fuel cost savings."

Source: Nicholas Chase, "*Potential of liquefied natural gas use as a railroad fuel,*" Energy Information Administration, US Department of Energy, April 14, 2014

Economics of Natural Gas vs. Diesel Fuel (cont'd)

Figure IF3-3. Discounted fuel cost savings for a new locomotive and tender using liquefied natural gas as a fuel compared to diesel, 2020-40

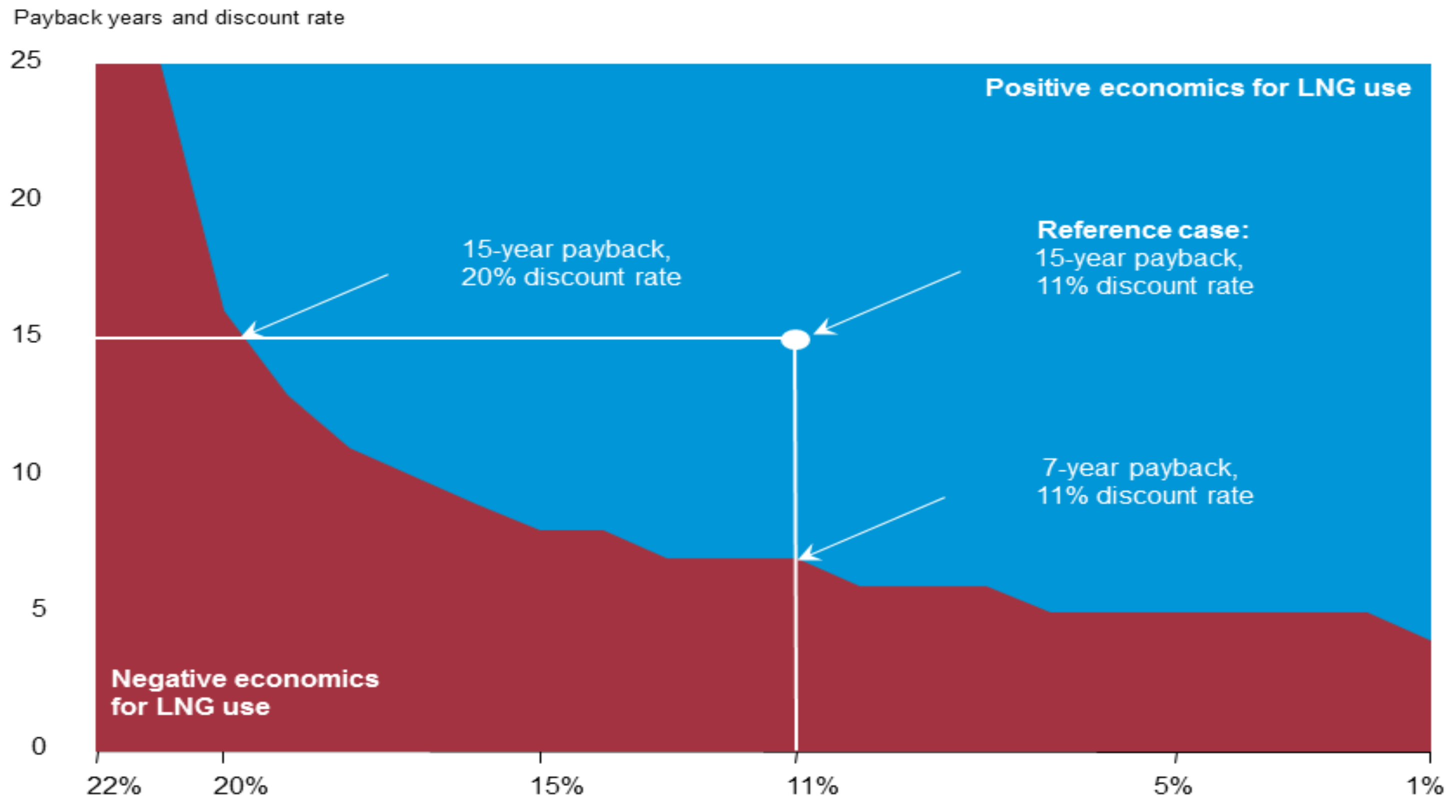


"The net present value of future fuel savings for an LNG locomotive compared to a diesel counterpart is well above the $1 million higher cost of the LNG locomotive and tender."

Source: Nicholas Chase, "*Potential of liquefied natural gas use as a railroad fuel,*" Energy Information Administration, US Department of Energy, April 14, 2014

Economics of Natural Gas vs. Diesel Fuel (cont'd)

Figure IF3-4. Net present value calculation for locomotives using liquefied natural gas at Reference case fuel prices

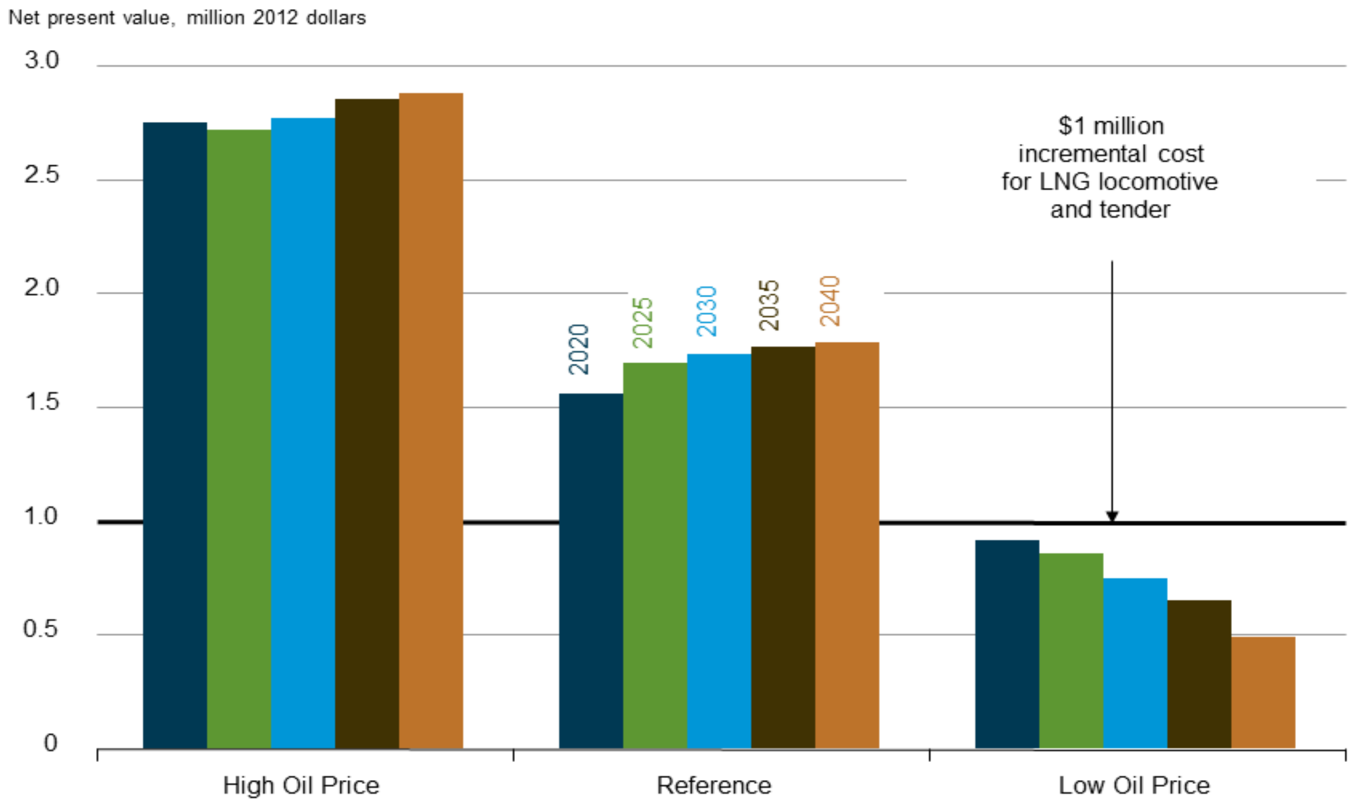


"Relatively large changes in payback period, discount rate, or fuel prices would be required to change LNG fuel economics for railroad use from favorable to unfavorable."

Source: Nicholas Chase, "*Potential of liquefied natural gas use as a railroad fuel,*" Energy Information Administration, US Department of Energy, April 14, 2014

Economics of Natural Gas vs. Diesel Fuel (cont'd)

Figure IF3-5. Discounted average fuel cost savings for a new locomotive and tender using liquefied natural gas as a fuel compared to diesel in three cases, 2020-40



"Uncertainty about future fuel prices suggests that there is some risk for companies in making such a fundamental change in freight rail operations."

Source: Nicholas Chase, "*Potential of liquefied natural gas use as a railroad fuel,*" Energy Information Administration, US Department of Energy, April 14, 2014

Related Concepts to Avoid

- **Propane**
  - Heavier than air; explosive
  - More expensive than LNG per unit of energy
  - Not available domestically in large quantities
- **Turbine engines**
  - More expensive than diesel engines per unit of horsepower
  - Use almost as much fuel when idling as at full power
  - Not really suitable for railroad applications; they like to run at constant speed and they like cold inlet air
- **Hydrogen**
  - H_2 is the smallest molecule; requires precision "plumbing" on locomotive
  - Unlike methane, it does not exist naturally on earth; requires more energy to produce it than can be obtained from it as a fuel
  - Possibly attractive when surplus hydro, nuclear, and geothermal energy is available to produce the hydrogen from methane

Summary

- The implementation of natural gas locomotives requires "systems thinking."
- The economics of natural gas as a loco fuel are attractive now, but only on specific routes.
- Railroads might mitigate the effects of future price fluctuations with long term NG contracts.
- The technology works.
- It reduces GHG emissions.
- Education of railroad workers, customers, and communities must take place.
- On BN, the train crews, union reps, locomotive maintainers, communities, and even Congressmen became advocates of natural gas as a locomotive fuel.

Questions?

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