# Decarbonization
# &
# Increased Energy Efficiency:

# The Dual Challenge for Railroads

Michael Iden, P.E.

TIER 5 LOCOMOTIVE LLC
Established 2013

# Topics

DECARBONIZATION (GLOBAL PERSPECTIVE)

RAILROADS & ENERGY:  WHERE WE'VE BEEN; WHAT'S AHEAD?

SEEING WHAT'S NEXT (?) TO DECARBONIZE RAILROADS

PROPULSION, ENERGY & INFRASTRUCTURE ALTERNATIVES

CLOSING THOUGHTS

RECOMMENDATIONS

MANAGERS MISCONCEPTIONS ABOUT TECHNOLOGY

# Key definitions

| | | |
|---|---|---|
| Decarbonization: | reduction of carbon dioxide ($CO_2$) | |
| Energy: | capacity for doing work | [kw-hr or hp-hr] |
| Efficiency: | ratio of useful work to the total energy expended | |
| (Mechanical) Power: | time derivative of work | (kw or hp] |
| Work: | force applied to an object physically moved through a distance | [kw-hr or hp-hr] |

# Decarbonization

"Big breakthroughs happen when what is suddenly possible meets what is desperately needed"

Thomas Friedman

https://www.nasa.gov/multimedia/imagegallery/image_feature_1249.html

# Various plans to address the challenge


https://netzeroamerica.princeton.edu/about (365-page report is available)

"Building a net-zero America will require immediate, large-scale mobilization of capital, policy and societal commitment, including at least $2.5 trillion in additional capital investment into energy supply, industry, buildings, and vehicles over the next decade relative to business as usual … major investment decisions must start now, with levels of investments ramping up throughout the transition."

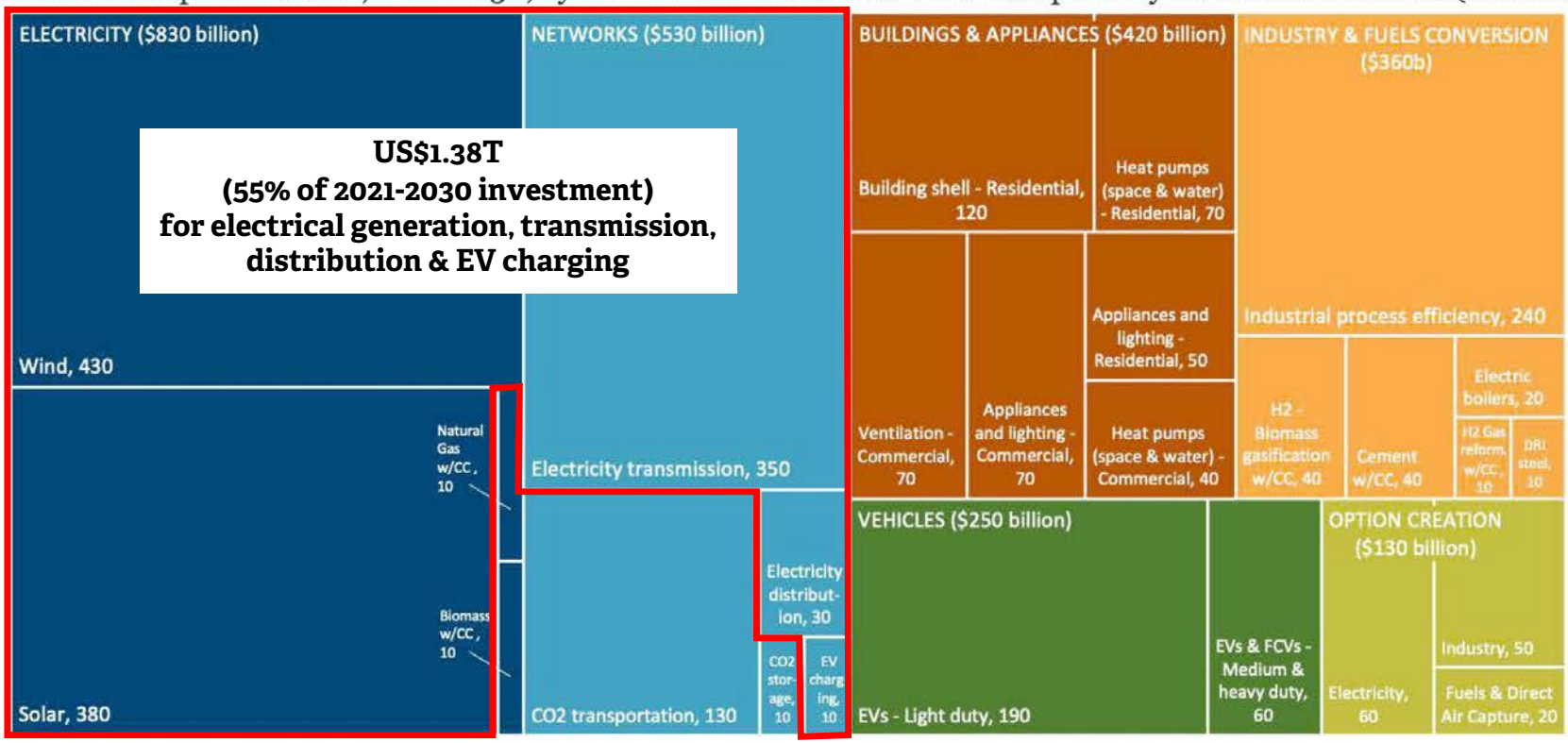
This plan includes <u>five</u> (5) different plan variations

# Net-Zero America: min. US$2.5T invested by 2030

## Executive summary (9/9)

## Added capital invested (vs. REF) in 2020s is at least $2.5T

Total additional capital invested, 2021-2030, by sector and subsector for a net-zero pathway vs. business as usual (billion 2018$)




Includes capital invested pre-financial investment decision (pre-FID) and capital committed to projects under construction in 2030 but in-service in later years.
All values rounded to nearest $10b and should be considered order of magnitude estimates. Incremental capital investment categories totaling less than $5B excluded from graphic.
**Other potentially significant capital expenditures *not* estimated** in this study include establishment of bioenergy crops and decarbonization measures in other industries besides steel and cement, non-$CO_2$ GHG mitigation efforts, and establishing enhanced land sinks.

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The New York Times

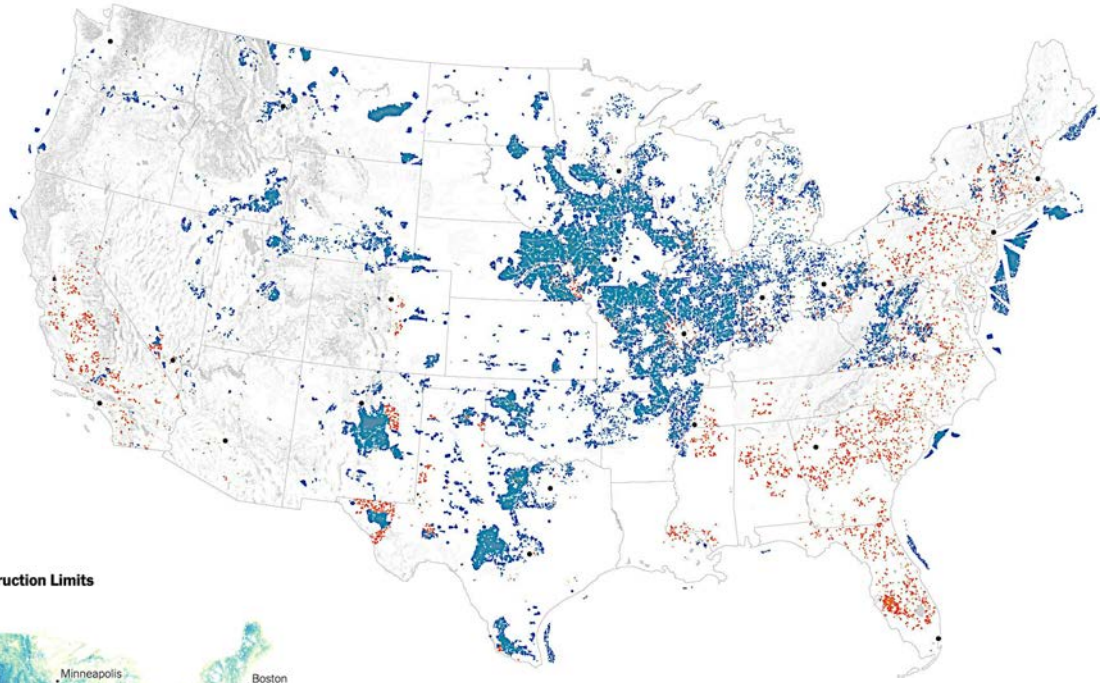
# Where Wind and Solar Power Need to Grow for America to Meet Its Goals

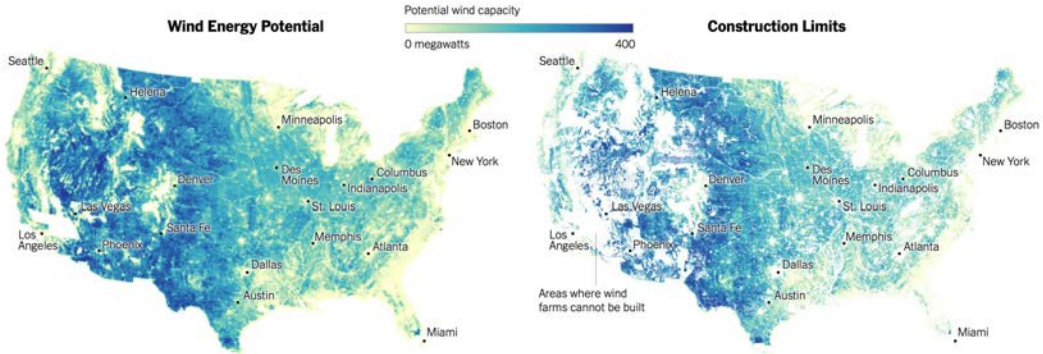
By Veronica Penney May 28, 2021

Wind & Solar generation needed by 2050 (re Princeton/Net-Zero America) >

Western states generally have more wind power potential but also more build issues in mountainous terrain (and will require longer HV transmission infrastructure to reach heaviest power demands).

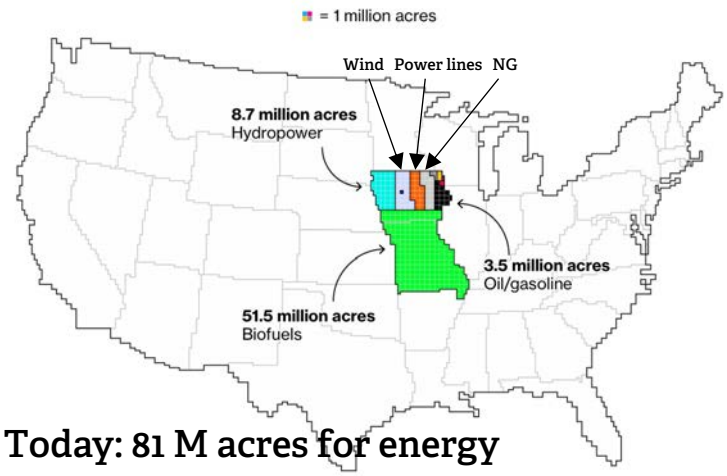
Midwestern states have lower wind power potential but also lower build constraints.



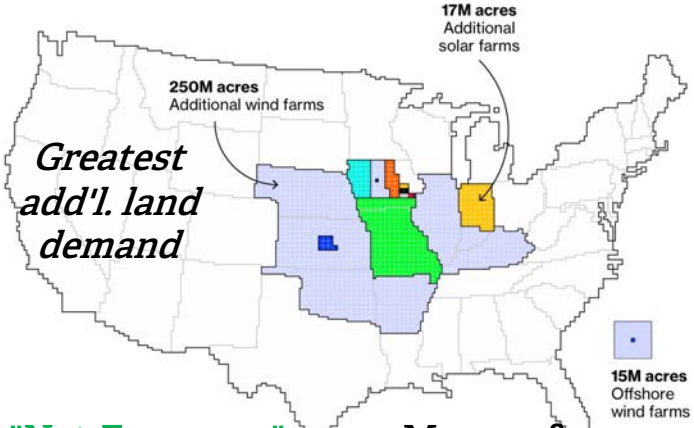



National Renewable Energy Laboratory reference access wind supply curve; Princeton's Net-Zero America Report - By: Veronica Penney/The New York Times

# Decarb. v land req'd (different plans)




Today: 81 M acres for energy



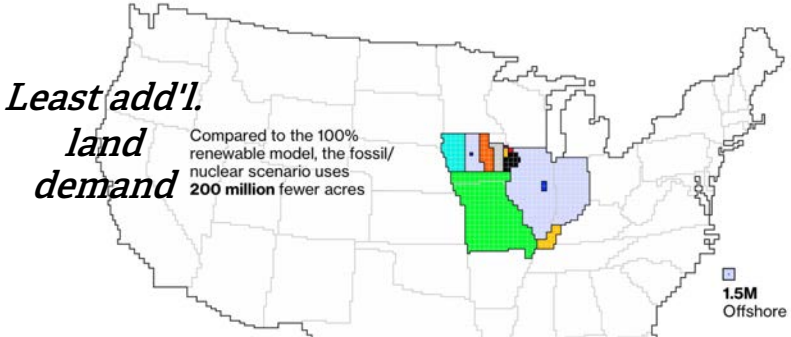

Princeton "Net-Zero 2050": >300 M acres for energy.
4x more electric generation. No fossil or nuclear generation.
Synthetic eFuels, H2 and storage batteries provide "peak power".

www.bloomberg.com/graphics/2021-energy-land-use-economy/

**The U.S. Will Need a Lot of Land for a Zero-Carbon Economy**

By Dave Merrill
Published: April 29, 2021 | Updated: May 2, 2021
*Updates to acknowledge an opposing perspective and related study.*

At his international climate summit last week, President Joe Biden vowed to cut U.S. greenhouse gas emissions in half by 2030. The goal will require sweeping changes in the power generation, transportation and manufacturing sectors. It will also require a tremendous amount of land.




Bloomberg Green alternative: 44% electricity from wind & solar, 50% from +250 nuclear plants and renewable NG turbines with CCS (Carbon Capture & Sequestration (TBD)).

# International maritime activity

**Mærsk Mc-Kinney Møller Center**
for Zero Carbon Shipping

PRESS RELEASE

Industry Partners join forces to assess the technical-, financial- and environmental potential of converting existing vessels to zero carbon fuels and -technology as part of the transition to a global zero carbon fleet by 2050.

*Copenhagen, 12 May 2021*

SHIPPING MATTERS

**U.S. Push for Carbon-Neutral Ships Expected to Reveal Industry Divisions**

The Biden administration is calling for drastic cuts in shipping emissions, but some developing nations may not be on board

May 5, 2021 https://www.wsj.com/articles/u-s-push-for-carbon-neutral-ships-expected-to-reveal-industry-divisions-11620207002?page=1

"… assess the technical, financial and environmental potential of converting existing vessels to zero carbon fuels and –technology … investigate retrofit possibilities for existing vessels enabling dual-fuel operation on either methanol or ammonia as well as conventional fuel oil …"

"… switch to non-carbon-based fuels would cost an estimated $3 trillion globally … 60,000 ocean vessels … Ships typically take two years or so to be delivered and remain in operation for around 25 years …"

THE WALL STREET JOURNAL. Michael Iden

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SHIPPING MATTERS

**Shipping's Carbon-Cutting Fuel Tanks So Far Remain Empty**

The industry faces a 2050 emissions-reduction target with choices yet to be made on what clean fuels to use

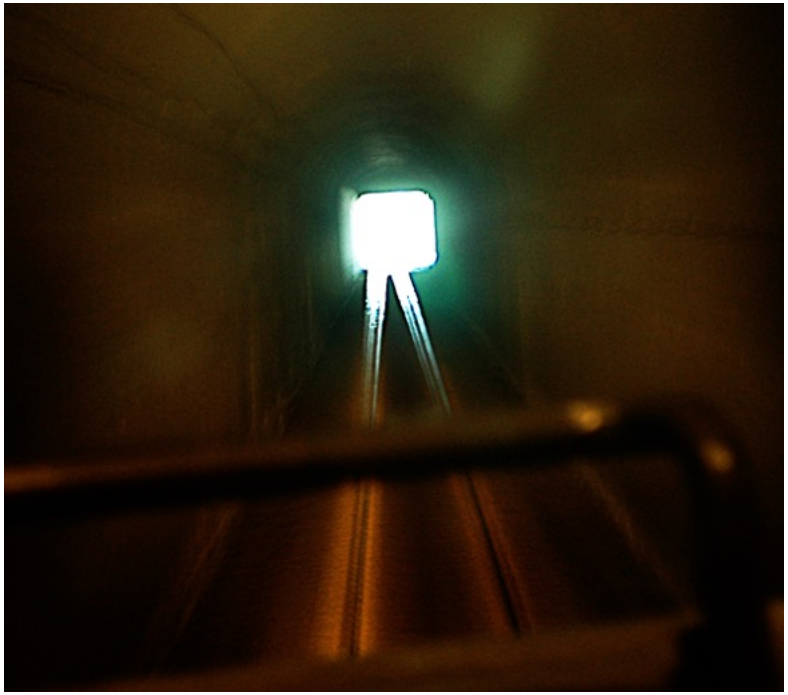
June 1, 2021 https://www.wsj.com/articles/shippings-carbon-cutting-fuel-tanks-so-far-remain-empty-11622109600

"We can build green vessels, but with no consensus on what kind of fuel will be used, the deadlines are just a theoretical exercise that can't be met," … "First you need the fuels, then the necessary volumes and a global bunkering network that will all have to come together at a competitive price. We're only at the start of a long and expensive process."

# Key points: various decarbonization plans

- Eliminate use of fossil fuels
- Convert electrical generation to renewable sources (wind & solar)
- Increase electrical generation to accommodate renewable's lower duty cycle
- Increase electrical transmission to "wheel" more power around nation
- Increase electrical distribution to electrify more fossil-fueled end uses
- Develop and install large-scale energy storage
- Enable manufacturing zero-carbon hydrogen ($H_2$)
- Enable production of eFuels ($H_2$ to synthetic liquids)
- Facilitate conversion of motor vehicles to $H_2$ fuel cells and batteries
- Improve energy efficiency of end uses
- For transportation: "vehicles" + "fuel/energy" + "infrastructure"
- Net-zero won't be simple, easy or "free"

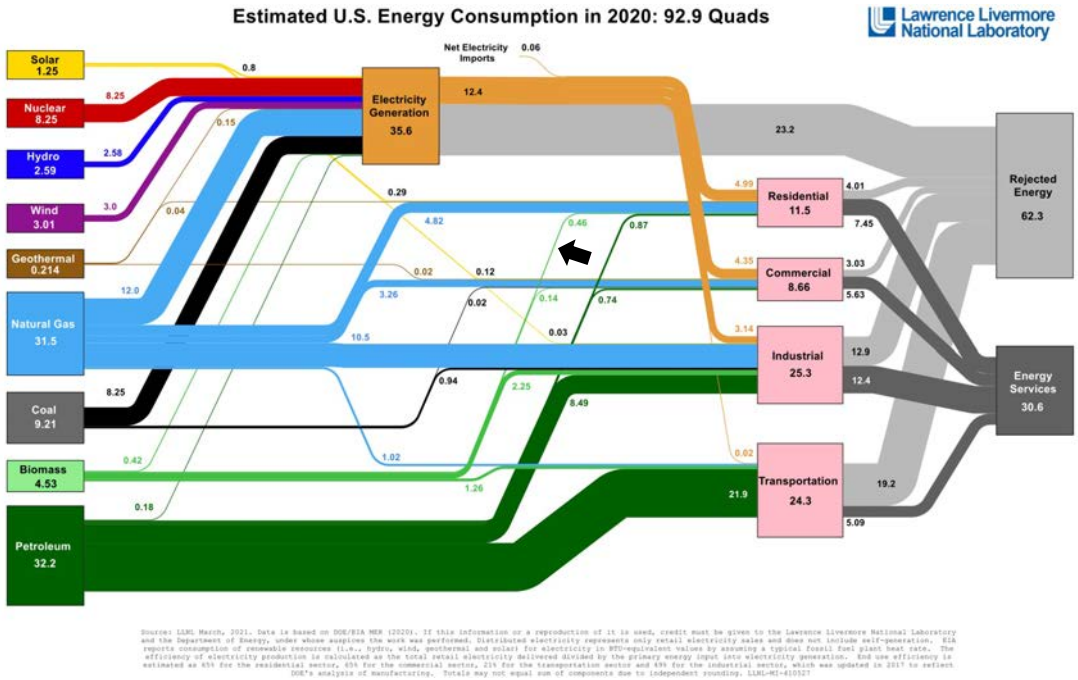
# RRs & energy: where we've been; what's ahead?



"It's tough to make predictions, especially about the future."

Yogi Berra, New York Yankees

# US (incl. US RR) energy use in 2020




https://www.llnl.gov/news/pandemic-drives-down-us-energy-use-2020

"*Rejected energy*"
(67% of all energy used)
= waste heat from inefficiencies

"*Energy services*"
energy converted into useful purpose
(heat, light, mfg, transportation, etc)

Transp. has greatest ineff. (79%)
primarily from gasoline cars

*1 quad = $10^{15}$ Btu or $1.055 \times 10^{18}$ Joules*

Total US energy use in 2020 = 92.7 quads = 667,510,796,683 US equiv. gallons of diesel fuel

US Class 1 RR fuel use in '20 = 0.47 quad = ~3.4 billion USG of diesel fuel

*US class 1 RRs consumed 0.5% of all US energy and 1.9% of US petroleum in 2020*

# Railroads: energy used & "fuel efficiency"

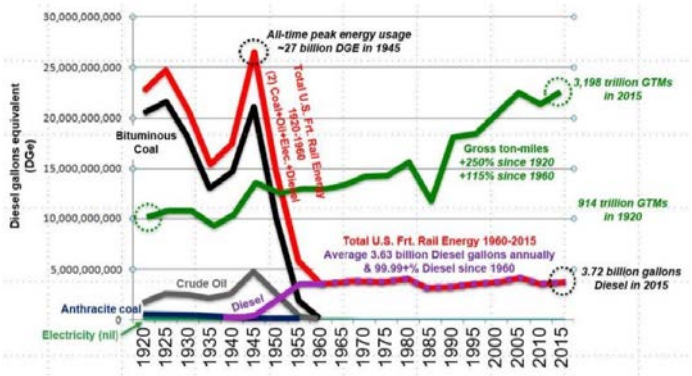



FIGURE 1. PLOT OF U.S. FREIGHT RAILROAD LOCOMOTIVE ENERGY CONSUMED (BY TYPE OF ENERGY) AND (TOTAL ESTIMATE DIESEL GALLONS EQUIVALENT BASIS).

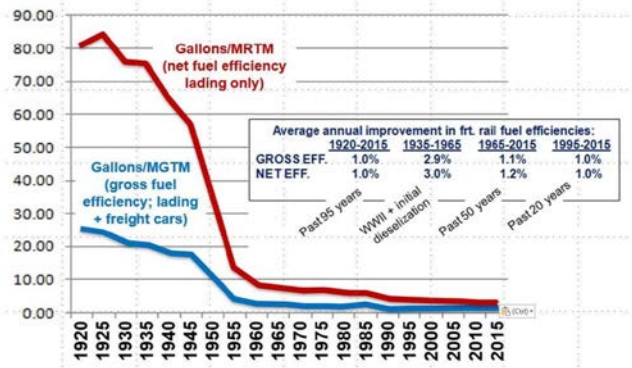
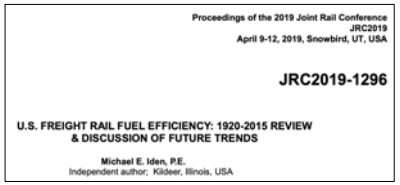



FIGURE 2. PLOT OF U.S. FREIGHT RAILROAD FUEL EFFICIENCY 1920-2015, BASED ON MOVEMENT OF FREIGHT LADING ONLY (REVENUE TON-MILES) AND ALSO MOVEMENT OF FREIGHT LADING-PLUS-FREIGHT CAR WEIGHT (GROSS TON-MILES).


Proceedings of the 2019 Joint Rail Conference
JRC2019
April 9-12, 2019, Snowbird, UT, USA

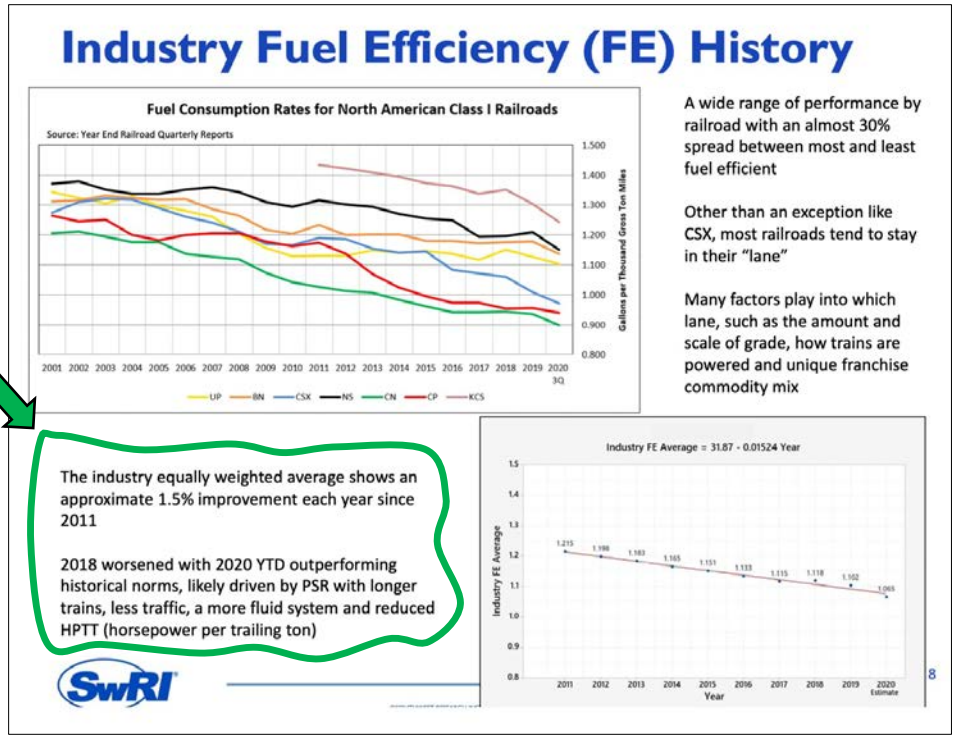
JRC2019-1296

U.S. FREIGHT RAIL FUEL EFFICIENCY: 1920-2015 REVIEW & DISCUSSION OF FUTURE TRENDS

Michael E. Iden, P.E.
Independent author; Kildeer, Illinois, USA

Dieselization 1940-1960 gave US RRs a one-time 700% improvement in $USG_{(equivalent)}$/MGTM due to gross inefficiencies of steam locomotives!

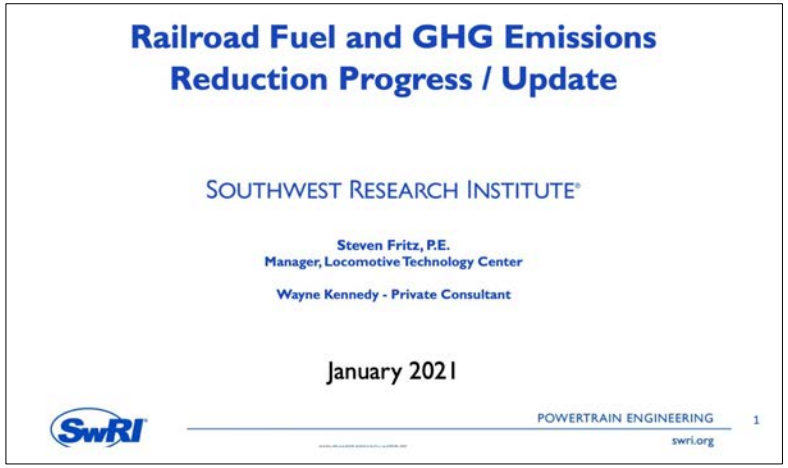
For past several decades, fuel eff. has been improving only modestly:

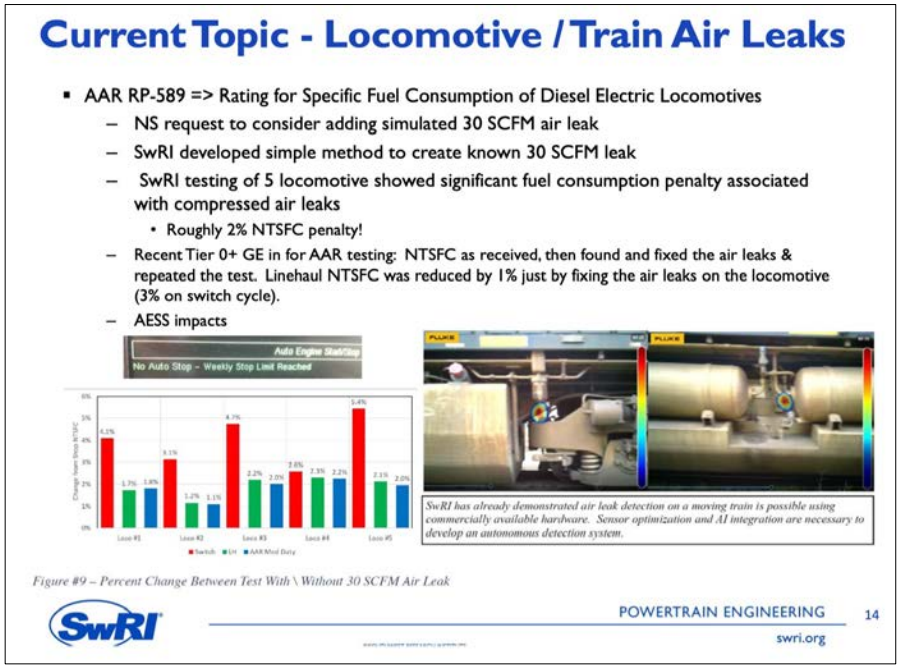


# RR energy efficiency improvements

Many potential improvements can (and should) be made <u>now</u>

Examples: eliminate air leaks on locomotives = estimated 2% NTSFC improvement
eliminate air leaks on entire train = even greater fuel savings




Get these efficiency improvements done as soon as possible!

# Alternative fuels: trade-offs

Carbon emissions

Criteria emissions (NOx, PM, etc)

Energy content (> work performed)

Commercial availability

Technical suitability

Cost

# Beware: HD truck energy eff. improvements

SuperTruck 1 2010-2016 US DOE & truck industry (50:50) $ 284 million
*(aerodynamics)*

SuperTruck 2 2017-2020 US DOE & truck industry (50:50) $ 160 million
*(engine/transmission eff., double MPG (5.5>10+) by '25-'30)*

*SuperTruck 3 2021- US DOE & truck industry (50:50) $ 200 million
*(electrification of HD trucks, FCs, batteries, refueling/charging)*

Total DOE-industry spending on Heavy Duty truck efficiency $ 644 million
**SuperTruck focus now shifting to zero-carbon*

Platooning (V2V control, close-gap at speed) ...
7-to-10% improvement in fuel efficiency by reducing aero drag

Autonomous trucks: 10% MPG improvement

*Driver in cab of autonomous truck passing through Champaign at 55 MPH watching this Hay Seminar to earn his PDH credits*

# Truck technology & competitiveness

Large fleets typically "refresh" tractor fleets every ~2 years

Rapidly evolving technologies

Impact on rail v truck competitiveness (energy eff., opex, transit times, customer relationships)

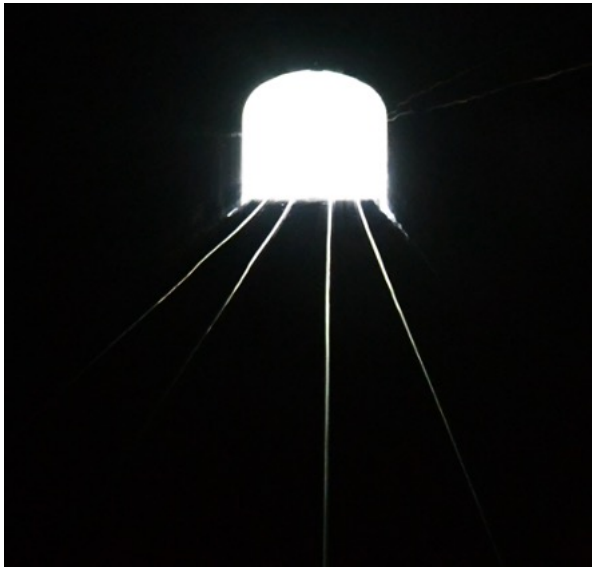
TuSimple is partnering with Navistar to sell
SAE Level 4 ("high automation") autonomous Class 8 trucks in 2024

~7,000 sales reservations already received (customers include Schneider, U.S. Xpress, et al)

Recent demonstration hauling fresh vegetables Nogales (AZ)-Oklahoma City:

- 951 miles one-way
- 24'06" trip time using 1 driver (includes 10'0" federal rest time)
- 14'06" trip time autonomous non-stop

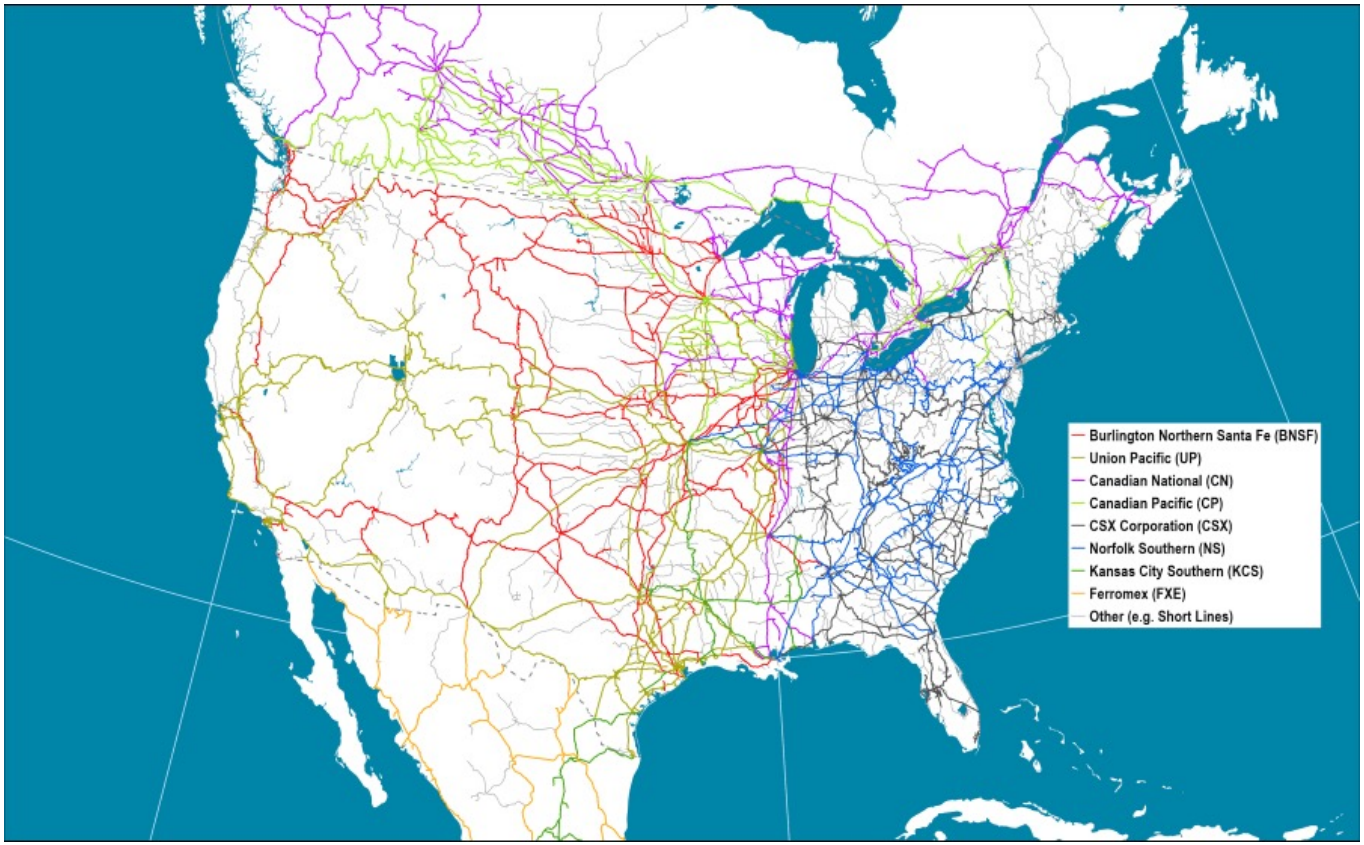
# Seeing what's next (?) to decarbonize RRs



"The past is a good predictor of the future only when conditions in the future resemble conditions in the past. And what works for a firm in one context might not work for another firm in a different context."

Dr. Clayton Christensen, "Seeing What's Next",
Harvard Business School Press, 2004

# Class 1 railroads:
# 127 in 1950 … 7 in 2021




# 3 national networks in 1950 … 1 in 2021

# Steam-to-diesel ('40-'60) v Diesel-to-(TBD)?


- Alternative fuels?
- $H_2$ fuel cell locos.?
- Battery electric locos.?
- Electric locos.?

| | Steam > Diesel | Diesel > Decarb. (potential) |
|---|---|---|
| R&D and preparation time | 20 years (1920-1940) | 9 years (2021-2030) |
| Commercialization | 20 years (1940-1960) | 20 years (2030-2050) |
| Incumbent technology age | 120 years (1820-1940) | 101 years (1920-2021) |
| Incumbent fleet condition | Worn out by WWII | Mature & being modernized |
| Impact on loco. infra. | Simplified & reduced | Likely complex & widespread |
| RR competition driving change | Autos. (for passengers) | HD trucks (for freight) |
| Economics driving change | Opex reduction | Climate, carbon cost, community |

Decarb. of RRs: more complex, a lot of Capex, less time & various risks/unknowns

# Economics of RR dieselization: why it was done

Six (6) economic reasons why U.S. (and Canadian) railroads dieselized 1940-1960:

(1) Thermal (and energy) efficiency was >3x that of the best steam locomotives.

(2) Availability 90-95% compared to 50-60% for the newest steam.

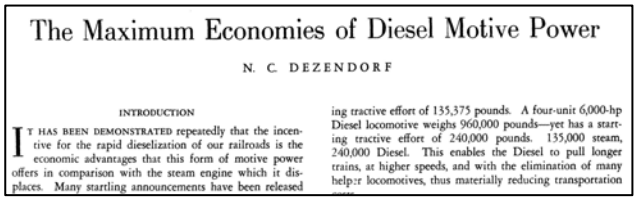
(3) Tractive effort exceeded TE of biggest steam even with lower horsepower.

(4) Electric transmission facilitated Dynamic Braking for retardation.

(5) Repair costs ½ that of steam due to mass produced precision parts.

(6) Modular design allowed flexibility in assigning locos v "steam for specific trains".

From: "The Maximum Economies of Diesel Motive Power," by Nelson Dezendorf (VP General Motors & Gen. Mgr. of Electro-Motive Div.), The Analysts Journal, 3Q 1951



The Maximum Economies of Diesel Motive Power

N. C. DEZENDORF

INTRODUCTION

IT HAS BEEN DEMONSTRATED repeatedly that the incentive for the rapid dieselization of our railroads is the economic advantages that this form of motive power offers in comparison with the steam engine which it displaces. Many startling announcements have been released

ing tractive effort of 135,375 pounds. A four-unit 6,000-hp Diesel locomotive weighs 960,000 pounds—yet has a starting tractive effort of 240,000 pounds. 135,000 steam, 240,000 Diesel. This enables the Diesel to pull longer trains, at higher speeds, and with the elimination of many helper locomotives, thus materially reducing transportation

# Most economics of dieselization have been "booked"

Six (6) economic reasons why U.S. (and Canadian) railroads dieselized 1940-1960:

(1) Thermal (and energy) efficiency was 3x that of the best steam locomotives.
We will discuss energy efficiency of alternatives to Diesels.

(2) Availability 90-95% compared to 50-60% for the newest steam.
Will more-complex technologies have equal availability of diesel?

(3) Tractive effort exceeded TE of biggest steam even with lower horsepower.
TE per locomotive is unlikely to change.

(4) Electric transmission facilitated Dynamic Braking for retardation.
Dynamic braking already exists (some regeneration may occur).

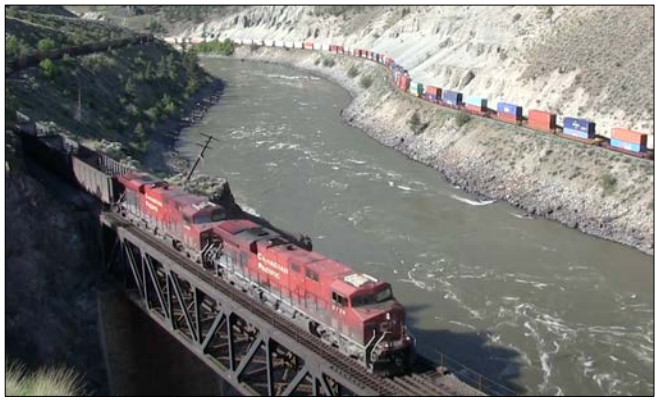
(5) Repair costs ½ that of steam due to mass produced precision parts.
Repair (and overhaul) costs of new technologies are unknown at this time.

(6) Modular design allowed flexibility in assigning locos v "steam for specific trains".
Size, weight, power & TE of new tech. locos. is unlikely to change ...
and RRs may end up having different locos. assigned to specific territories

# How decarbonization may change RRs


< NS & Ferromex locos. on UP in Chicago

We've become comfortable with (and increasingly dependent on) "universally usable" high-HP diesel-electric locos.



< CP and CN trains operating directionally on both RRs along the Thompson River in BC

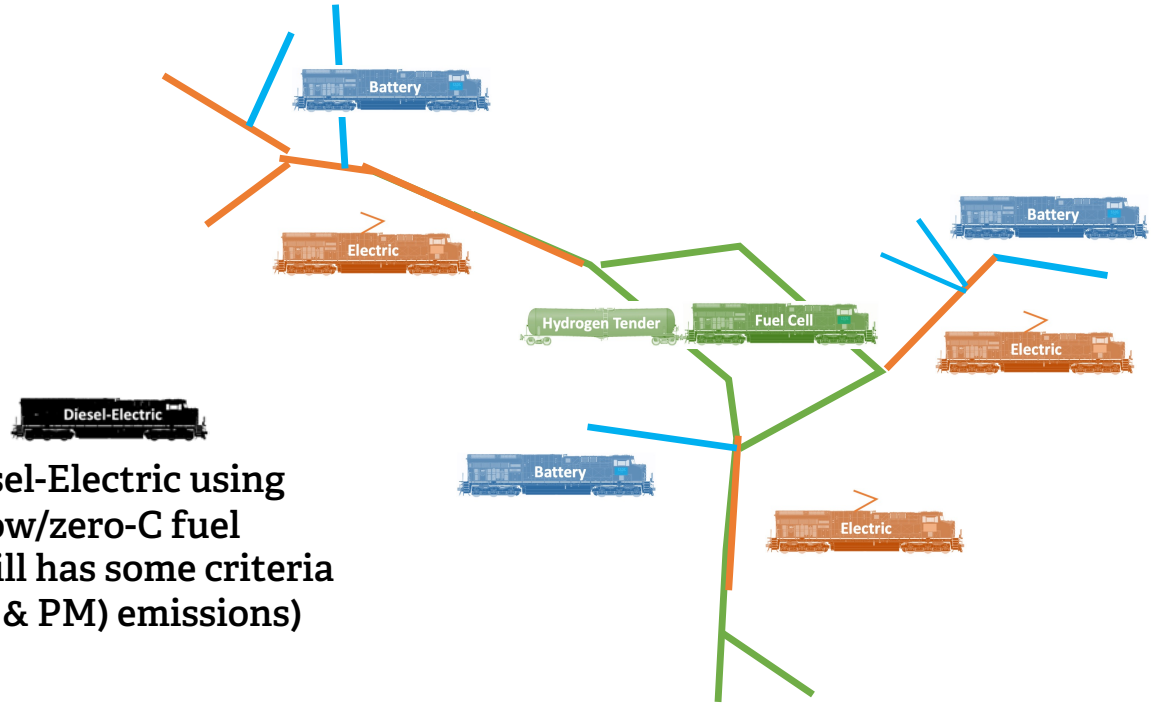
https://www.youtube.com/watch?v=ctUKhtJ28HU

Different propulsion technologies may be optimized for specific RRs, territories and/or operations. How would 2 RRs, for example, operate in a "joint territory" albeit with different propulsion schemes (for example, $RR_A$ = fuel cell locos. and $RR_B$ = battery locos.)?

# Altering RR networks & "multiple loco. fleets"

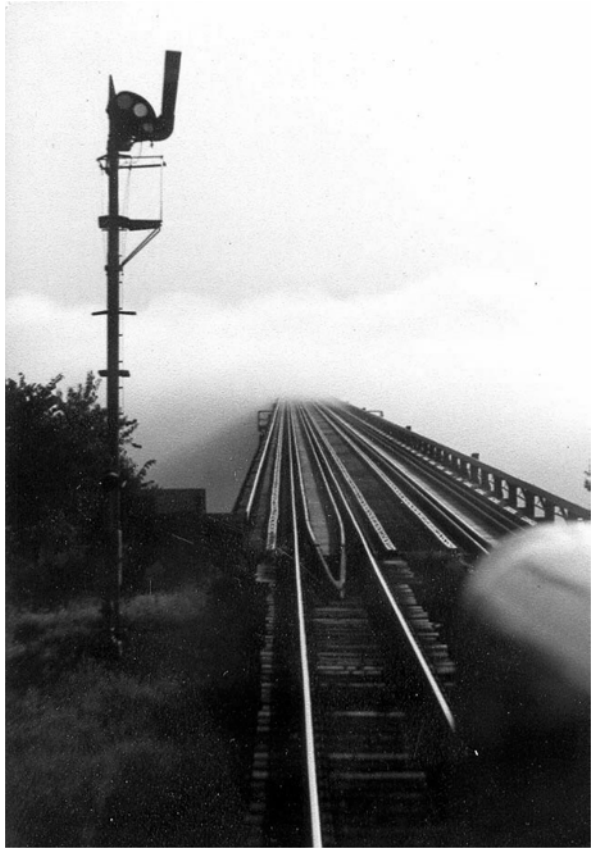
A Class 1 railroad may find it advantageous (for economic/ROI and energy availability, as two example factors) to "step back" from today's "network operations model".
*Must investigate all possible technologies, risks and the economics.*

Hypothetical example: Electrification on heavy-density routes between largest terminals and in areas where renewable electricity is abundant (and economically advantageous).
$H_2$ fuel cells in other corridors.
Battery locomotives in shorter-length secondary corridors.




Diesel-Electric using low/zero-C fuel (but still has some criteria ($NO_x$ & PM) emissions)

# RR propulsion, energy & infra. alternatives

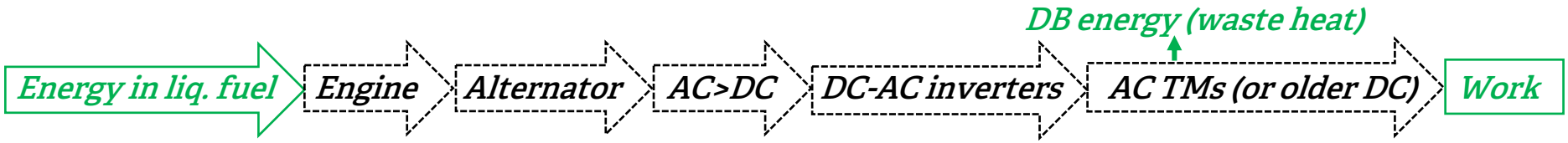


"The most important decision we make is whether we believe we live in a friendly or hostile universe."

Albert Einstein

# Diesel-Electric loco. (incumbent technology)





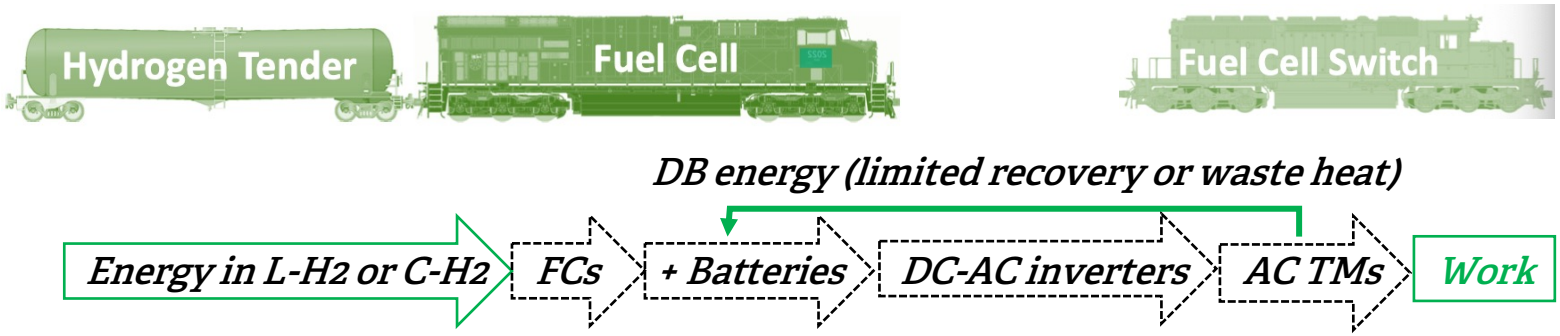

- Generates $CO_2$ & criteria emissions ($NO_x$, PM, etc) using petroleum fuels
- Eliminating criteria emissions will be challenging even with biofuels

- 38,400 units registered in Umler (24,597 = Class 1 RRs + 13,803 other RRs & private)
- Average & median ages (Umler) 28.1 and 23.8 years (and increasing)
- ~14,000 units are 4000+ hp, 6-axle & AC traction
- ~9,500 units are 1500-2000 hp, 4-axle & DC traction

- Mature technology
- Commercial availability
- Established supply base (2 major OEM, several smaller rebuilders)

- Compatible operation across continental network (US, Canada & Mexico)
- Compatible parts supply, maintenance skills & facilities " " " " " "
- Compatible refueling infrastructure " " " " " "
- Universally-available energy (diesel, FAME & HDRD) via pipeline, truck, barge, etc

# $H_2$ Fuel Cell (w/ Batteries) loco.




- Zero-emissions loco. (as a "point source"), but ...
- Zero-carbon $H_2$ production needed for true decarbonization (little capacity exists today)

- 4 experimental $H_2$ Fuel Cell loco. conversions announced (3=Canada; 1=US)

- 1 experimental switcher (operated briefly in 2009-2010), no line-haul experience
- No commercial availability at this time
- Limited supply base (for zero-carbon $H_2$)

- No operation across continental network (US, Canada & Mexico)
- No compatible parts supply, maintenance skills & facilities " " " " " "
- No compatible refueling infrastructure " " " " " "
- Very limited small quantities of $H_2$ manufactured in US & Canada (mostly high-carbon)
- $H_2$ tender (liquefied or gaseous) likely for long-distance line-haul
- May be hybrid FC+battery (optimizing FC eff. & DB recovery but added complexity)

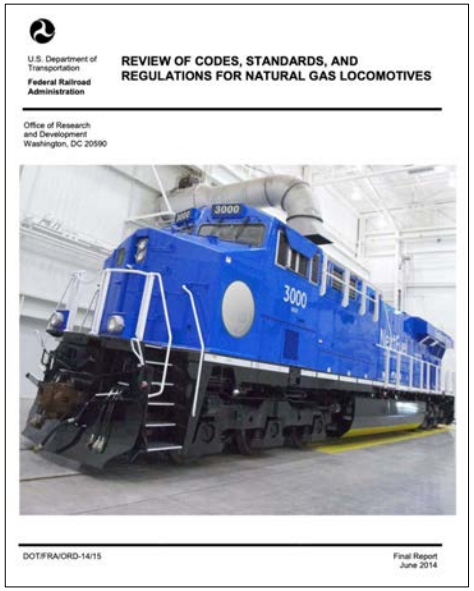
# Hydrogen ($H_2$) compared to methane ($CH_4$)

| | Hydrogen | Natural Gas |
|---|---|---|
| Liquefied $H_2$ temperature | -423°F (-253°C) | -260°F (-162°C) |
| Liquefied He temperature | -452°F (-269°C) | |
| "Absolute zero" temperature | -459°F (-273°C) | |
| Liquefaction energy req'd. | 6x that of LNG | |
| Compression energy req'd. | 11x that of CNG | |
| Gas density v air | 7% | 55% |
| Flammability range in air | 4-74% volume | 5-14% volume |
| Oxygen min. for ignition | 5% | 10-12% |
| Min. spark energy for ignition | 0.02 Joule | 0.28 Joule |
| Flame color | colorless>blue | yellow-red |

Hydrogen as loco. energy carrier <u>will</u> be subject to FRA requirements for gaseous-fuel safety analyses, authorizations, etc from 2014

FRA-funded compendium of codes, standards & regulations for natural gas locomotives (right) should be updated for hydrogen

https://railroads.dot.gov/sites/fra.dot.gov/files/fra_net/3907/Codes%20Standards%20and%20Regulations_20140623_FINAL.pdf


U.S. Department of Transportation
Federal Railroad Administration

REVIEW OF CODES, STANDARDS, AND REGULATIONS FOR NATURAL GAS LOCOMOTIVES

Office of Research and Development
Washington, DC 20590

DOT/FRA/ORD-14/15

Final Report
June 2014

# Infrastructure & rolling stock needed for $H_2$

Double cryogenic trailer LNG refueling shown on CN

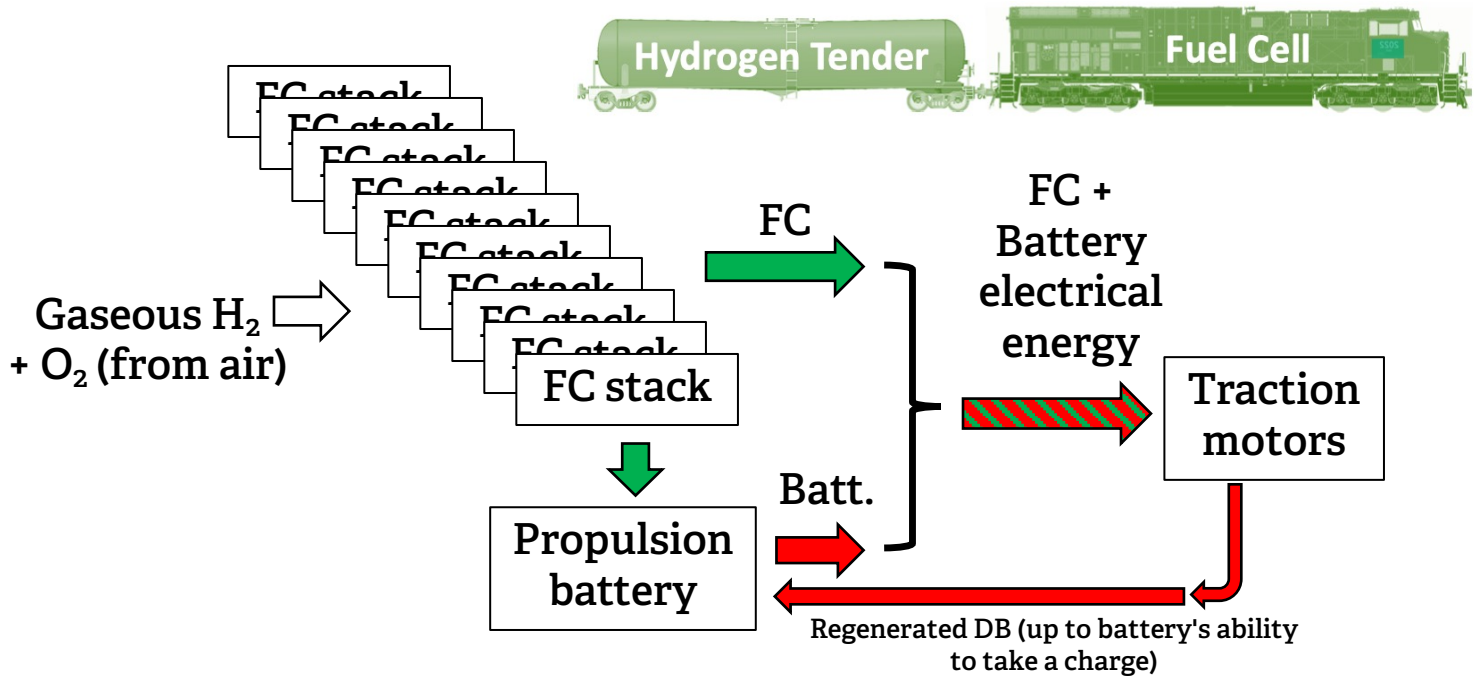

Vacuum insulated LNG transfer hose at UP test

***Zero-carbon*** hydrogen production (manufacturing) plants
Compressor (C-$H_2$) or liquefaction (L-$H_2$) facilities
Gaseous or Liquefied $H_2$ in tender (but gaseous to the loco.)
$H_2$ Fuel Tenders likely required for high-HP locos.
Transportation of $H_2$ to RR refueling locations (+ storage?)

Liquefied $H_2$ is 2$^{nd}$ coldest material on earth

Loco. shops must be modified for NFPA and regulatory codes to accommodate presence of any $H_2$ gas (similar to methane gas) … explosion-proof electricals, increased ventilation, etc

# $H_2$FC w/ Battery: "Rated power" v "hybrid power"



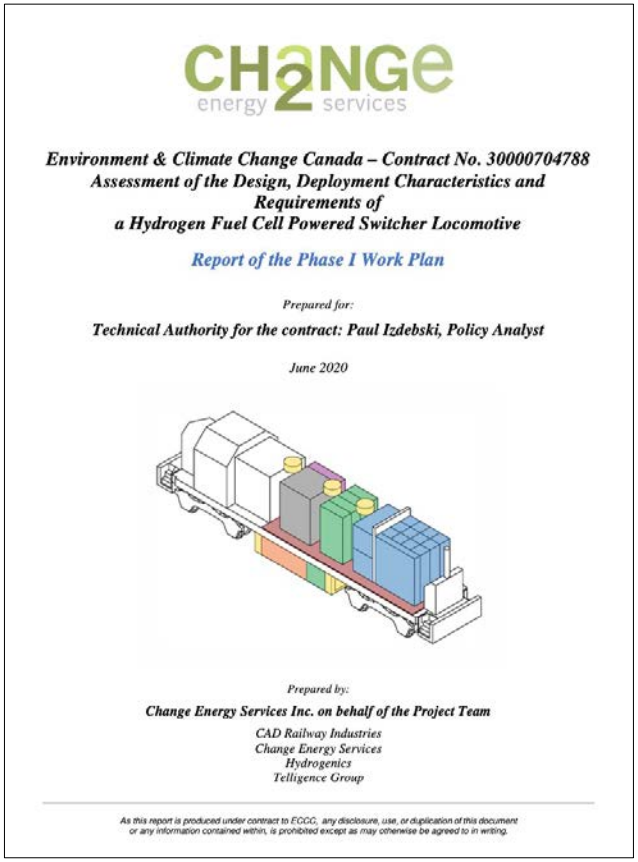

Hybrid concept allows FCs to generate power at low loco. load to charge battery

Propulsion battery reduces number of FC stacks

But if loco. duty cycle "draws down" batteries ... *loco. may degrade to FC-only power*

Example: FC (1.6 MW, 2145 hp) + Battery (1.6 MW, 2145 hp) or FC-only (1.6 MW, 2145 hp)

# FC switcher report for Env. & Cl. Change Canada ('20)



CHANGE energy services

*Environment & Climate Change Canada – Contract No. 30000704788*
*Assessment of the Design, Deployment Characteristics and Requirements of a Hydrogen Fuel Cell Powered Switcher Locomotive*

*Report of the Phase I Work Plan*

*Prepared for:*

*Technical Authority for the contract: Paul Izdebski, Policy Analyst*

*June 2020*

*Prepared by:*

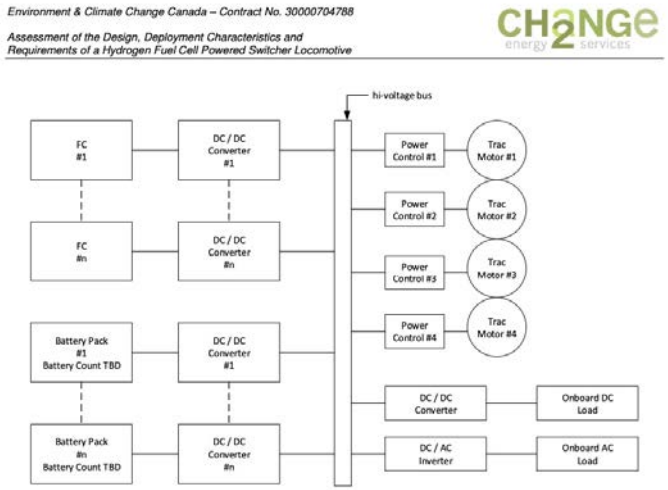
*Change Energy Services Inc. on behalf of the Project Team*

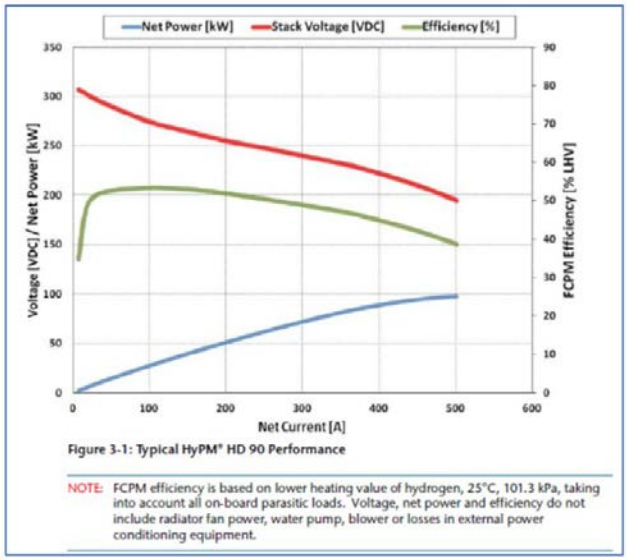
*CAD Railway Industries*
*Change Energy Services*
*Hydrogenics*
*Telligence Group*

*As this report is produced under contract to ECCC, any disclosure, use, or duplication of this document or any information contained within, is prohibited except as may otherwise be agreed to in writing.*

https://tcdocs.ingeniumcanada.org/sites/default/files/2020-08/Assessment%20of%20the%20Design%2C%20Deployment%20Characteristics%20and%20Requirements%20of%20a%20Hydrogen%20Fuel%20Cell%20Powered%20Switcher%20Locomotive.pdf

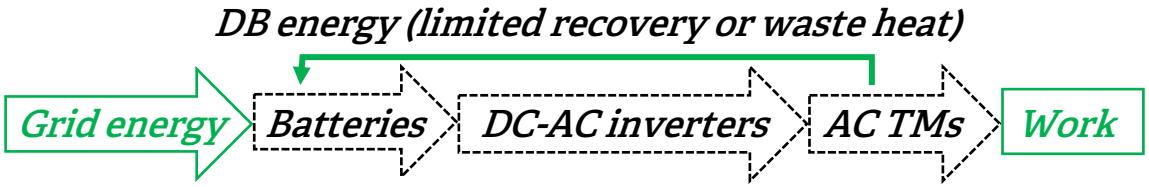
125 pages



# Battery loco.






- Zero-emissions loco. (as a "point source"), but ...
- Zero-carbon electricity must become widely available

- 1 experimental road unit tested in California early-2021
- 1 switcher to arrive on PHL in LA/LB this fall

- 126 previous "battery locos." have existed in the US since 1920 (see paper ASME JRC2014-3805)

- Not mature technology (versus large R&D & mfg. of lithium batteries)
- No commercial availability of integrated locos.
- Small production base

- Could have compatible operation across continental network (US, Canada & Mexico)
- But lacks compatible parts supply, maintenance skills & facilities " " " " " "
- And lacks compatible recharging infrastructure " " " " " "
- Power grid connectivity, support & pricing issues TBD

- Maximum potential for recovering dynamic brake energy: TBD

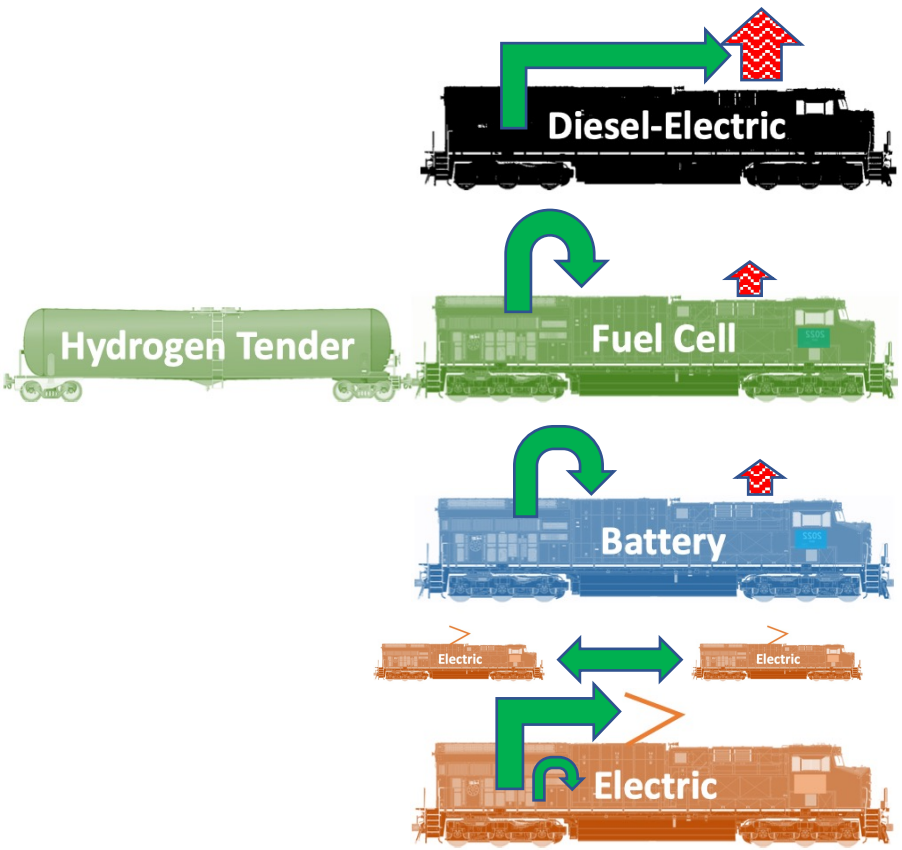
# Est. operating range: limited by onboard energy

| | Onboard energy | Nom. energy deliverable to rails |
|---|---|---|
|   | 5000 USG diesel | = 77 MWh at the rail |
|   | 16000 USG $H_2$ | = 77 MWh at the rail |
|   | 7.2 MWh | = 6 MWh at the rail |
|   | Limited by availability of energy from OCS and the grid | |

# Capturing Dynamic Braking energy

Potential for capturing DB energy greatest on long descending mountain grades and incrementally can "add up" if many stops or slow-downs are made.

* Battery is not, however, a "limitless" receiver of DB energy ... once "filled" (fully charged) any remaining DB energy has to be dissipated as waste heat.




All DB energy "lost" as heat (unless batt. hybridization, difficult to accomplish)

Recapture DB energy *up to storage capacity of supplemental propulsion battery* *

Recapture DB energy *up to storage capacity of primary propulsion battery* *

Largest amount of DB energy can be captured and transmitted through OCS to other trains and/or returned to the grid

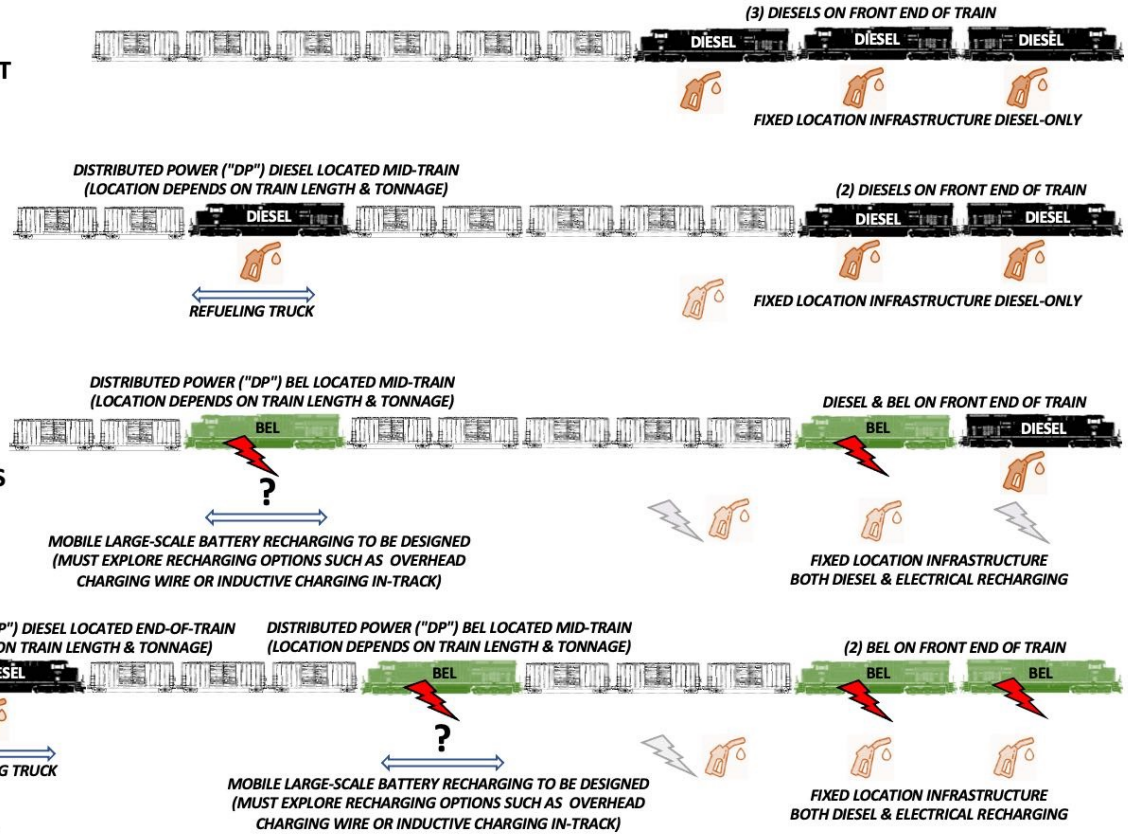
# Stationary refueling v recharging, esp. DP* locos.

**TRAIN #1: BASELINE TRAIN, ALL-DIESEL LOCOMOTIVES ON FRONT OF TRAIN**

**TRAIN #2: BASELINE TRAIN, ALL-DIESEL WITH A "DP" REMOTE DIESEL UNIT**

**TRAIN #3: SAME AS #2 EXCEPT (2) BEL'S SUBSTITUTED FOR (2) DIESEL'S ... FIXED FAST CHARGERS INSTALLED BUT PORTABLE (?) CHARGER FOR DP BEL ACCOUNT VARIABLE LOCATION IN TRAIN**

**TRAIN #4: TRAIN WITH REMOTE DIESEL & BEL UNITS ... FIXED FAST CHARGERS INSTALLED BUT PORTABLE (?) CHARGER FOR DP BEL**

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JRC2021-1030

BATTERY ELECTRIC LOCOMOTIVES & BATTERY TENDERS:
OPERATIONAL & INFRASTRUCTURE CHALLENGES TO WIDESPREAD ADOPTION

Michael E. Iden, P.E.
Tier 5 Locomotive LLC
Kildeer, IL

* DP = Distributed Power, loco(s) at mid- or end-of-train controlled from head-end

# Infrastructure needed for line-haul Battery locos.

Charging infrastructure!

Need grid connections and ability of grid to supply the power needed (not trivial, see below)

Time-of-day "power demand charges" may be the critical operating cost

Power demand for 6 MW Battery locomotive(s) compared to Tesla S autos, Tesla trucks and average U.S. homes:

| # 6 MW batt. locos. | # Tesla "S" autos | # Tesla HD trucks | # ave. US homes for 1 hour |
|---|---|---|---|
| 1 | 60 | 12 | 208 = 505 ave. US people |
| 2 | 120 | 24 | 415 |
| 8 | 480 | 96 | 1,661 |
| 16 | 960 | 192 | 3,322 |
| 32 | 1,920 | 384 | 6,644 = 17,275 ave. US people |

A railroad location recharging large numbers of Battery locos. simultaneously could equal the electricity demand of a small U.S. town

# Batt. charge example: North Platte, NE (pop. 23,892)

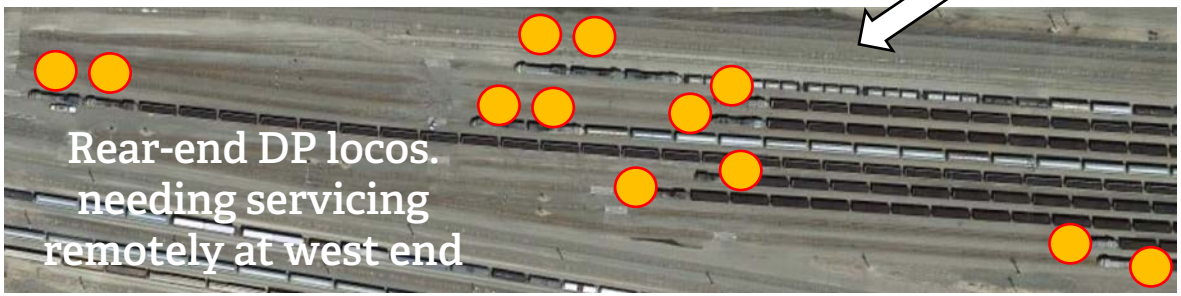
Union Pacific, North Platte (Nebraska)
Eastward run-thru fueling area:

Eight (8) trains with sixteen (16) locos.
(at the "head end") being refueled at one time:

Thirty two (32) fuel nozzles are available:

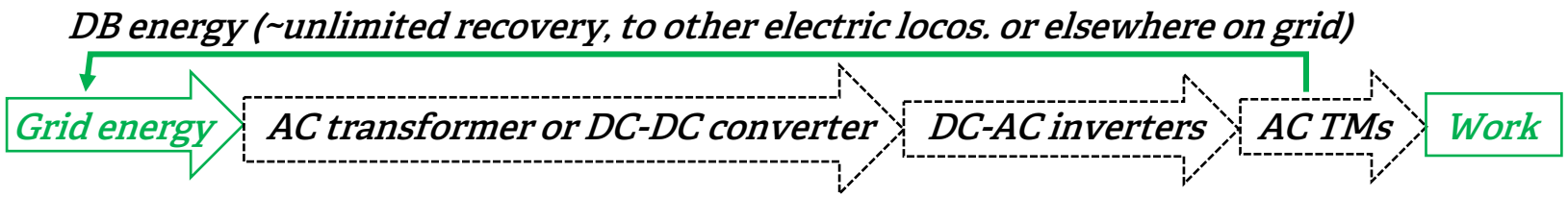

Google satellite images

Plus another twelve (12) "Distributed Power" remote locos. at the "rear end" of each train at various locations 128-to-140 cars to the west, all to be refueled by fuel trucks:




16 units at "fixed" nozzles and 12 units at variable locations = 28 units being "energized"

# Electric loco.


- Zero-emissions loco. (as a "point source"), but ...
- Zero-carbon electricity must become widely available

- >5,000 built in US 1920-2019, thousands worldwide (see paper ASME JRC2014-3805)

- Mature technology worldwide
- Commercial availability on N. America of high-speed psgr/commuter
- Small production base

- Could have compatible operation across continental network (US, Canada & Mexico)
- But lacks compatible parts supply, maintenance skills & facilities " " " " " "
- And lacks compatible recharging infrastructure " " " " " "
- Power grid connectivity, support & pricing issues TBD
- *Include small "last mile battery" for yard & no-OCS op. (ex: under low bridges)*

# Some closing thoughts


"Disruptive products or services initially are inferior to existing offerings in the attribute that matters most in the mainstream."

Prof. Clayton Christensen, "Seeing What's Next"

# $H_2$ & grid electricity: zero-C (in the future)

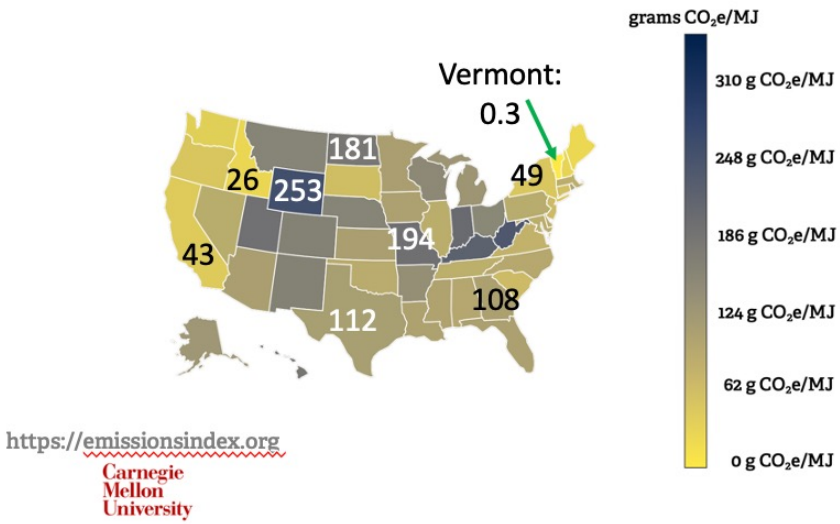
Hydrogen is considered "green" but can be "high carbon."
Carbon intensity depends on how it is manufactured.
The same applies to grid electricity.

Various decarbonization plans all depend on future production of massive amounts of renewable (zero-carbon) electricity.

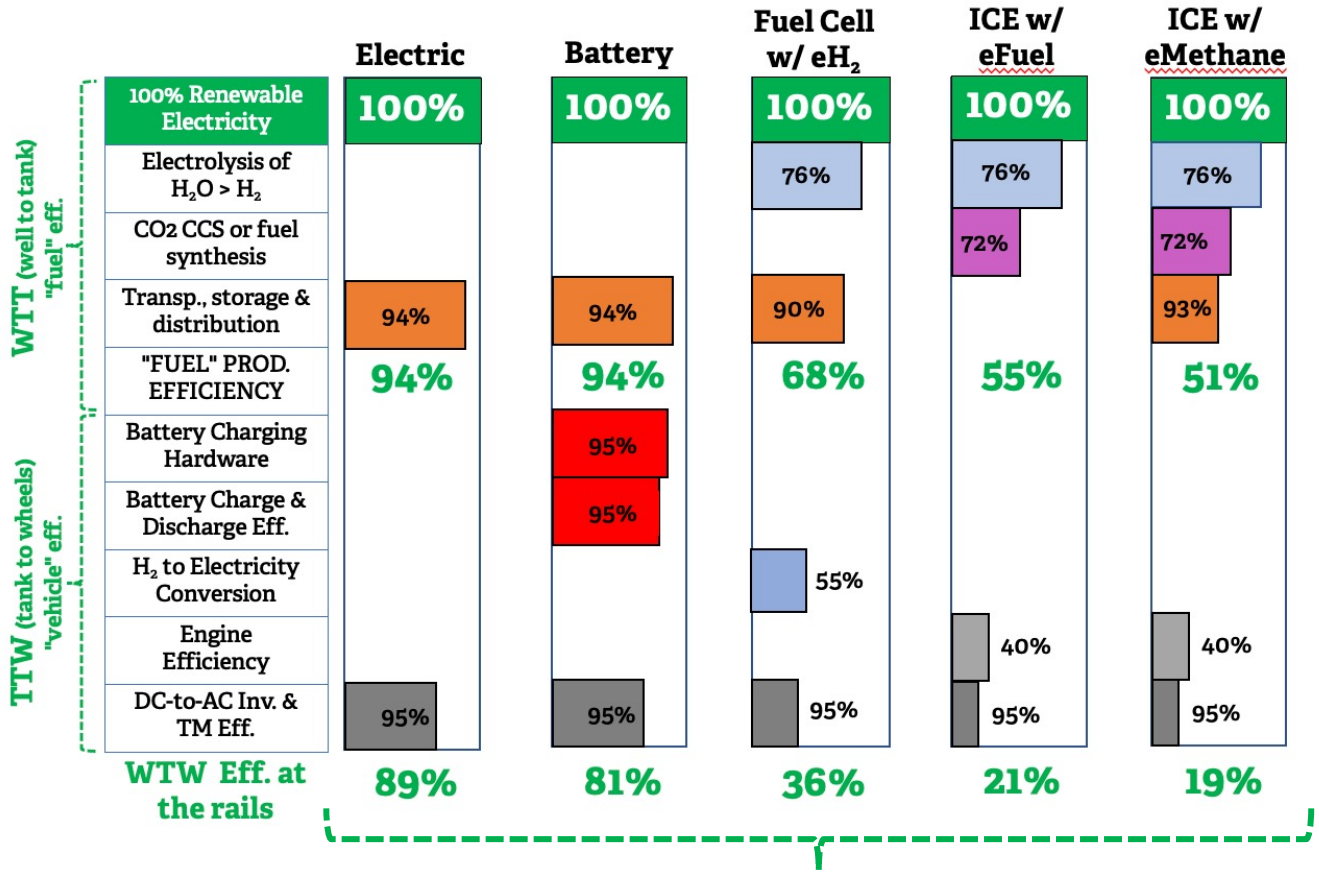
**Table E.1. Hydrogen Fuel Lookup Table Pathways**

| | Fuel Pathway Description | Total CI $gCO_2e/MJ$ |
|---|---|---|
| 1. | Compressed gaseous H2 produced in California from central reforming of fossil natural gas | 125.56 |
| 2. | Liquefied H2 produced in California from central reforming of fossil natural gas | 173.42 |
| 3. | Compressed H2 produced in California from central reforming of biomethane from landfills | 100.78 |
| 4. | Liquefied H2 produced in California from central reforming of biomethane from landfills | 149.19 |
| 5. | Gaseous H2 produced in California from on-site electrolysis using California average grid electricity | 165.21 |
| 6. | Gaseous H2 produced in California from on-site electrolysis using solar- or wind-generated electricity | 11.01 |

https://ww2.arb.ca.gov/sites/default/files/classic//fuels/lcfs/lcfs_meetings/110617lookuptable.pdf



# Well-to-Wheels (WTW) efficiency




* WTW = well-to-wheels

Assess "operating practicalities" such as operating range versus WTW energy efficiencies.

Battery has greater WTW eff. than $H_2$FC using e$H_2$ (but opposite regarding energy capacity & op. range).

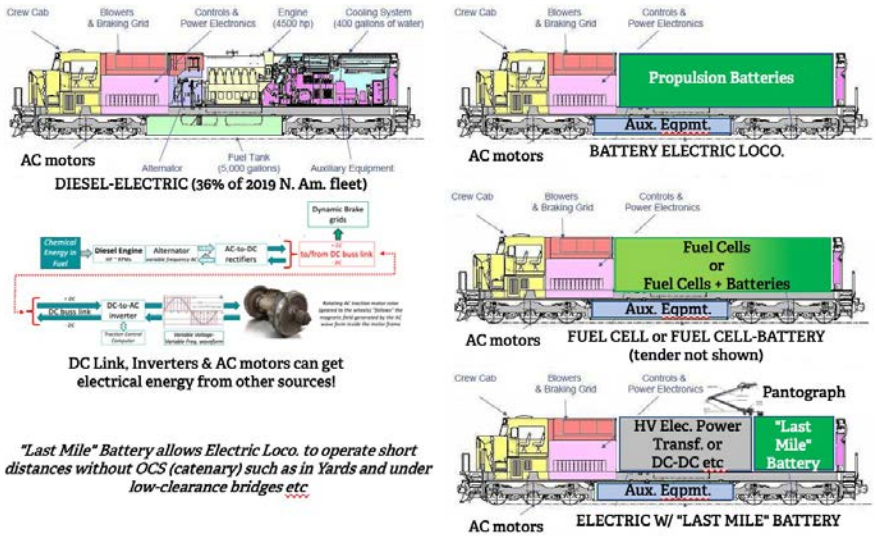
Every "energy conversion process" has efficiency losses!

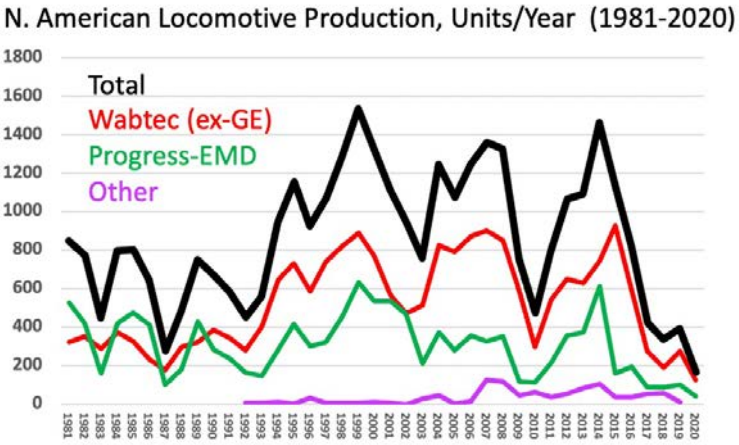
# Locomotive industry compared to HD trucks

0-to-1500 new locomotives per year (compared to 100,000-or-more Class 8 HD trucks)

Tesla reportedly considering annual production of 25,000 HD battery tractor trucks

Locomotive application of fuel cells and propulsion batteries will be a minor market



# Recommendations

1. This is an industry issue; RRs and suppliers must be jointly involved.
2. Need regulatory harmonization between US, Canada (and Mexico?) ASAP.
3. Develop thorough understanding of all technologies and energy sources.
4. Develop financial modeling to guide decisions. (Note US DOE ARPA-E project!)
5. Don't "pre-select", "pre-eliminate" or "early prioritize "any technology or energy source.
6. Building experimental "test" locomotives is good, however ... "hand built" prototypes never validate commercial reliability or success. (See "RGT" in #7 below.)
7. Start with simpler "switchers" first, then move to "line haul" locos. Validate using multi-unit Reliability Growth Testing (RGT) fleets on "real" railroads, not test tracks.
8. "Running around a test track" accumulates mileage but seldom reveals design or component flaws. "Real railroad" operation and maintenance of pre-production locos. before commercialization is critical. Test, test, then buy. Avoid buy, buy and modify.
9. Pay attention to Steele's "managers misconceptions about technology" (next slide).

# "Managers Misconceptions About Technology"

1. Invention (creating something new)
2. Innovation (initial applications)
3. Diffusion & commercialization ("making the choice, and spending $s to acquire bankable assets")

## Misconceptions regarding technology:

1. Always go for "best possible"
2. Technology is picked rationally
3. Change always occurs as planned
4. Success follows initial application
5. Technology has intrinsic value
6. Radical change will always succeed
7. Success is guaranteed by investment
8. Enhancements guarantee progress
9. New technologies can be grafted onto existing businesses and operations

## Realities of successful tech. change:

1. Use only what is "good enough"
2. Past practice limits future change
3. Plan for things to go wrong ("Murphy's law")
4. Future unknowns are risky
5. Customer (user, not seller) determines value
6. New is not necessarily better
7. Infrastructure is often the weakest link
8. Standards, constraints, routines are critical
9. A new technology and supporting existing business systems must be jointly produced and installed

From: Lowell Steele in his 1989 book, Managing Technology, McGraw-Hill, pages 52-67
(follow-up to Harvard Business Review Nov-Dec1983, "Managers Misconceptions About Technology")

Lowell Steele was the Staff Executive for Corporate Technology Planning at General Electric

# Questions & comments

"The pessimist sees only the tunnel;
the optimist sees the light at the end of the tunnel;
the realist sees the tunnel and the light – and the next tunnel."

Sydney J. Harris, American journalist (1917-1986)