Decarbonization & Increased Energy Efficiency:
The Dual Challenge for Railroads

Michael Iden, P.E.
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

**Efficiency:** ratio of useful work to the total energy expended

**(Mechanical) Power:** time derivative of work

**Work:** force applied to an object physically moved through a distance
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

"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 five (5) different plan variations

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

- **US$1.38T** (55% of 2021-2030 investment) for electrical generation, transmission, distribution & EV charging

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-CO₂ GHG mitigation efforts, and establishing enhanced land sinks.
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.
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".

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

"... 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 ..."

“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 (H₂)
- Enable production of eFuels (H₂ to synthetic liquids)
- Facilitate conversion of motor vehicles to H₂ 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

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

"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

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

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

The industry equally weighted average shows an approximate 1.5% improvement each year since 2011

2018 worsened with 2020 YTD outperforming historical norms, likely driven by PSR with longer trains, less traffic, a more fluid system and reduced HPTT (horsepower per trailing ton)
RR energy efficiency improvements

Many potential improvements can (and should) be made now

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

<table>
<thead>
<tr>
<th>SuperTruck 1</th>
<th>2010-2016</th>
<th>US DOE &amp; truck industry (50:50)</th>
<th>$284 million</th>
</tr>
</thead>
<tbody>
<tr>
<td>*SuperTruck 2</td>
<td>2017-2020</td>
<td>US DOE &amp; truck industry (50:50)</td>
<td>$160 million</td>
</tr>
<tr>
<td>*SuperTruck 3</td>
<td>2021-2024</td>
<td>US DOE &amp; truck industry (50:50)</td>
<td>$200 million</td>
</tr>
</tbody>
</table>

Total DOE-industry spending on Heavy Duty truck efficiency $644 million

*SuperTruck focus now shifting to zero-carbon

Autonomous trucks: 10% MPG improvement

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

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
“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.”

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)?

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

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) **Ttractive 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 vs "steam for specific trains".

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** $\frac{1}{2}$ 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 vs "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

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

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). H₂ fuel cells in other corridors. Battery locomotives in shorter-length secondary corridors.

Diesel-Electric using low/zero-C fuel (but still has some criteria (NOₓ & 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 CO₂ & criteria emissions (NOₓ, 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
H₂ Fuel Cell (w/ Batteries) loco.

- Zero-emissions loco. (as a "point source"), but ...
- Zero-carbon H₂ production needed for true decarbonization (little capacity exists today)

- 4 experimental H₂ 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 H₂)

- No operation across continental network (US, Canada & Mexico)
- No compatible parts supply, maintenance skills & facilities
- No compatible refueling infrastructure
- Very limited small quantities of H₂ manufactured in US & Canada (mostly high-carbon)
- H₂ 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\(_4\))

<table>
<thead>
<tr>
<th></th>
<th>Hydrogen</th>
<th>Natural Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquefied H(_2) temperature</td>
<td>-423°F (-253°C)</td>
<td>-260°F (-162°C)</td>
</tr>
<tr>
<td>Liquefied He temperature</td>
<td>-452°F (-269°C)</td>
<td>-260°F (-162°C)</td>
</tr>
<tr>
<td>&quot;Absolute zero&quot; temperature</td>
<td>-459°F (-273°C)</td>
<td></td>
</tr>
<tr>
<td>Liquefaction energy req'd.</td>
<td>6x that of LNG</td>
<td></td>
</tr>
<tr>
<td>Compression energy req'd.</td>
<td>11x that of CNG</td>
<td></td>
</tr>
<tr>
<td>Gas density v air</td>
<td>7%</td>
<td>55%</td>
</tr>
<tr>
<td>Flammability range in air</td>
<td>4-74% volume</td>
<td>5-14% volume</td>
</tr>
<tr>
<td>Oxygen min. for ignition</td>
<td>5%</td>
<td>10-12%</td>
</tr>
<tr>
<td>Min. spark energy for ignition</td>
<td>0.02 Joule</td>
<td>0.28 Joule</td>
</tr>
<tr>
<td>Flame color</td>
<td>colorless&gt;blue</td>
<td>yellow-red</td>
</tr>
</tbody>
</table>

Hydrogen as loco. energy carrier **will** 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

Infrastructure & rolling stock needed for H₂

*Zero-carbon* hydrogen production (manufacturing) plants
   Compressor (C-H₂) or liquefaction (L-H₂) facilities
Gaseous or Liquefied H₂ in tender (but gaseous to the loco.)
H₂ Fuel Tenders likely required for high-HP locos.
Transportation of H₂ to RR refueling locations (+ storage?)

Liquefied H₂ is 2nd coldest material on earth

Loco. shops must be modified for NFPA and regulatory codes to accommodate presence of any H₂ gas (similar to methane gas) ... explosion-proof electricals, increased ventilation, etc
H₂FC 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)**
Decarbonization & Increased Energy Efficiency: The Dual Challenge for Railroads
UIUC Hay Seminar, June 4, 2021

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


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 $\text{H}_2$ = 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

* 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:

<table>
<thead>
<tr>
<th># 6 MW batt. locos.</th>
<th># Tesla &quot;S&quot; autos</th>
<th># Tesla HD trucks</th>
<th># ave. US homes for 1 hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60</td>
<td>12</td>
<td>208 = 505 ave. US people</td>
</tr>
<tr>
<td>2</td>
<td>120</td>
<td>24</td>
<td>415</td>
</tr>
<tr>
<td>8</td>
<td>480</td>
<td>96</td>
<td>1,661</td>
</tr>
<tr>
<td>16</td>
<td>960</td>
<td>192</td>
<td>3,322</td>
</tr>
<tr>
<td>32</td>
<td>1,920</td>
<td>384</td>
<td>6,644 = 17,275 ave. US people</td>
</tr>
</tbody>
</table>

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:

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.

DB energy (~unlimited recovery, to other electric locos. or elsewhere on grid)

Grid energy → AC transformer or DC-DC converter → DC-AC inverters → AC TMs → Work

- 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"
H₂ & 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

<table>
<thead>
<tr>
<th>Fuel Pathway Description</th>
<th>Total CI gCO₂e/MJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Compressed gaseous H₂ produced in California from central reforming of fossil natural gas</td>
<td>125.56</td>
</tr>
<tr>
<td>2. Liquefied H₂ produced in California from central reforming of fossil natural gas</td>
<td>173.42</td>
</tr>
<tr>
<td>3. Compressed H₂ produced in California from central reforming of biomethane from landfills</td>
<td>100.78</td>
</tr>
<tr>
<td>4. Liquefied H₂ produced in California from central reforming of biomethane from landfills</td>
<td>149.19</td>
</tr>
<tr>
<td>5. Gaseous H₂ produced in California from on-site electrolysis using California average grid electricity</td>
<td>165.21</td>
</tr>
<tr>
<td>6. Gaseous H₂ produced in California from on-site electrolysis using solar- or wind-generated electricity</td>
<td>11.01</td>
</tr>
</tbody>
</table>

https://www2.arb.ca.gov/sites/default/files/classic/fuels/lcfs/lcfs_meetings/110617lookuptable.pdf
Well-to-Wheels (WTW) efficiency

<table>
<thead>
<tr>
<th>WTW (well to tank)</th>
<th>Electric 100%</th>
<th>Battery 100%</th>
<th>Fuel Cell w/ eH₂ 100%</th>
<th>ICE w/ eFuel 100%</th>
<th>ICE w/ eMethane 100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;fuel&quot; eff.</td>
<td>94%</td>
<td>94%</td>
<td>90%</td>
<td>76%</td>
<td>76%</td>
</tr>
<tr>
<td>WTT (well to tank)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;vehicle&quot; eff.</td>
<td>89%</td>
<td>81%</td>
<td>36%</td>
<td>21%</td>
<td>19%</td>
</tr>
<tr>
<td>WTW Eff. at the rails</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

Battery has greater WTW eff. than H₂ FC using eH₂ (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
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


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

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2021 Tier 5 Locomotive LLC

Decarbonization & Increased Energy Efficiency: The Dual Challenge for Railroads
UIUC Hay Seminar, June 4, 2021
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)