Exploring Decarbonization Options using A-STEP

Dr. George List, Dr. Andreas Hoffrichter, Lynn Harris

2023 FRA Rail: On Track Decarbonization Workshop

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Lead Investigators

Principal Investigator (PI)
Task 8 Lead
George F. List, Ph.D., PE

Project Manager (PM)
Task 4 & 5 Lead
Jeremiah Johnson, Ph.D.

Task 6 Lead
Eleni Bardaka, Ph.D.

Task 8
Ishtiak Ahmed, Ph.D.

Task 1 Lead
Andreas Hoffrichter, Ph.D.

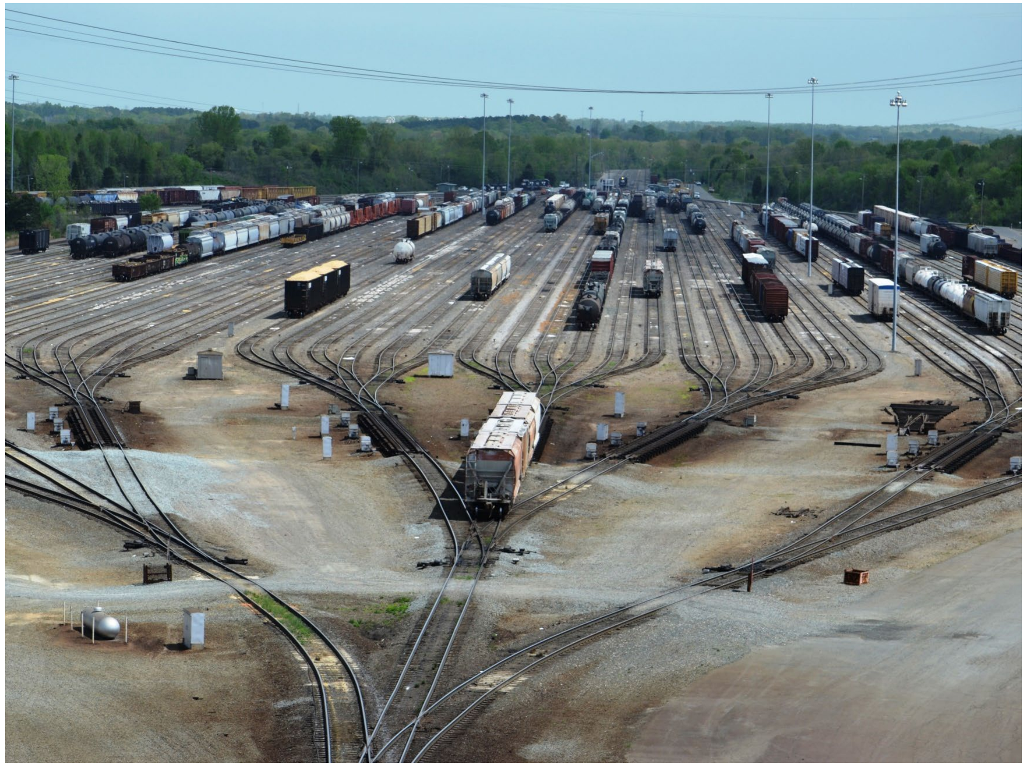
Task 7 Lead
Lynn Harris

Task 2 Lead
Hesham Rakha, Ph.D., P.Eng.

Task 3 Lead
Yue Cao, Ph.D.

Objective, Scope, Deliverables

- *Objective*: identify ways in which the rail freight industry in the US could be shifted to use of alternate fuels, aiding with decarbonization
- *Scope*: rail freight industry, present to 2050, any reasonable alternate energy sources: hydrogen, batteries, biofuels, electrification
- *Deliverables*: suite of tools that can be used for purposes of analysis and a small number of illustrative case studies

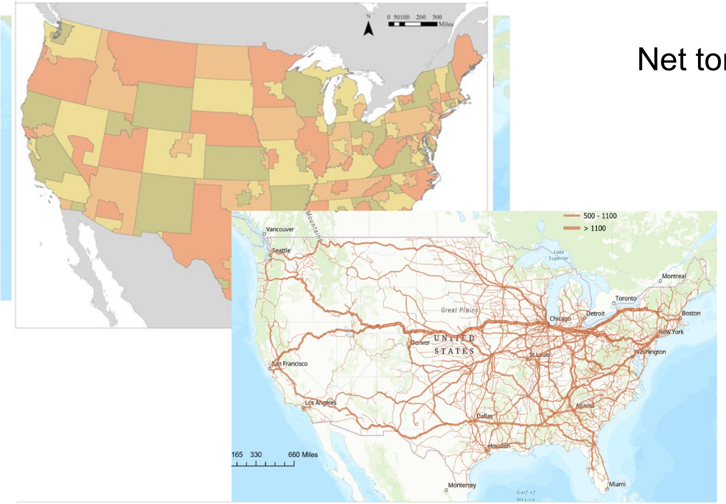


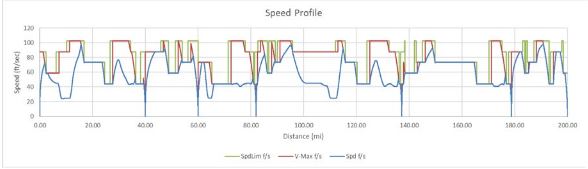
Decarbonization Toolset

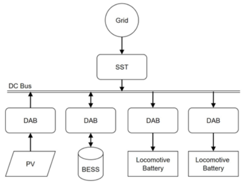
Tool	Input	Output
Freight Demand	Economic / technical / environmental strategic plan	FAF interregional eight flows by year
Freight Traffic Assignment	Freight flows and FRA rail network	Ton-miles by FRA network link and Temoa region
Single / Network Train Simulation	Ton-miles by link and region and propulsion technology options	Energy use by propulsion type and Temoa region
Energy Delivery Infrastructure	Energy use by type and region and energy source options	Energy provision by type and location
Energy Source Optimization	Rail and other sector energy demand and sourcing options	Energy supply and demand by Temoa region and year
Probabilistic Cost Assessment	Rail activity and resources, cost model, and unit costs	Regional and national total and levelized costs and sensitivity

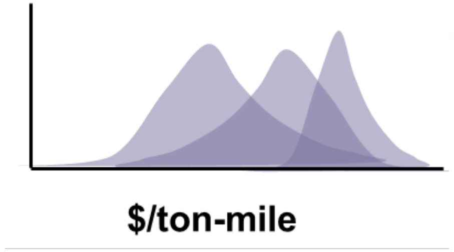
Python / Open-Source / Technical Documentation / User-Manual

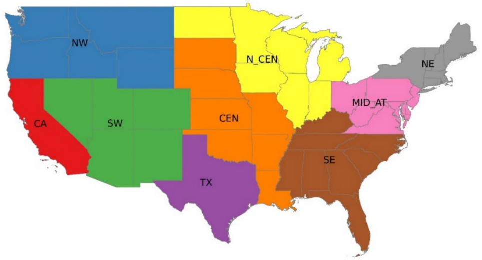
Process Steps











Rail Freight Demand Scenarios

Decarbonization Energy Pathways

Net ton flows from/to FAF regions

Energy use objectives and source availability

Nationwide Rail Traffic Assignment[1]

Net ton miles by Temoa region

Train Simulation Based Energy Use Adjustment[2]

Activity assessments by Temoa region[3]

Energy use by Temoa region and type

Energy Delivery Infrastructure

Investments by Temoa region[4]

Charging station energy and power demands[5]

Energy Source Optimization

Energy sourcing and flows by Temoa region

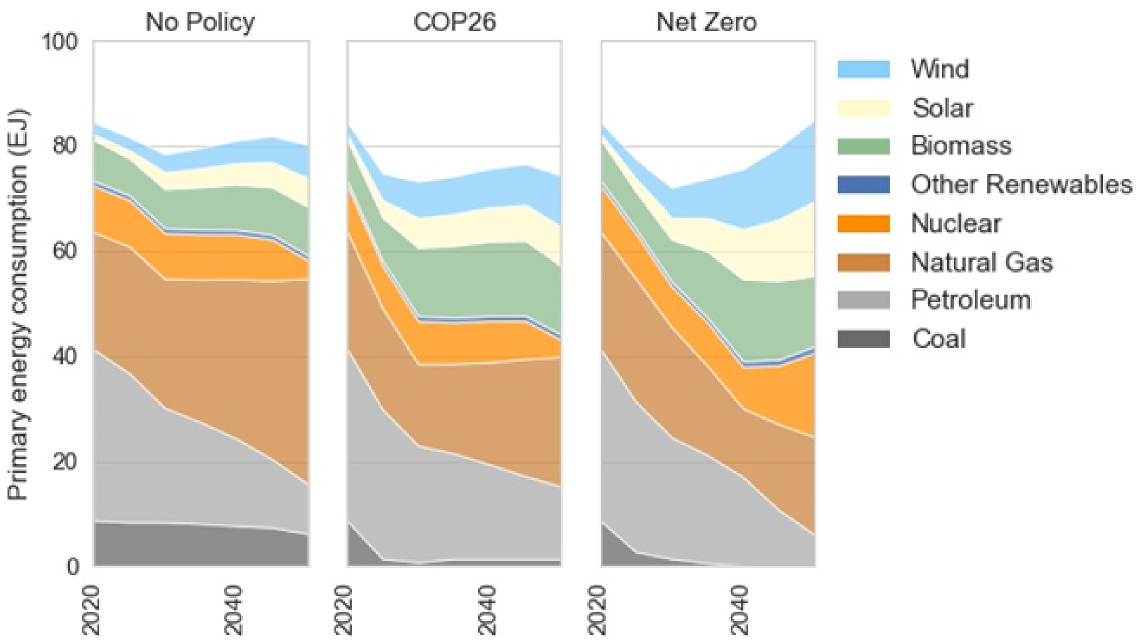
Probabilistic Cost Assessment

Revisions to assumptions

Notes:
1. Directional net ton flows by link and Temoa region
2. Based on single train and network level simulation models
3. Such as train miles, locomotive miles, gross ton-miles, and sensitivities (probabilistic assessments)
4. Investment and operating costs

Energy System Decarbonization Pathways

Policies that tighten carbon constraints result in continued growth in renewables so that in a net zero CO_2 scenario, renewables account for 50% of energy supply



- No Policy: increase in natural gas, solar and wind; persistence of coal; decline in petroleum
- COP26: more renewables squeeze out coal, natural gas increases
- Net Zero: tremendous increases in wind, solar, and biomass; uptick in nuclear, some natural gas and petroleum remain (to be offset with BECCS or DAC)

Notes: COP26 – 26th United Nations Climate Change conference
BECCS – Bio-Energy with Carbon Capture and Storage
DAC – Direct Air Capture

Tool – Single Train Simulator

Locomotives and Power Cars								
Parameter	Diesel	BioDiesel	DieHyb	BioHyb	HydHyb	BatLoco	BatTend	HydTend
Unit ID	1	2	3	4	5	6	7	8
Weight (tons)	214	214	214	214	214	214	100	100
#Axles	6	6	6	6	6	6	4	4
Length (ft)	74.5	74.5	74.5	74.5	74.5	74.5	65	65
wt/axle (tons)	53.5	53.5	53.5	53.5	53.5	53.5	70	70
teLim-μ (kips)	107	107	107	107	107	107	50	50
propMax (kw)	2420	2420	3300	3300	3300	3300	0	0
BatMax-DC (kw)	0	0	2000	2000	2000	2000	1000	1000
CatMax-DC (kw)	0	0	3300	3300	3300	3300	0	0
AuxMax*-DC (kw)	2420	2420	1000	1000	1000	1000	0	0
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Cars						
Parameter	DblStk	CovHop	OpnHop	BoxCar	TnkCar	Gond
Unit ID	11	12	13	14	15	16
Gross (tons)	110.0	143.0	143.0	143.0	143.0	143.0
Tare (tons)	22.5	33.0	22.0	40.5	38.7	34.2
#axles	4	4	4	4	4	4
wt/axle (tons)	27.5	35.75	35.75	35.75	35.75	35.75
Length (60-90')	76.8	64.6	53.1	67.9	55.6	57.8
Empty (%)	40%	30%	30%	20%	30%	20%

Dist (mi)	SpdLim (mph)	Grade (%)	Curve (DoC)	Catenary (0,1)	Elev ft	dDist (m)
0	60	0.000	0.000	0	0	0
0.30903	60	0.299	0.000	0	4.881888	0.3090302
0.619703	60	0.873	0.247	0	19.20991	0.3106731
0.930192	60	1.070	0.625	0	36.7486	0.3104885
1.240877	60	1.596	0.260	0	62.93776	0.3106855
1.550029	60	1.094	0.889	0	80.79986	0.309152
1.860712	60	1.333	0.563	0	102.6609	[illegible]
2.171398	60	0.677	0.004	0	113.7667	[illegible]
2.482083	60	0.490	0.000	0	121.7982	[illegible]
2.792769	60	-0.862	0.000	0	107.6644	0.3106855
3.103454	60	-0.024	0.000	0	107.2708	0.3106855
3.41414	60	0.562	0.000	0	116.4834	0.3106855
3.724825	60	-1.687	0.000	0	88.80632	0.3106855
4.035511	60	-1.363	0.312	0	66.4538	0.3106855
4.346064	60	-1.365	0.572	0	44.0692	0.3105531
4.65635	60	-1.023	0.857	0	27.30215	0.310286
4.966289	60	-1.036	0.879	0	10.35451	0.3099392
5.276922	60	-0.675	0.438	0	-0.71826	0.3106327
5.587005	60	-0.089	0.207	0	-2.17005	0.3100828
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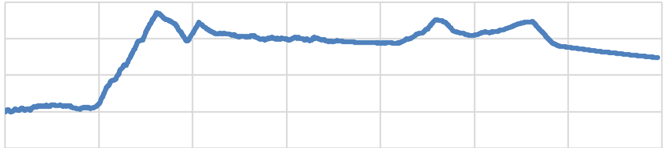

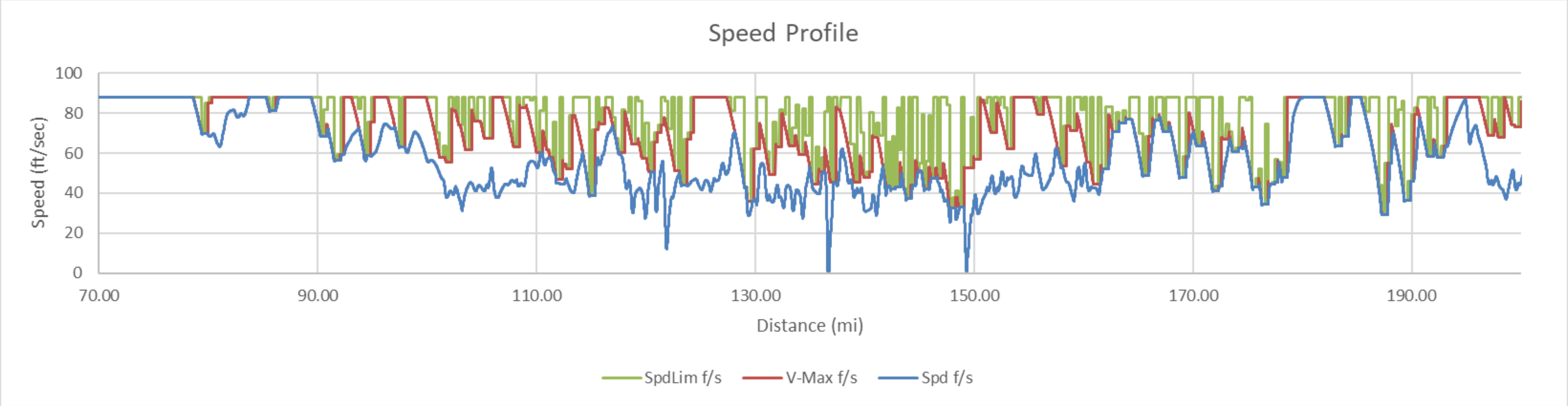

Energy Consumption Analysis – By Type and Region

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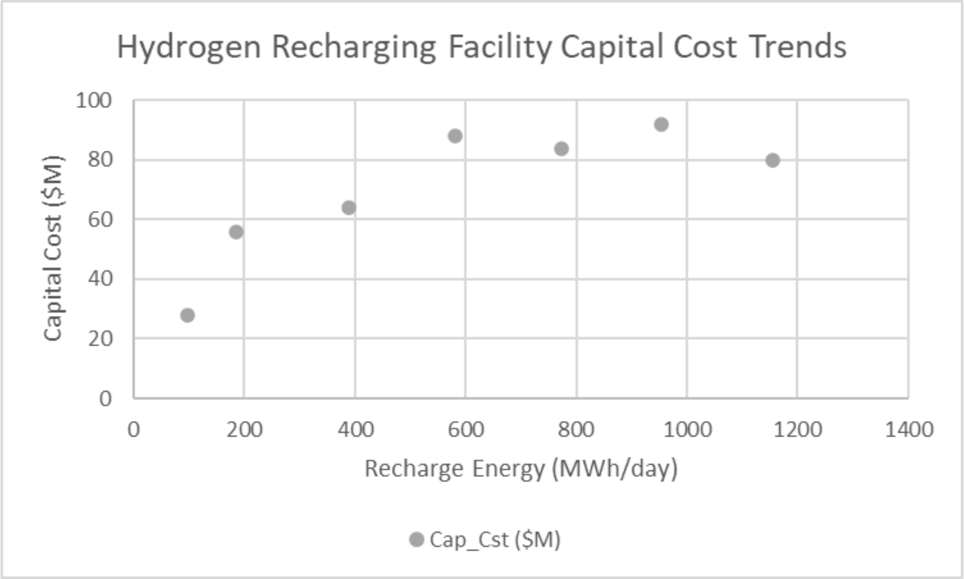
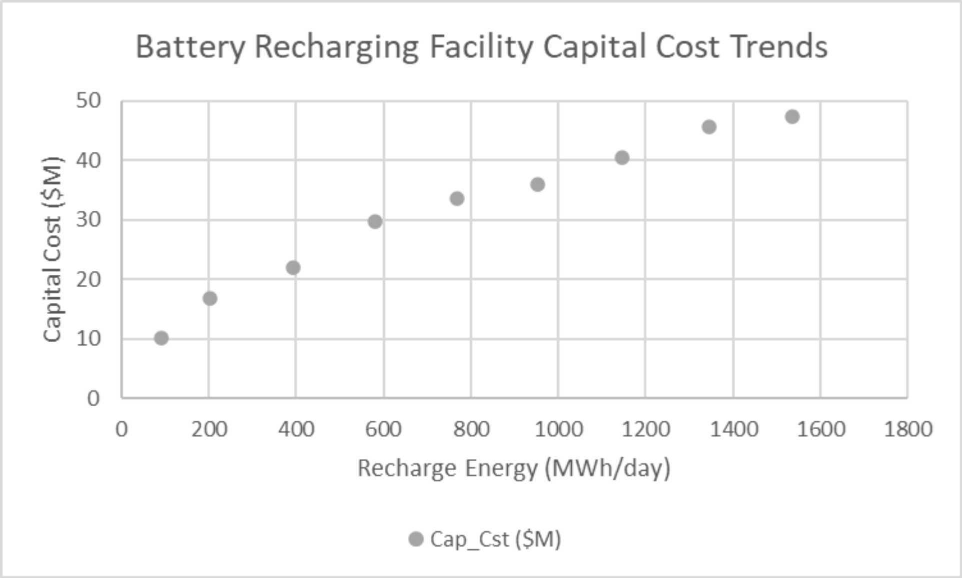
- Regional variations due to terrain and motive power requirements
- Strategic decisions about what options, where, and why
- Overall efficiency depends on the energy delivery chain – well to tank to wheel
- Carbon footprint depends on energy sourcing – for battery, hydrogen - natural gas, nuclear, hydro, solar, wind……

Region	Diesel	Diesel Hybrid (Battery 60%)		BioDiesel	BiodieselHybrid (Battery 60%)		Battery Electric	Hydrogen FC (Battery 60%)		Catenary Electric
	(gal/week)	Battery (kWh/week)	Tank (gal/week)	(gal/week)	Battery (kWh/week)	Tank (gal/week)	(kWh/week)	Battery (kWh/week)	Tank (kg/week)	(kWh/week)
NW	7,930,078	9,924,742	7,220,968	8,611,401	9,946,230	7,764,871	117,923,173	234,759,865	184,382	120,633,369
CA	2,029,270	2,710,110	1,884,581	2,192,049	2,721,300	2,026,531	30,585,082	64,175,827	50,516	29,705,729
SW	5,601,591	7,703,222	5,144,084	6,028,556	7,727,304	5,531,354	83,979,086	171,513,011	134,461	83,349,350
N_CEN	12,764,181	16,631,813	11,914,596	13,742,060	16,726,638	12,809,943	204,060,234	407,188,780	320,382	185,888,783
CEN	17,246,869	24,035,399	15,683,422	18,565,441	24,100,709	16,862,893	268,589,853	511,902,953	399,729	260,152,227
TX	5,134,985	6,636,186	4,711,680	5,528,173	6,660,045	5,065,930	80,506,774	155,246,907	121,748	77,026,326
NE	786,311	1,283,321	705,415	845,769	1,284,556	758,570	11,978,818	23,043,719	17,868	11,810,462
MID_AT	5,579,509	8,933,146	5,137,103	6,001,927	8,961,875	5,524,187	77,747,568	177,888,640	139,090	80,377,891
SE	6,217,883	9,839,063	5,588,865	6,687,993	9,850,056	6,009,914	93,747,042	182,310,923	141,531	93,854,450
Total/week	63,290,679	87,697,003	57,990,713	68,203,369	87,978,712	62,354,194	969,117,629	1,928,030,626	1,509,707	942,798,586
Total/year	3,291,115,322	4,560,244,146	3,015,517,084	3,546,575,187	4,574,893,006	3,242,418,071	50,394,116,732	100,257,592,538	78,504,775	49,025,526,447
Literature	3,000,000,000	112,997,313,433	3,000,000,000	3,225,806,452	105,087,501,493	3,225,806,452	47,978,682,098	3,791,249,107,536	686,188,632	47,978,682,098
Ratio to Diesel Energy	109.70%	4.04%	100.52%	109.94%	4.35%	100.51%	105.03%	2.64%	11.44%	102.18%
Energy (kWh)	123,962,455,472	4,560,244,146	113,581,830,363	124,233,634,169	4,574,893,006	113,579,258,649	50,394,116,732	100,257,592,538	2,616,564,150	49,025,526,447
Ratio to Diesel Energy	100.0%	95.3%		100.2%	95.3%		40.7%	83.0%		39.5%
Cost (billion $)	$ 15.07	$ 0.57	$ 13.81	$ 18.51	$ 0.57	$ 16.93	$ 6.30	$ 12.53	$ 0.11	$ 6.13
Saving (billion $)	$ -	$	0.69	$ (3.44)	$	(2.42)	$ 8.77	$	2.43	$ 8.95
Unit Cost	$ 4.58	$ 0.13	$ 4.58	$ 5.22	$ 0.13	$ 5.22	$ 0.13	$ 0.13	$ 1.40	$ 0.13
Source	https://afdc.energy.go	https://www.electricc	https://afdc.energy.gov	https://afdc.energy.g	https://www.electri	https://afdc.energy.go	https://www.electr	https://heshydrogen.com/hydrogen-fuel-c		https://www.electr

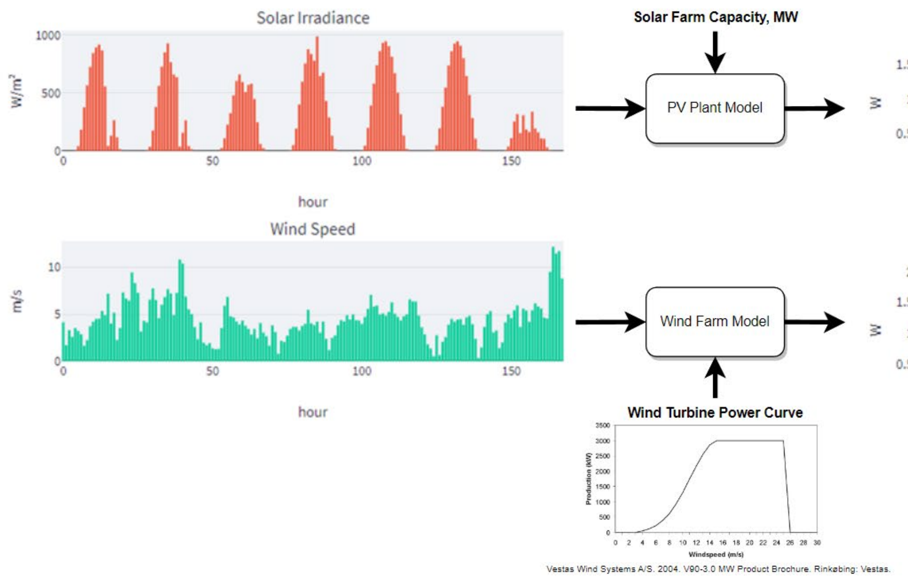
Facility Sizing and Load Assessment

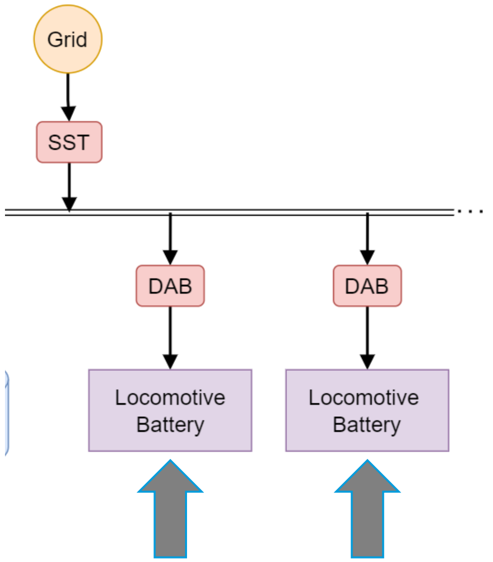
- The tender and locomotive arrival pattern is critically important
- Treating the problem using simulation is also critically important
- There are issues about when to do the recharging, influenced by peak load pricing by the utilities
- Making sure there is an adequate “ready reserve” of tenders is important
- Such assessments highlight the importance of the “upon arrival” charge policies for locomotives and tenders
- It’s not just about facility sizing and cost estimation.

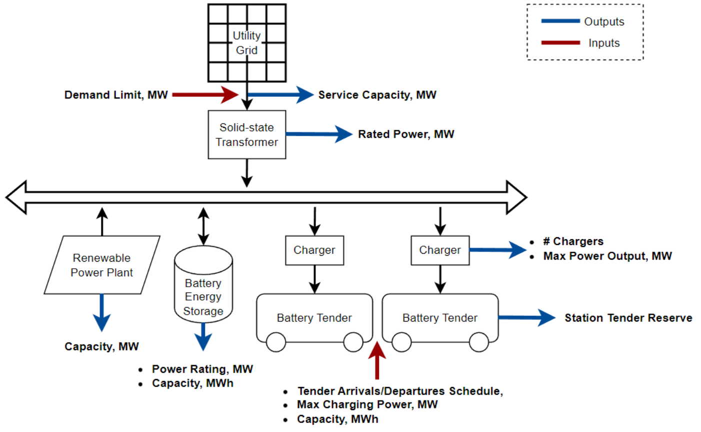




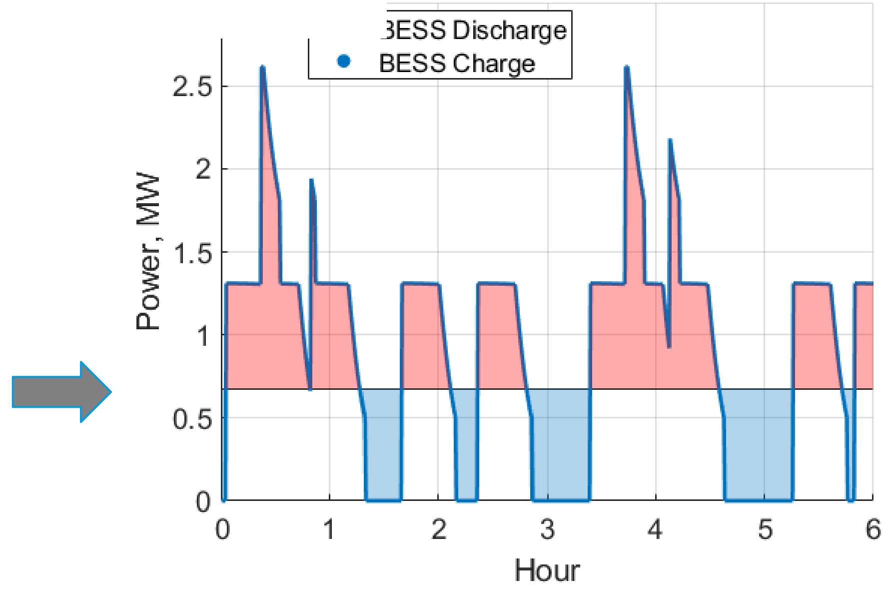
Tool – Recharging Facility Designer







Average Load



Tool – Recharging Facility Designer

About   Train Schedule   Demand Profile   Battery-electric   Hydrogen

A-STEP: Achieving Sustainable Train Energy Pathways

Module 8: Infrastructure Requirements

Demand Profile

Chargers

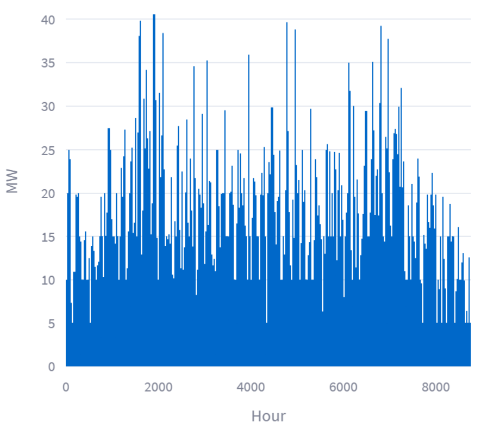
20

Average Station Demand, MW

6.5

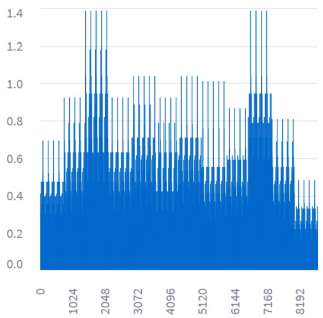
Download charger schedules as CSV

Download 15-minute demand profile as CSV

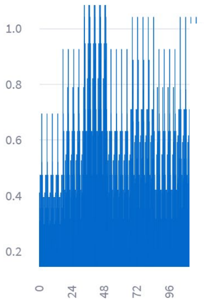


🚋 Tender Arrival/Departure Schedule Generator 🕔

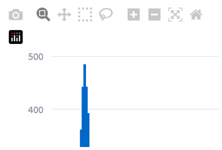
Hourly Train Arrival Distribution



Hourly Train Departure Distribution



Fuel Remaining in Arriving Tenders



2	7.13	2
3	10.87	2
4	14.01	2
5	18.7	2
6	33.4	2
7	34.17	2
8	34.27	2
9	34.48	2

Total Train Arrivals

4	15.8	2
5	20.23	2
6	22.01	2
7	30.56	2
8	41.08	2
9	42.48	2
10	51.32	2
11	52.17	2
12	55.3	2
13	59.2	2

epartures

ad departure schedule as CSV

Results

Total Hydrogen Dispensed, kg

4566380

Total Hydrogen Cost, $

9132760

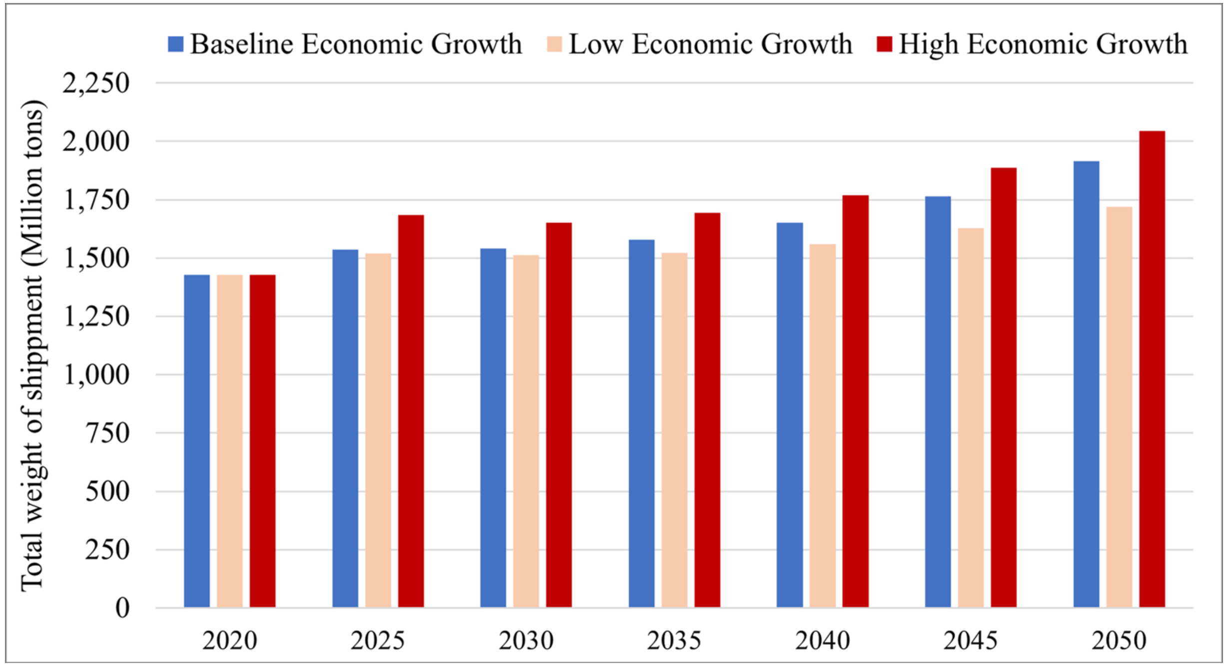
Total Electricity Consumption, MWh

6.39

Total Electricity Cost, $

959

Freight Demand Scenario Illustrations



Freight flow by rail for future years. [Source: FAF 5.2 estimates [1]]

Macroeconomic factors used to develop the economic scenarios [2]:

- Growth of Gross Domestic Product
- % Change in Industrial Production
- % Change in Non-residential Fixed Investment
- Increase in Light Vehicle Sales
- % Change in Productivity
- Housing Starts

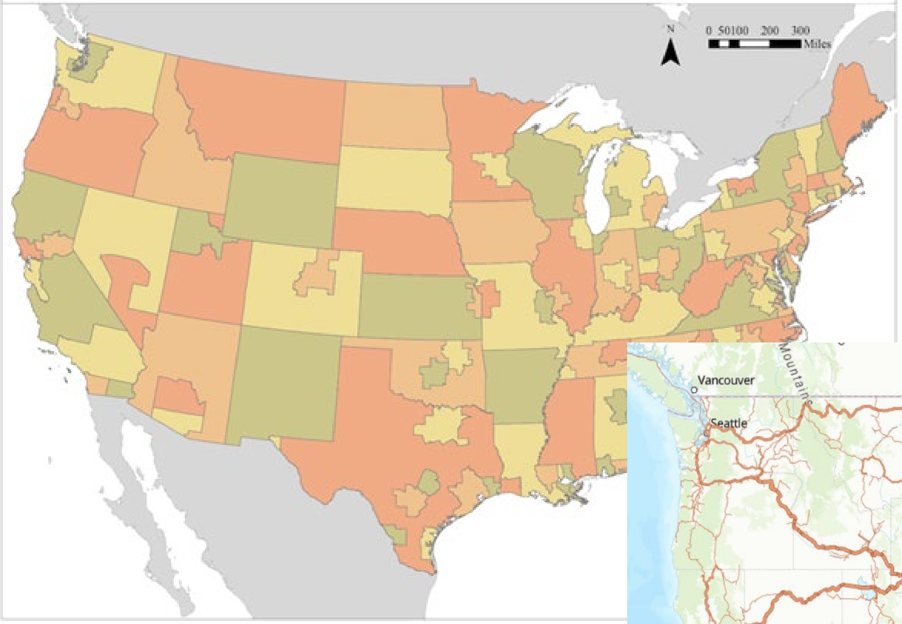
[1] BTS, 2022. Freight Analysis Framework [WWW Document]. Bur. Transp. Stat. URL https://www.bts.gov/faf (accessed 4.21.22).

[2] Fullenbaum, R. and Grillo, C., 2016. Freight analysis framework inter-regional commodity flow forecast study: final forecast results report (No. FHWA-HOP-16-043).

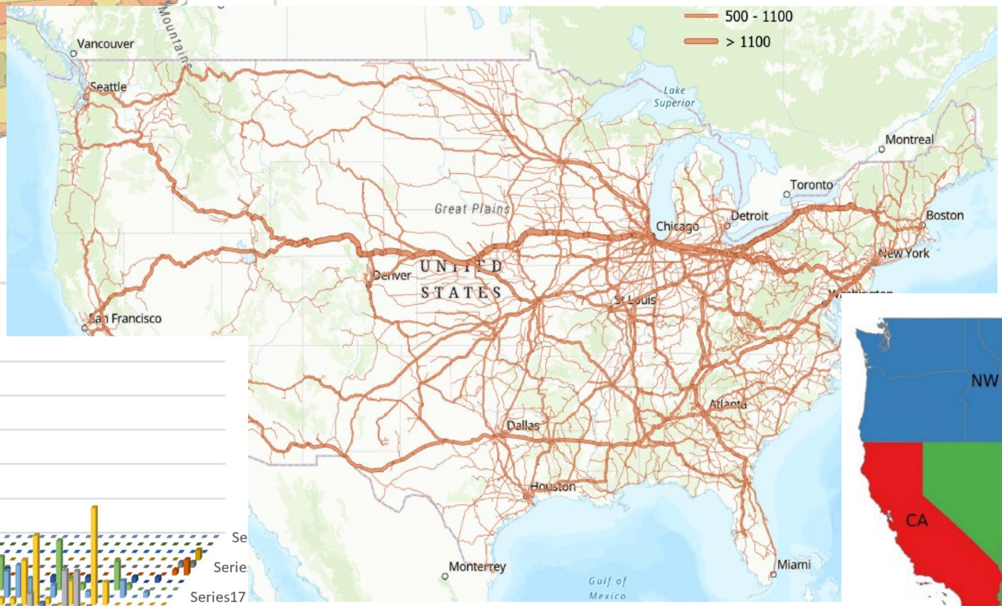
Rail Freight Traffic Assignment

- *Objective*: Create credible assignment of freight flows to the national rail network, so defensible estimates can be created of energy infrastructure investments and energy demands by Temoa region and year
- *Outputs*: 1) ton-miles by Temoa region, 2) tonnage flows by FRA network link, 3) energy demand by major yard

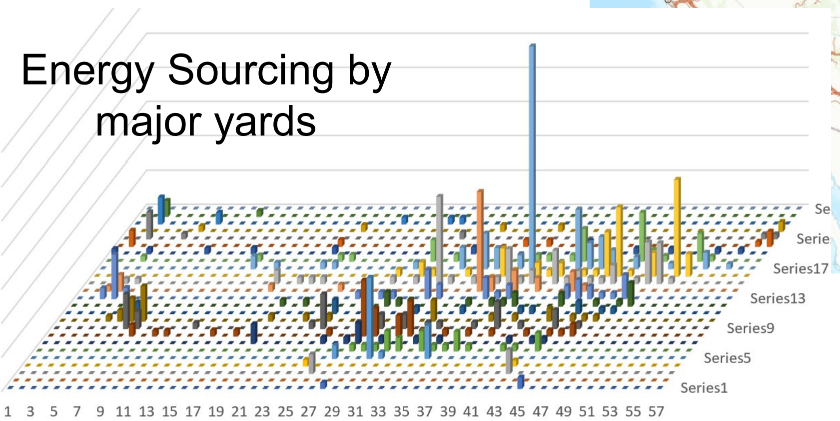
Freight Flows between FAF Regions



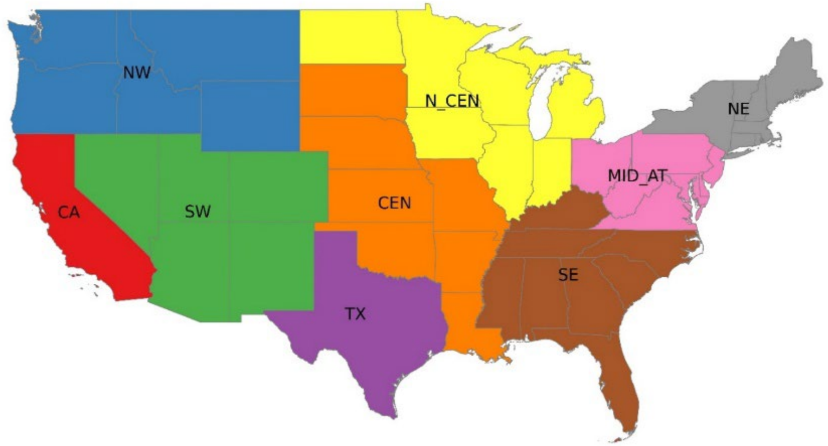
Flow Assignment to FRA Rail Network



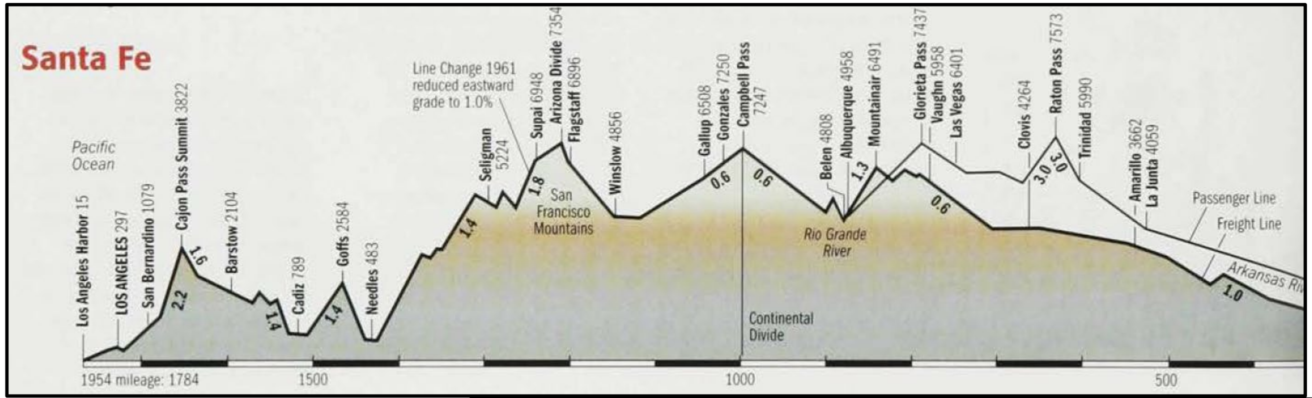
Energy Sourcing by major yards



Ton-Miles by Temoa Region



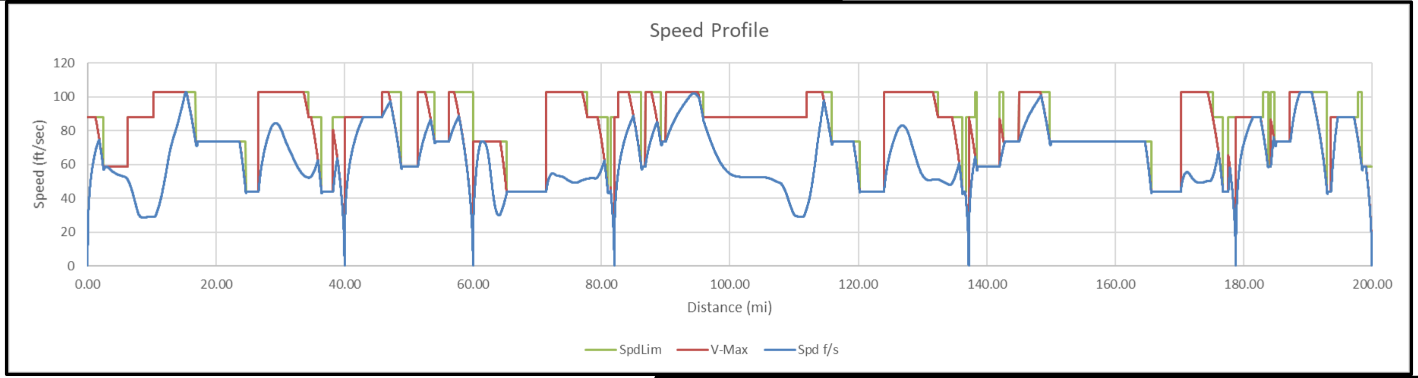
Energy Intensity and Sourcing Breakdown

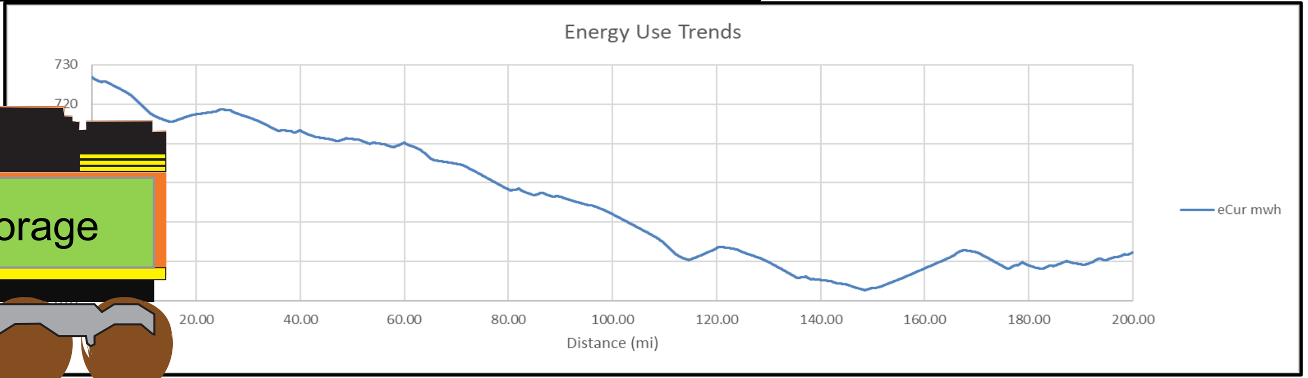


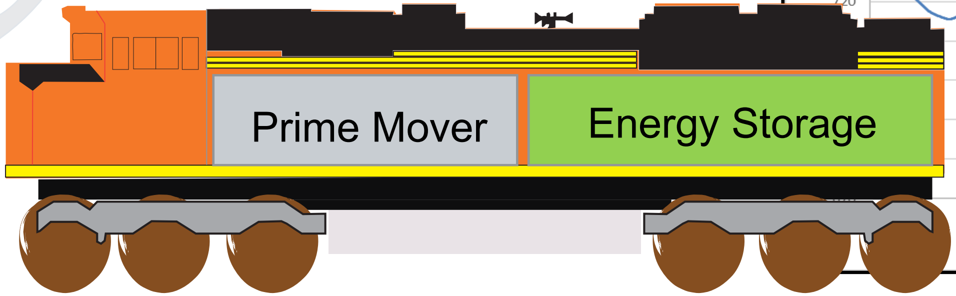
Source: Trains Magazine, April 2004

Single Train and Network Simulators

- Tractive effort
- Resistance
- Power demand
- Energy consumption
- Regenerative braking
- Distributed power
- Multiple energy sources
- Train conflicts

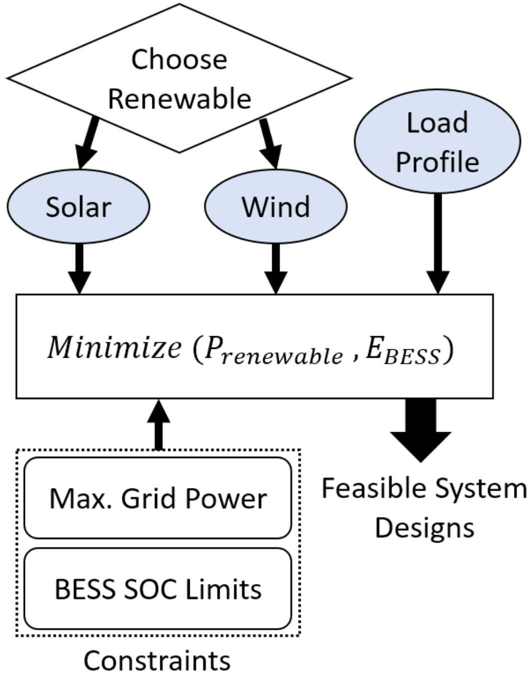


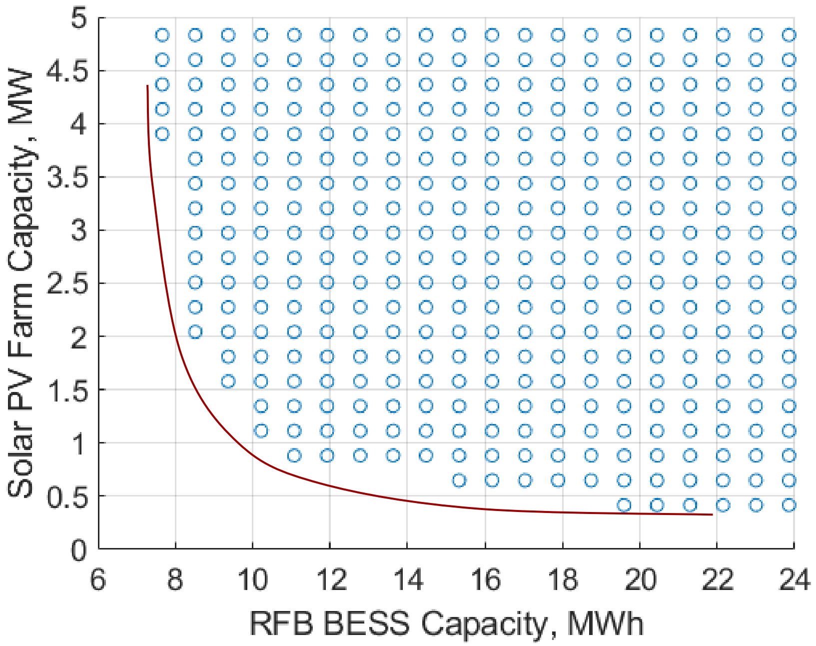




Infrastructure Investment Assessment (3)

- Sizing/optimization tool output: example trade-off between minimum battery energy storage capacity and solar PV capacity, shown in Pareto front





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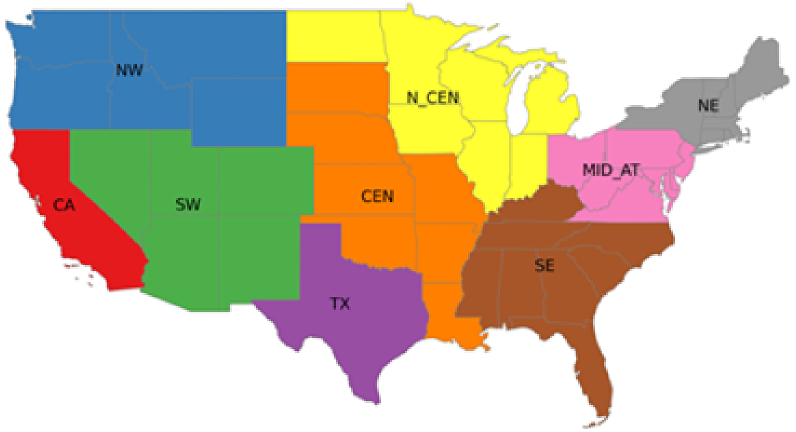
Nationwide Energy Demand / Supply Assessment

- Time horizon until 2050, solved myopically; each time period represented by 8 days (hourly)

2020 → 2025 → 2030 ···· → 2050

Nine model regions



- Over 3000 distinct demands; 80,000 processes
  - Techno-economic data derived from NREL, EPA, EIA, etc.
  - Fuel prices are exogenous, based on AEO scenarios (Reference and Low Oil Price)
- We use modeling to generate alternatives (MGA) to explore alternate feasible solutions with near-minimum system costs

Recap

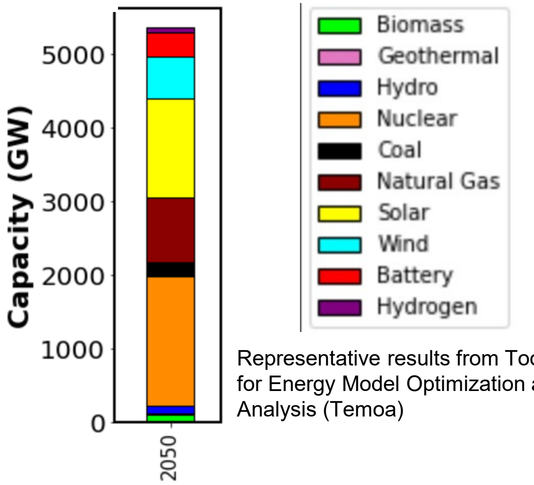
Energy System Futures

Decarbonization Scenarios

1. Business as Usual
2. 50% Reduction by 2050
3. Net Zero by 2050

Energy System Sensitivities

1. High/low renewable cost
2. Subsidized hydrogen
3. High/low oil and gas prices



Representative results from Tools for Energy Model Optimization and Analysis (Temoa)

Rail Freight Futures

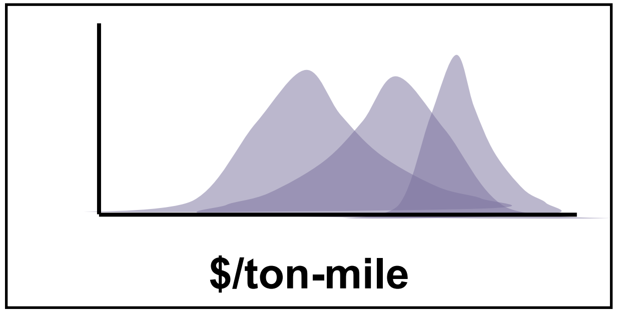
Six rail freight futures representing fundamental shifts in how we move goods and materials

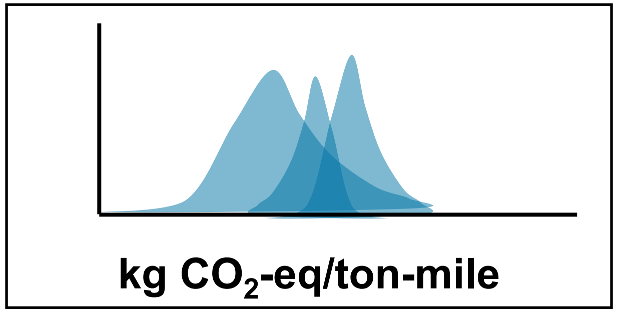
1. Reduced fossil fuels
2. Shifting population to the Sunbelt
3. Decreased agricultural production
4. Agricultural shifting
5. Increased maritime access to the East Coast

Impact and Option Assessments

Spatially and temporally resolved costs

- Energy intensity assessment through train simulation
- Capital investment needs
- Nationwide energy demand and supply
- Fuel and electricity unit costs
- Operations and maintenance costs

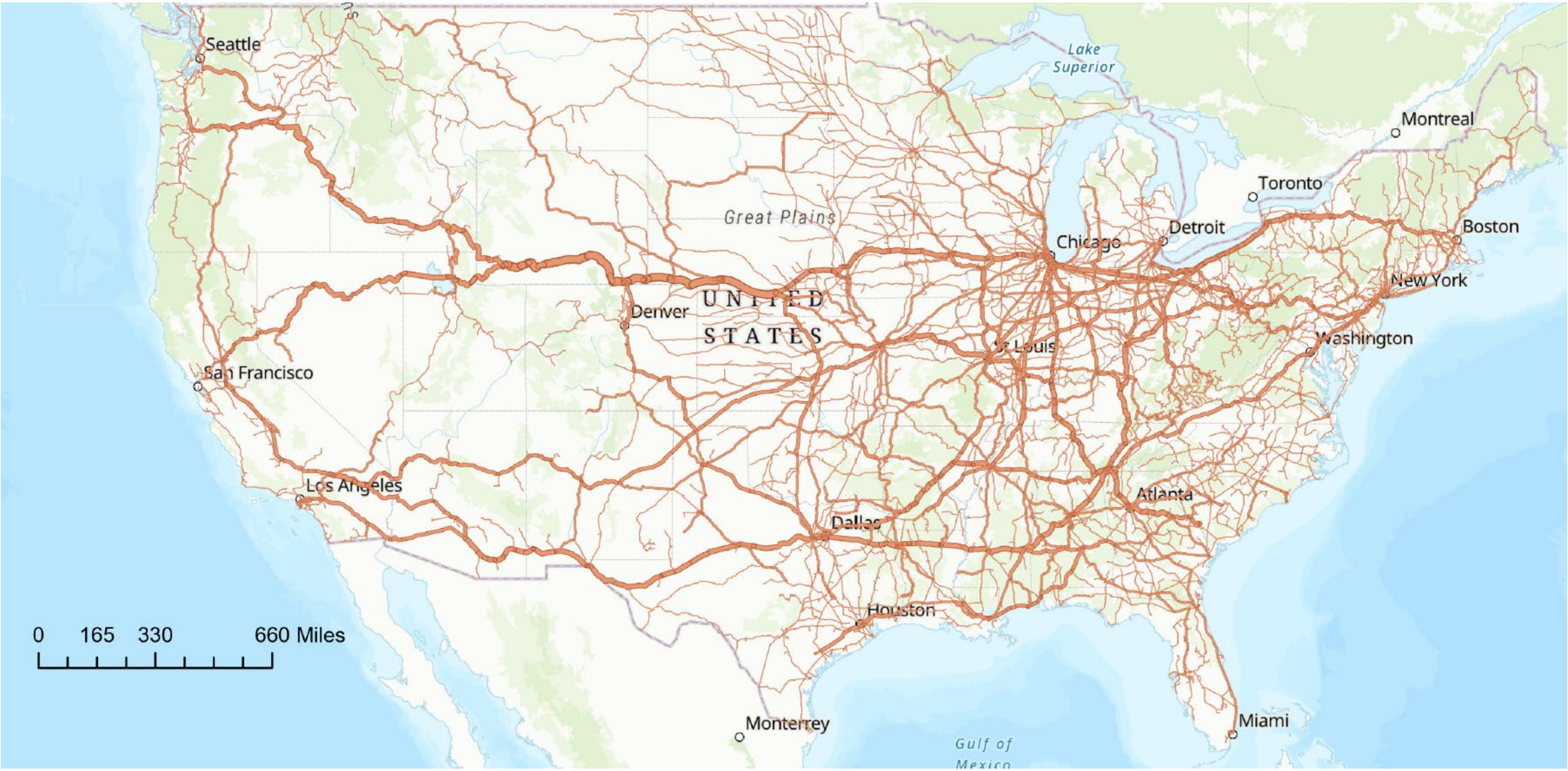




Project Outreach

- A publicly available, free, and open-source software tool (A-STEP)
- Provide techno-economical analyses for decarbonizing freight rail
- Provide insights for decision-making guiding freight rail decarbonization (e.g., whether there need to be incentives to speed adoption of new technologies)
- Help potential adopters identify paths, identify risk factors, and monitor the most salient aspects of technology deployment

Thank You / Questions



Acknowledgement: Support provided by the LOCOMOTIVES initiative, ARPA-E

Backup

Freight Demand Scenarios

Estimates of future freight demand for three economic scenarios as developed by the Freight Analysis Framework (FAF) team [1]:

1. Baseline economic growth
2. Low economic growth
3. High economic growth

- Five rail freight demand sub-scenarios:

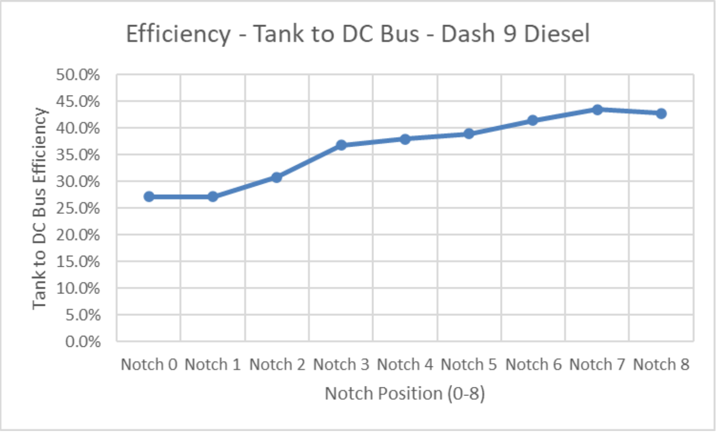
    a. Reduced fossil fuels
    b. Population shift to the sunbelt
    c. Decreased agricultural production
    d. Shift in agricultural production
    e. Increased maritime access to East Coast

Sub-scenarios a-e are used in combination with the economic scenarios 1-3.

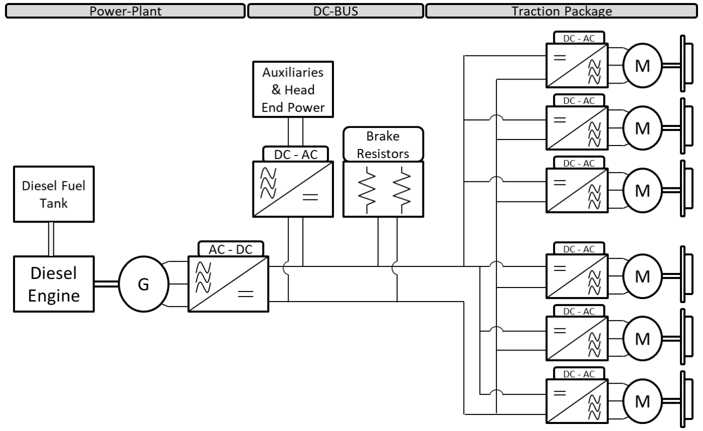
[1] BTS, 2022. Freight Analysis Framework [WWW Document]. Bur. Transp. Stat. URL https://www.bts.gov/faf (accessed 4.21.22).

Milestone M1.5: Functioning single train model and documentation report

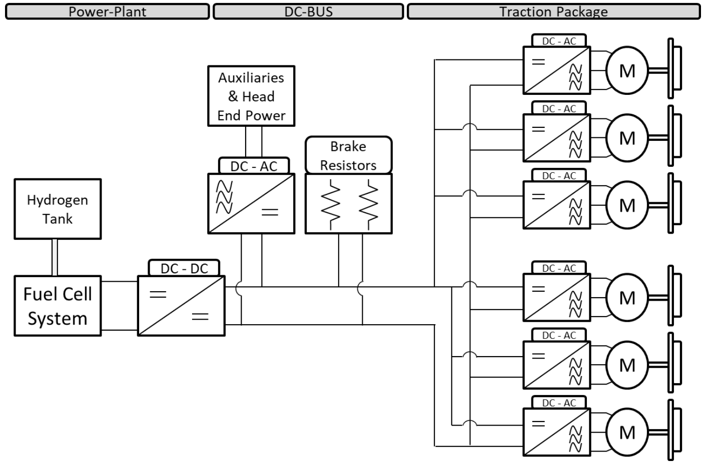
Efficiency Maps to Represent Propulsion System:
Tank to DC Bus
DC Bus to Wheel



Diesel-Electric Powertrain (With AC traction motors)



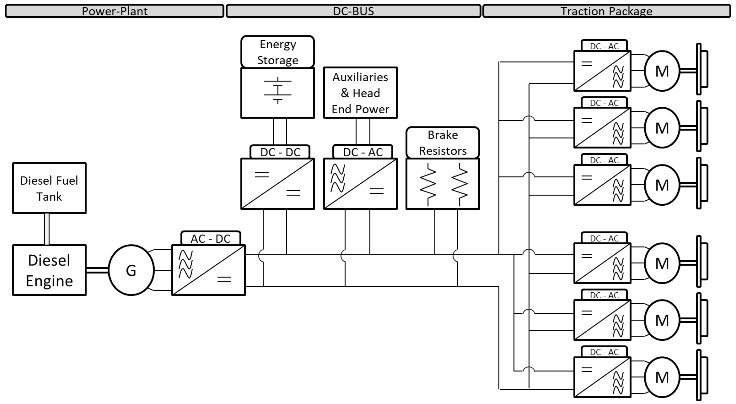
Hydrogen Fuel Cell Powertrain



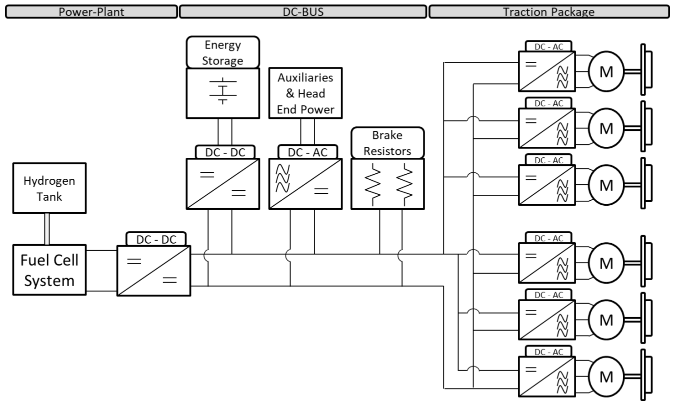
Milestone M1.5: Functioning single train model and documentation report

Additional Propulsion Systems:

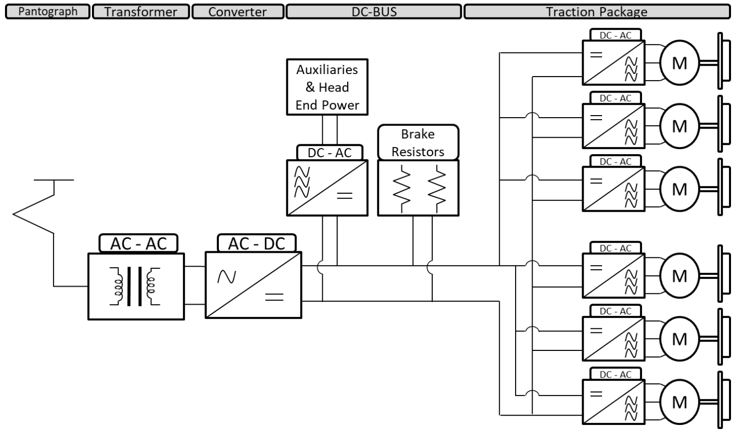
Diesel-Electric Hybrid Powertrain



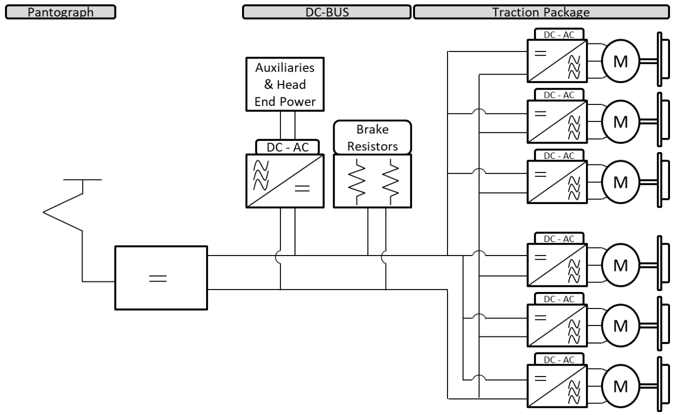
Hydrogen Fuel Cell Hybrid Powertrain



AC Electric Locomotive



DC Electric Locomotive



Tasks and Lead Participants

Institution	Participant	1 Single Train Perf. Sim	2 Multi Train Net. Sim.	3 Infrastr. Req'ts	4 Decarb. Energy Paths	5 Prob. Cost Modeling	6 Freight Demand Scen.	7 TT&O	8 Inte-grated Assess.
NC STATE UNIVERSITY	G. List (PI)	★	★	●			●	★	LEAD
NC STATE UNIVERSITY	J. Johnson (PM)	●	●	●	LEAD	LEAD	●	●	★
NC STATE UNIVERSITY	E. Bardaka					●	LEAD		●
DB	A. Hoffrichter	LEAD	★	★	●	●	●	★	★
DB	L. Harris	★	★	★	●	●	●	LEAD	★
VIRGINIA TECH	H. Rakha	★	LEAD					●	
VIRGINIA TECH	K. Ahn	★	★					●	★
Oregon State University	Y. Cao	★	★	LEAD	●	●		●	●
	Graduate Students	●	●	●	●		●	●	●
	Project Advisory Committee							★	

LEAD Task Leader ★ Major Contribution ● Contribution

Project Visualization

A-STEP

Achieving Sustainable Train Energy Pathways

Project Scope - Years

2020 → 2025 → 2030 → 2035 → 2040 → 2045 → 2050

Project Scope – Shift in Energy Sources

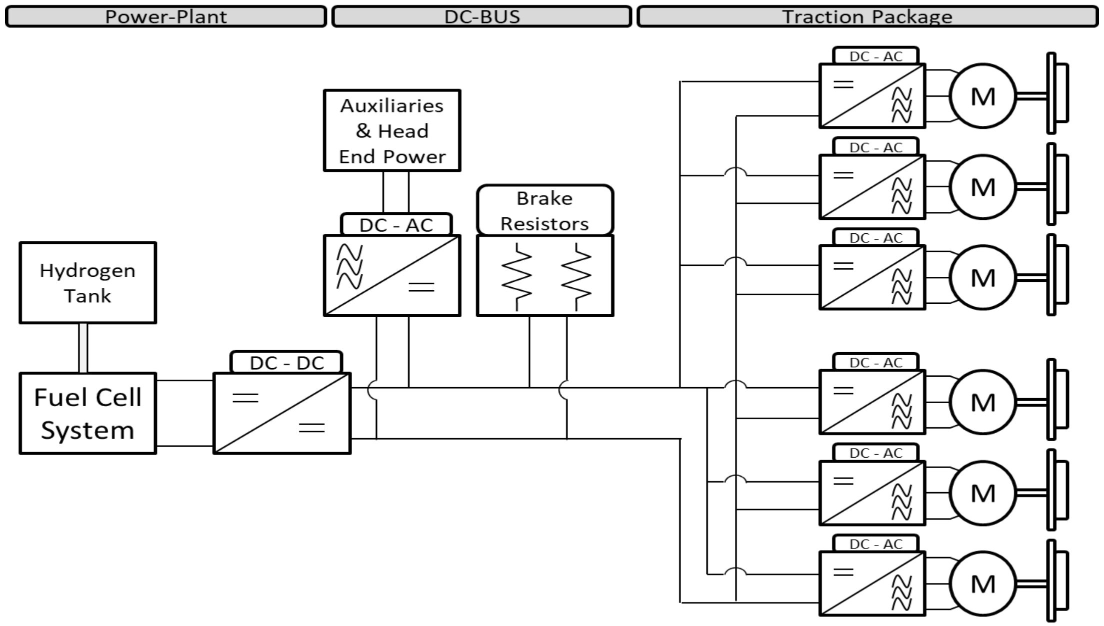
Freight → Shift to Alternate Energy Source → Decarbonization Toolset

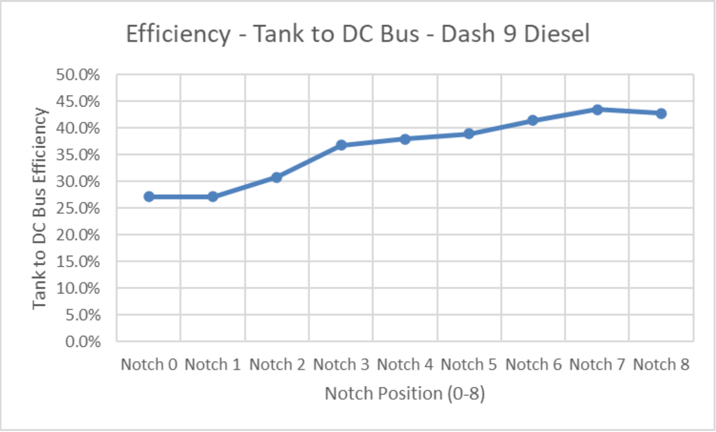
Major Focus on Hydrogen

Energy Sourcing - Details

Efficiency Maps to Represent Propulsion System:
Tank to DC Bus
DC Bus to Wheel

Hydrogen Fuel Cell Powertrain





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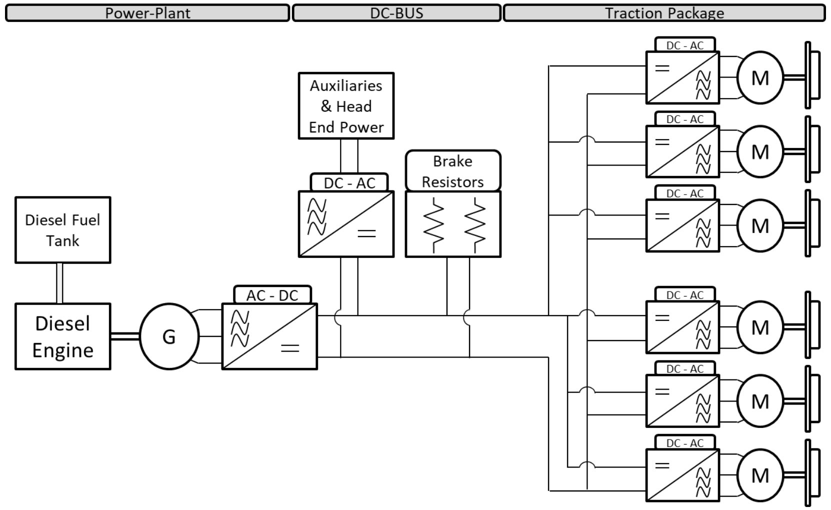
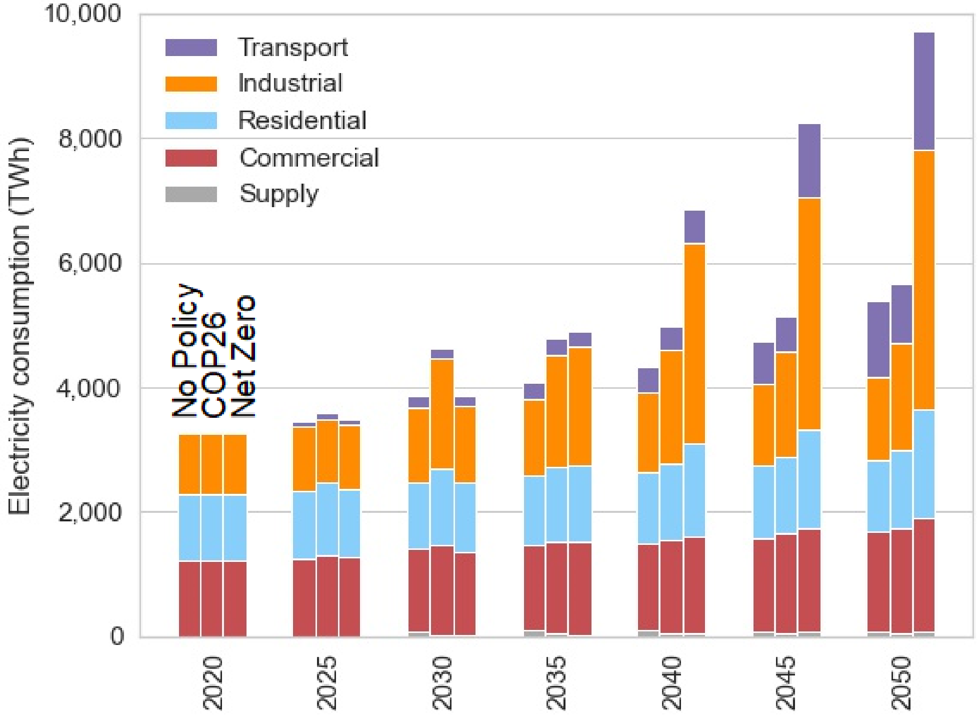
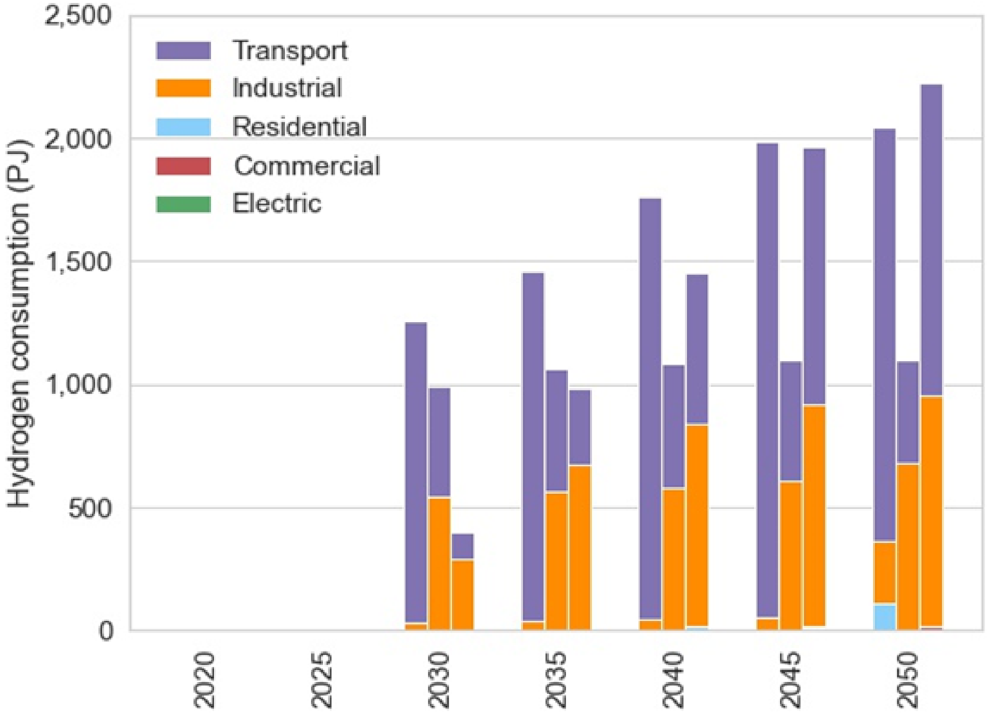


Energy System Decarbonization Pathways (2)

Industry and transport sectors drive growth in electricity and hydrogen demand





Single Train Simulator

- Example outputs