Decarbonization Analysis of Mobile Sources (FWP-FEAA443)

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Feasibility analysis for onboard mobile carbon removal roadmap

- ORNL FY23 – FY25
- $1M/21 months. NETL-collaboration

CC technologies
- Solid sorbents
- Liquid sorbents
- Membranes

→

Evaluation criteria
- Energy requirements
- CC efficiency & selectivity
- Integration & complexity
- Durability & maturity

→

Outputs
- Down selection
- Operational boundaries
- Packaging needs

Mobile Sector
- HD long haul trucking
- Rail
- Marine (ocean going)

→

Evaluation criteria
- Available space
- Thermodynamic assessment
- Ram airflow
- Water accessibility

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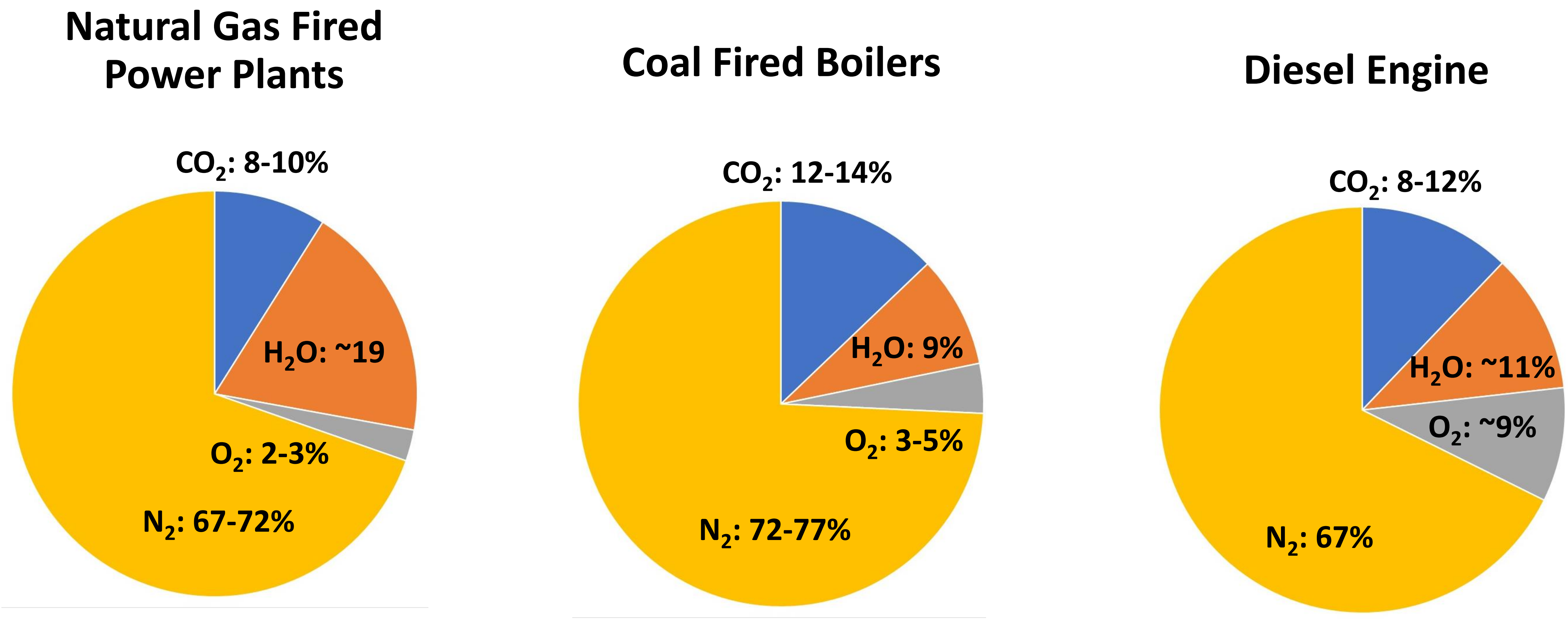
Outputs
- Opportunities for waste-heat recovery
- Opportunities for utilizing ram air and water

How does the exhaust for mobile sources differ from natural gas power plant and coal fired boilers?



A conventional diesel engine has more variable operation and will produce more oxygen in the exhaust.

General Exhaust Characteristics

Characteristic	Heavy Duty Truck			Rail[1]		Marine 2-stroke (distillate) 6 cyl[2]			
	Low load	Typical cruise	High load	Idle	Notch 8*	25% load	50% load	75% load	100% load
Fuel use, g/s	6	7.7	17.8	5	195	86	164	245	334
Intake air flow, g/s	158.6	171.3	389.9	1458	6992	10084	14760	20476	22662
Air/Fuel ratio	26.43	22.2	21.9	345	36	117	90	83.6	67.9
Exhaust flow, m^3/s	165	179	407	6.1	27.8	10170	14924	20720	22996
Exhaust temp, °C*	272	377	257	140	410	224	248	293	349
CO2, g/s	19.1	24.5	56.2	13.3	606.7	265	338	506.4	1068.6
H2O, g/s	7.48	9.6	22.02	4.9	223.4	116.4	148.4	222.9	480.4
NOx, g/s	0.007	0.004	0.002	0.32	10.1	3.5	5.6	10	26.8
CO, g/s	0.05	0.2	0.14	0.002	0.368	0.24	0.51	0.70	1.4
HC, g/s	0.009	0.02	0.077	0.032	0.143	0.13	0.15	0.25	0.66
SO2, g/s	<1ppm	<1ppm	<1ppm	75E6	0.003	<89ppm	<89ppm	<89ppm	<89ppm
O2, %	15	9	5	20	12	17.22	17.81	18	18.6

[1] Diesel Locomotive Fuel Efficiency & Emissions Testing. Report for NSW EPA. ABMARC. 2016
[2] DMD-S50MEC-16-1/LR. Technical File. Lloyd's Register Classification Society. 2017
*Note that Notch 8 is a high speed and load operating condition

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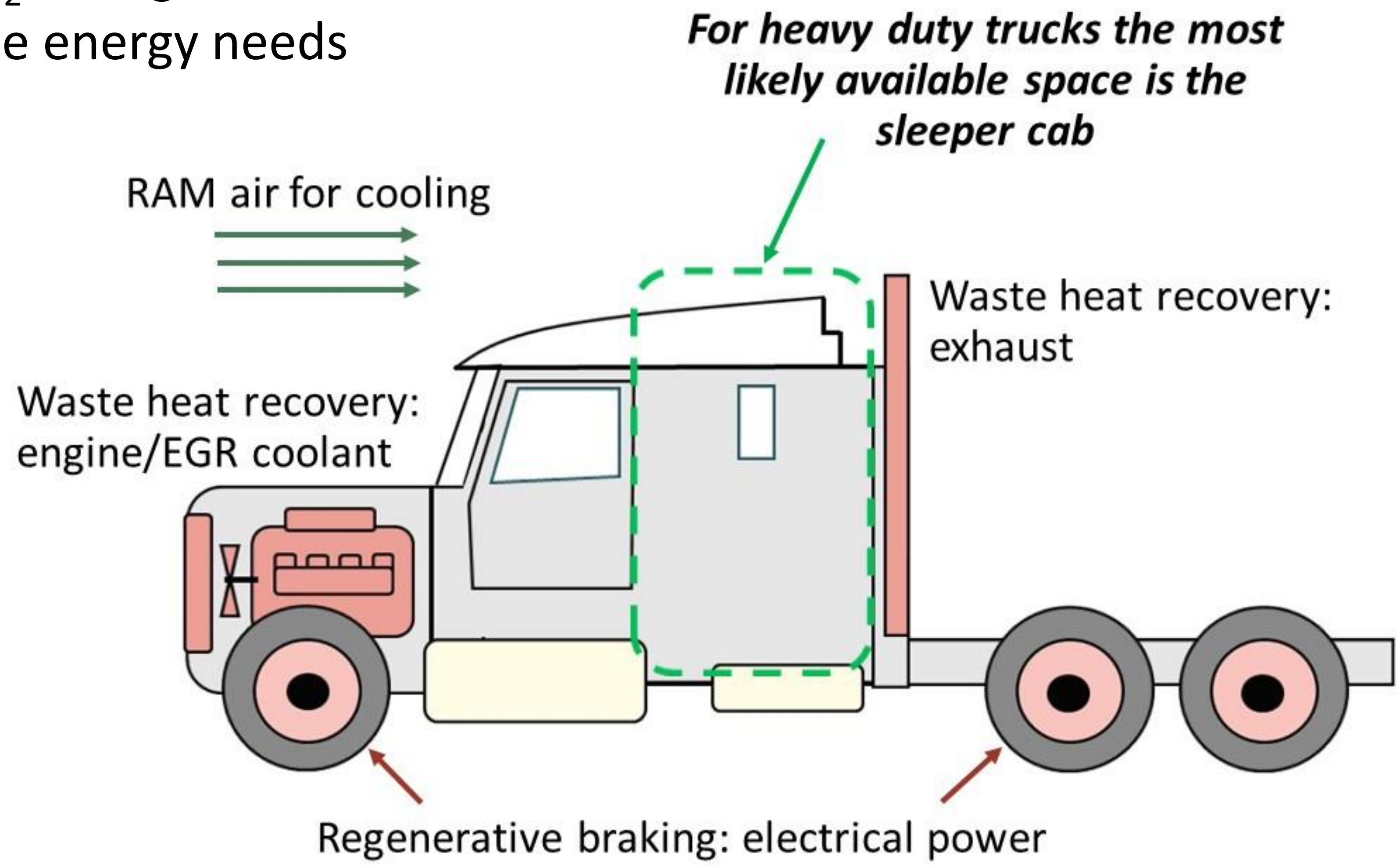
Heavy Duty Trucks: Available space and energy recovery options

- **Working demo produced by Aramco Americas**
  - Amine solvent/membrane
  - Onboard regeneration & CO_2 storage
  - Utilized waste heat to reduce energy needs
  - System placed downstream of aftertreatment system
- **Demo produced by Remora utilizes solid sorbents**

Sleeper cab dimensions:

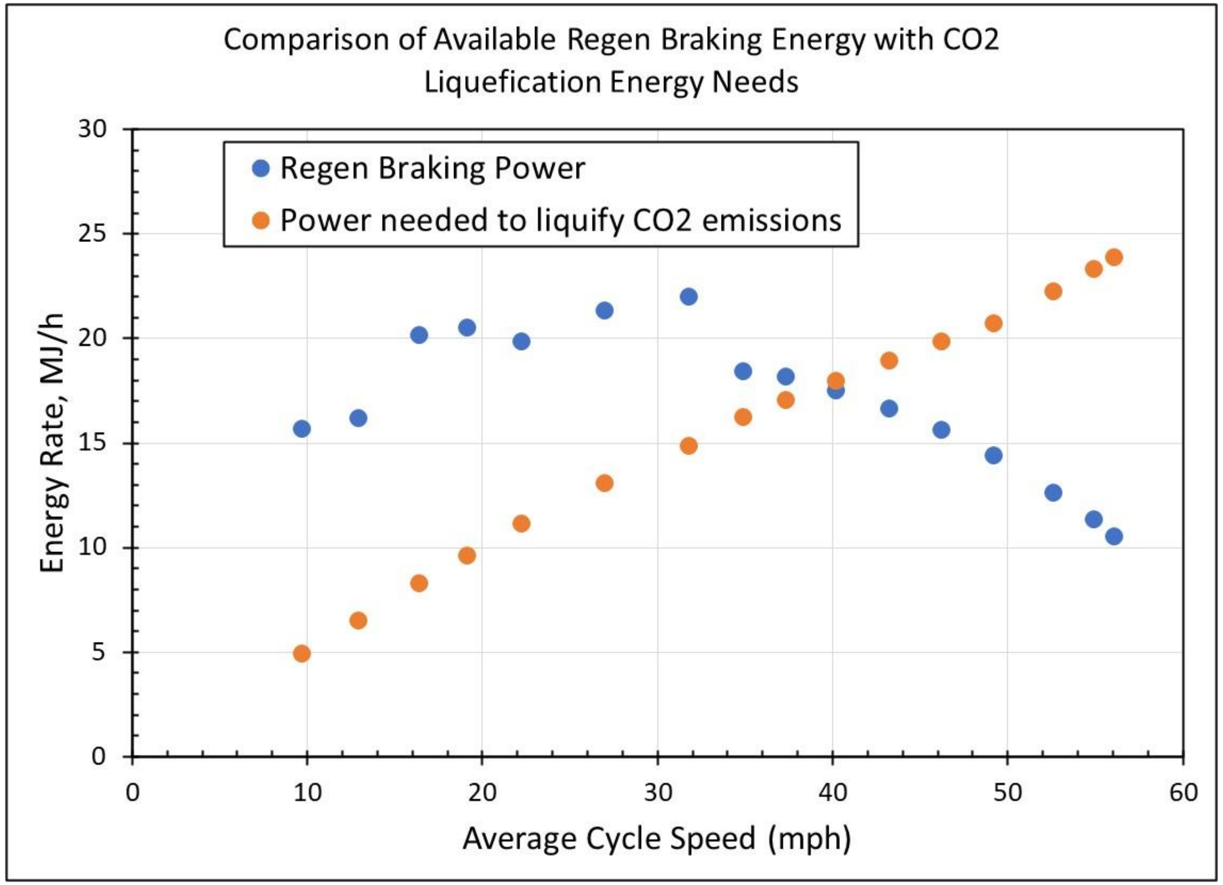
Height	11ft	3.35m
Depth	3.5ft	1.07m
Width	8ft	2.44m
Volume	$308ft^3$	$8.75m^3$



Available regenerative braking energy for heavy-duty (HD) trucks

Diesel System Efficiency				
HD vehicle & engine performance			EV regenerative braking efficiency	
Avg. cycle speed	Fuel efficiency	Energy efficiency		
Mph	Mpg	%	%	
9.7	6.437	28.4	27.4	Short haul
12.9	6.483	34.1	21.4	
16.4	6.486	34.5	21.0	
19.1	6.507	37.0	18.4	
22.2	6.530	39.8	15.4	
27.0	6.778	40.2	14.1	Regional
31.8	7.027	40.5	12.8	
34.9	7.050	43.4	9.8	
37.3	7.174	43.5	9.2	
40.2	7.329	43.7	8.4	
43.2	7.484	44.0	7.6	
46.2	7.639	44.2	6.8	Line haul
49.2	7.794	44.4	6.0	
52.6	7.748	44.5	4.9	
54.9	7.716	44.6	4.2	
56.1	7.701	44.7	3.8	

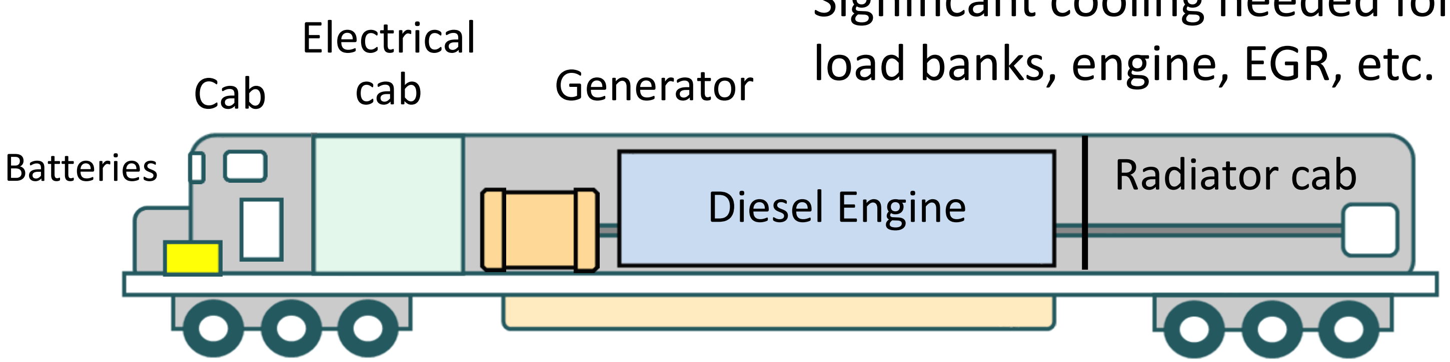
Analysis indicates that regenerative braking is best suited for short hauls



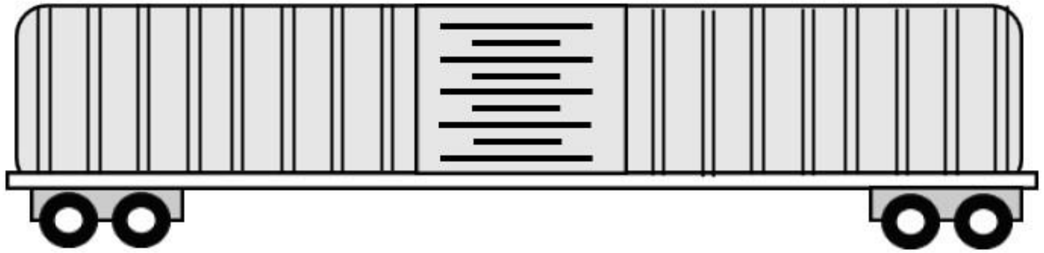
For rail, the most likely space for CO_2 storage is a separate car

- No known demos planned
- Engines have EGR, but no other exhaust aftertreatment
- Anticipated system volume less tanks would be ~ 9000 ft^3 (255m^3)
- CO_2 tank size, based on 5,000-gallon diesel fuel load would be ~ 1700 ft^3 (48m^3) based on a 95% capture eff.
- Likely also need to package emissions controls, ~ 300 ft^3 (8.5 m^3)
- Bottom line: Separate tender car will need to be used. Volume can support full CCS system

Significant cooling needed for load banks, engine, EGR, etc.



Channeling exhaust to tender car is nontrivial



Box Car dimensions:

Height	10ft	3m
length	50ft	15m
Width	10ft	3m
Volume	50,000ft^3	1415m^3

*A. Voice & E. Hamad. 16th Int. Conf. Greenhouse Gas Tech. 2022

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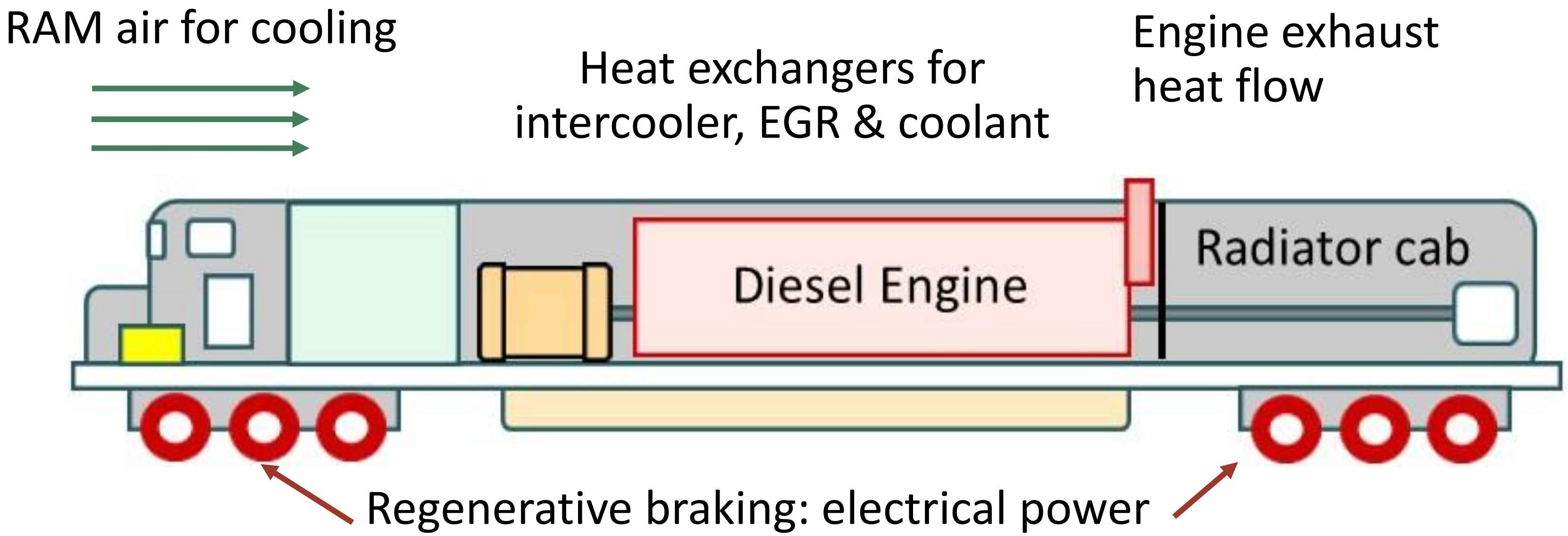
Points of energy recovery for rail: exhaust heat and electrical energy available from regenerative braking

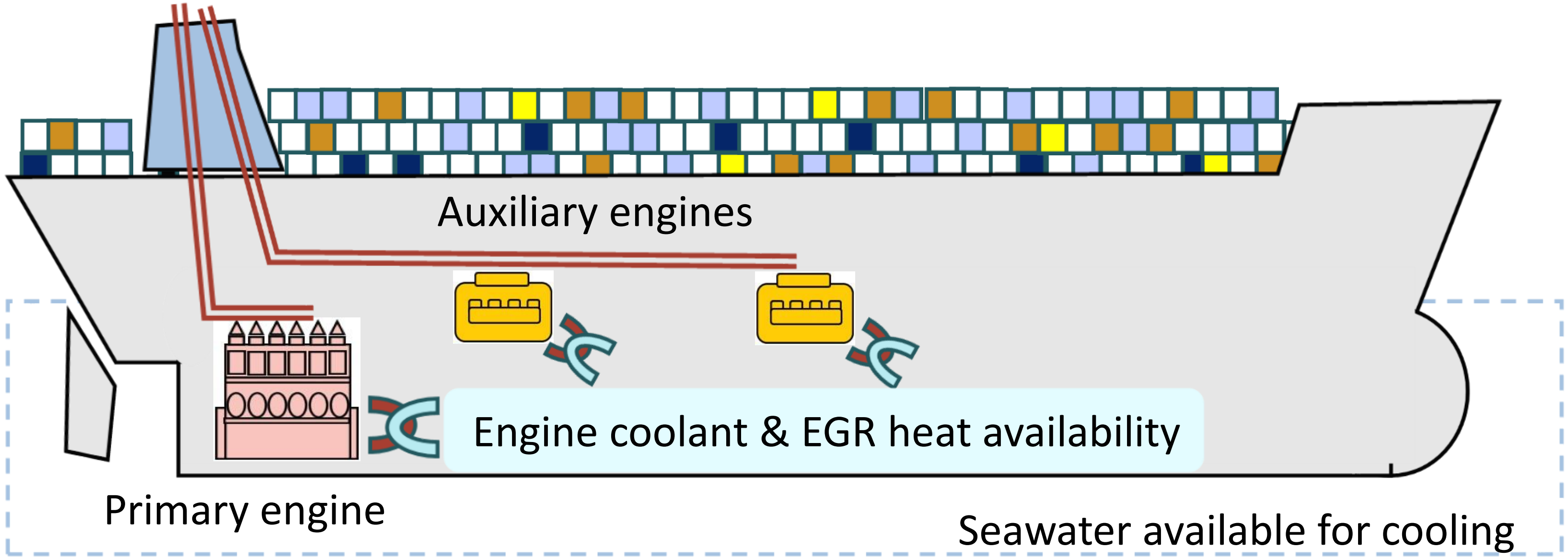
- Exhaust heat provides 5 – 8 kJ/g CO_2 which is sufficient for regeneration of CC solvent (e.g., amine solution)
- Regenerative braking energy currently dissipated as heat could be captured as electricity
  - Around 90 kWh electrical power is needed to liquefy one ton of CO_2. (S. Jackson and E. Brodal 2018 IOP Conf. Ser.: Earth Environ. Sci. 167 012031)

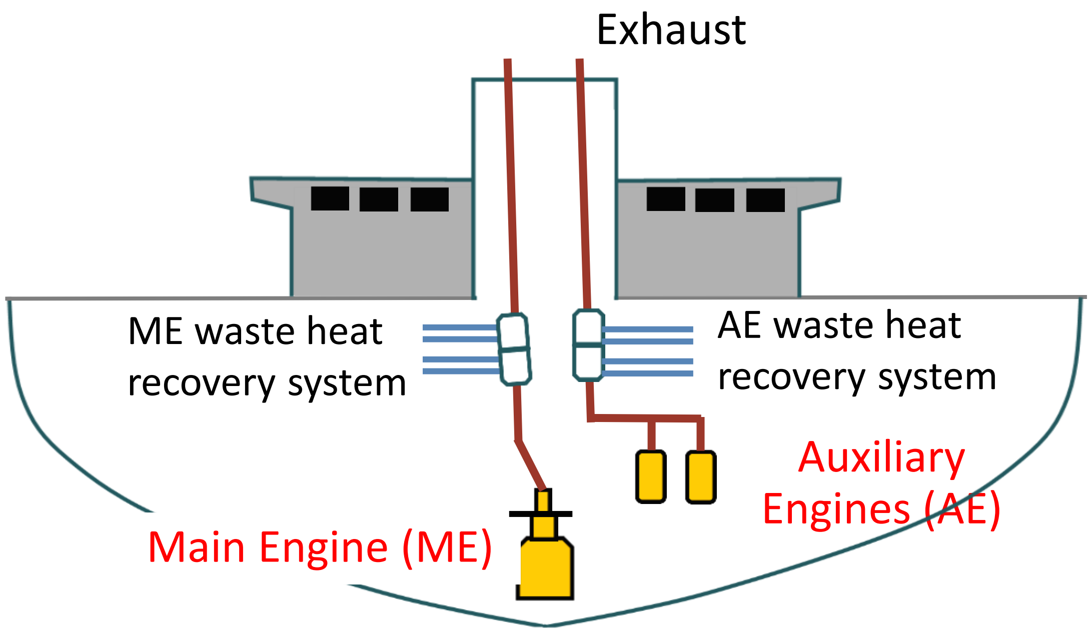


  - Mayrink et. al. showed 23.87% of fuel energy used could be recovered from regenerative braking (Energies 2020, 13, 963)
  - CO_2 compression and liquefaction would need on the order of 1% of the fuel energy per tank of fuel
- **Bottom line:** Rail has enough recoverable waste heat and electrical power to power an onboard CCS system

Points of energy recovery for marine shipping: exhaust heat

- In addition to the primary mover (2-stroke engine), ships are also equipped with boilers (to supply heat) and auxiliary (4-stroke engines) to provide electrical power
- Exhaust heat is utilized if the exhaust temperature > 250°C
- Seawater available for cooling
- Demonstrations planned for CCS using amine-based solvents
- Other demonstrations have considered limestone as solid sorbent





Summary

- Tabulated exhaust characteristics for each mobile sector option
- Assessed spatial needs and waste energy recovery options
  - HD trucking has known energy penalty associated with onboard CCS. This can be mitigated by regenerative braking for some drive cycles
  - Energy needs for a rail CCS system can be met by waste energy recovery. Penalty associated with towing additional tender car
  - Questions regarding maritime spatial allowances and energy penalties. Several demonstrations are in the works. Multiple approaches are being evaluated
- Future efforts to include:
  - TEA/LCA analysis
  - Baseline competition analysis

Thank you

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