Fuel Cell System Optimization for Rail and Maritime Applications

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U.S. DOE Hydrogen and Fuel Cells Program

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Project ID: FC329

Overview

Timeline

- Start date: Oct 2019
- End date: Open
- Percent complete: NA

Budget

- FY19 DOE Funding: 0
- Planned DOE FY20 Funding: $300K
- Total DOE Funding Received: $150K

Barriers (FC)

A. Durability

B. Cost

C. Performance
(System Thermal and Water Management, Air Management, Startup and Shut-down)

Partners/Interactions

- Caterpillar
- Cummins
- Wabtec
- Sandia National Laboratory

- This project analyzes configurations, performance and durability of heavy-duty fuel cell systems for rail (long-haul freight, regional and switcher locomotives) and maritime (feeder container ships, ferries and tugs) applications

Objectives and Relevance

Model and analyze configuration, performance and durability of heavy-duty fuel cell systems (HD-FCS) for rail (long-haul freight, regional and switcher locomotives) and maritime (feeder container ships, ferries and tugs) applications

- Optimize fuel cell system designs incorporating novel state-of-the–art materials and components, to achieve high efficiencies and lifetimes required for rail and marine applications
- Identify modular configurations for fuel cell systems that are scalable to MW sizes as needed in these applications
- Identify gaps and barriers. Recommend key research and development challenges for adoption of fuel cell technology in rail and marine applications
- Provide input to guide concurrent techno-economic analyses efforts

Relevance:

- HD-FCS for trucks, rail and maritime are relevant to the H2@Scale initiative as they can create a large-scale demand for H_2 and possible use (refueling) close to production site
- MW-scale diesel engines are highly developed, robust, and durable (34,000 MWh for freight locomotives, 25 years for maritime) with efficiencies exceeding 50%. HD-FCS must compete with them on performance basis
- Fuel cells and H_2 must also compete with the incumbent diesel technology on cost basis. This project provides inputs to the concurrent total-cost-of ownership (TCO) analyses;
- Opportunity for hydrogen and fuel cells: Tier 4 emission standards for locomotives and pending tighter EPA regulations for sulfur, NOx, CO and HC; pending IMO regulations for sulfur, NO_x (and CO_2) emissions in open seas

Milestones

Define and analyze configurations for fuel cell systems as replacement for Tier-4 diesel engines in long-haul locomotives	12/31/2019	Annual Milestone (Regular)
Define and analyze configurations for fuel cell systems as replacement for marine-gas oil and LNG combustion engines in container ships	3/31/2020	Annual Milestone (Regular)
Develop performance and durability requirements for fuel cell systems for long-haul locomotives	6/30/2020	Annual Milestone (Regular)
Develop performance and durability requirements for fuel cell systems for container ships	9/30/2020	Annual Milestone (Regular)

Reference Locomotive: GE ET44AC

Approach: FCS for Rail

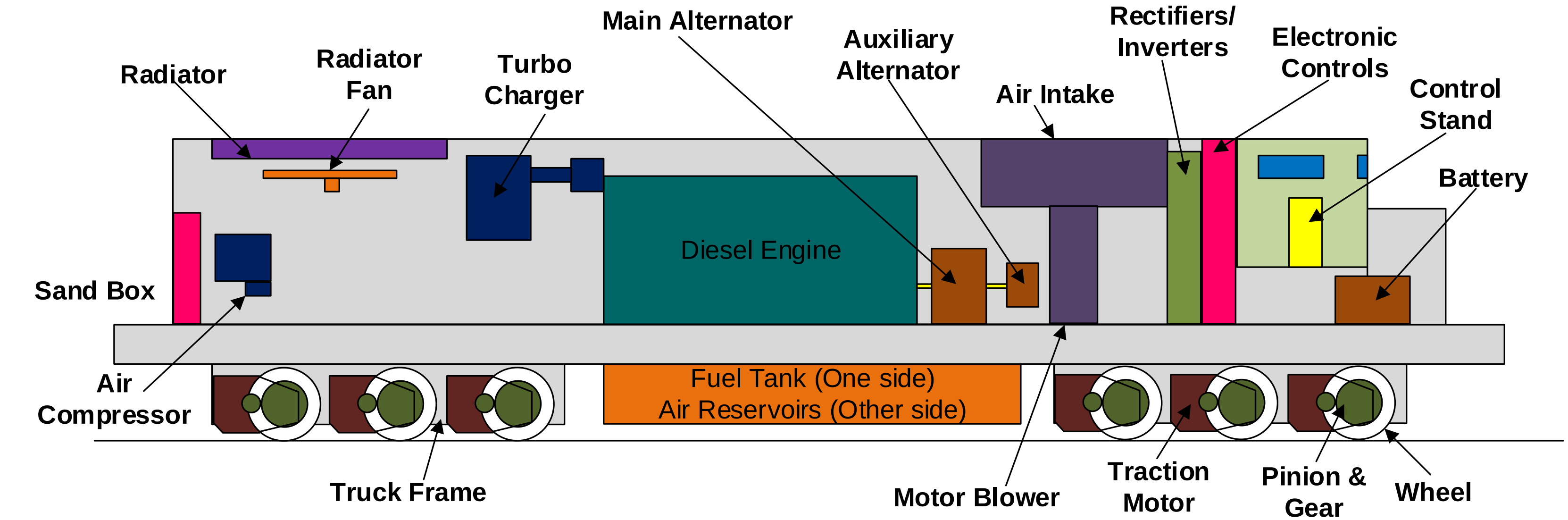
4,400 HP GE ET44AC Locomotive:

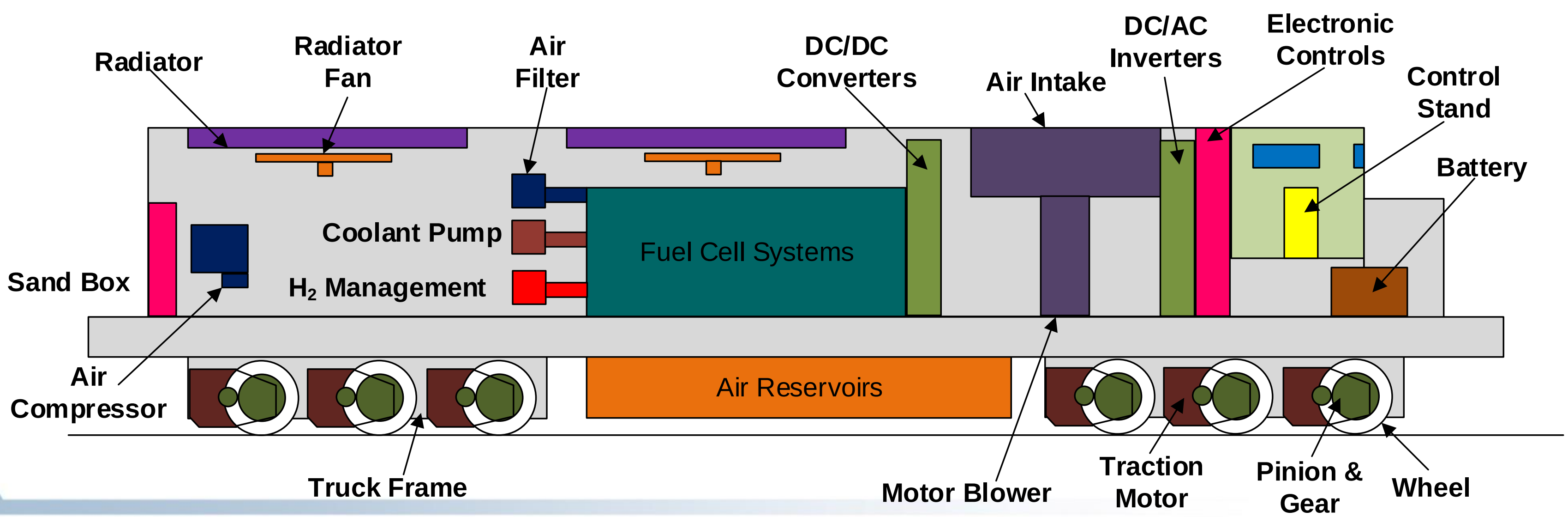
Meets Tier 4 emissions without any after-treatment

Model	ET44AC	ES44AC
Wheel arrangement	C-C	C-C
Length	74' 6"	73' 2"
Weight	426,000 lbs	432,000 lbs
Height	16' 1"	15' 5"
Engine control system	GE CCA	GE CCA
Engine	GEVO-12	GEVO-12
Number of cylinders	12	12
Traction horsepower	4,400	4,400
Traction alternator	GMG205	GMG205
Traction motors	GEB13	GEB13
Maximum speed	72 to 75 mph	72 to 75 mph
Fuel capacity	-	5,000 gals

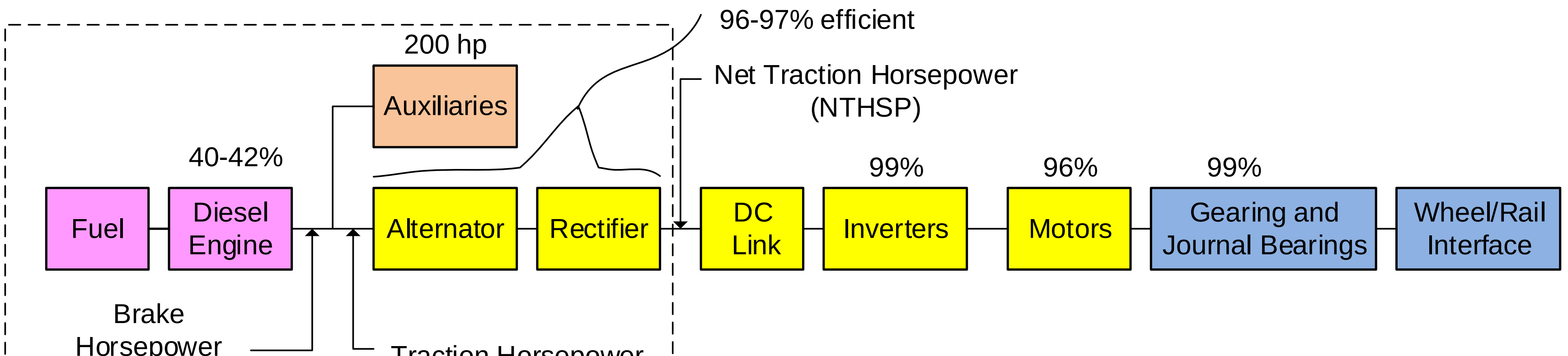
Fuel Cell Locomotive: Concept Development

FCS replaces the diesel engine and uses the existing electric drivetrain, bus bar and controls; LH_2 is stored in a separate tender car



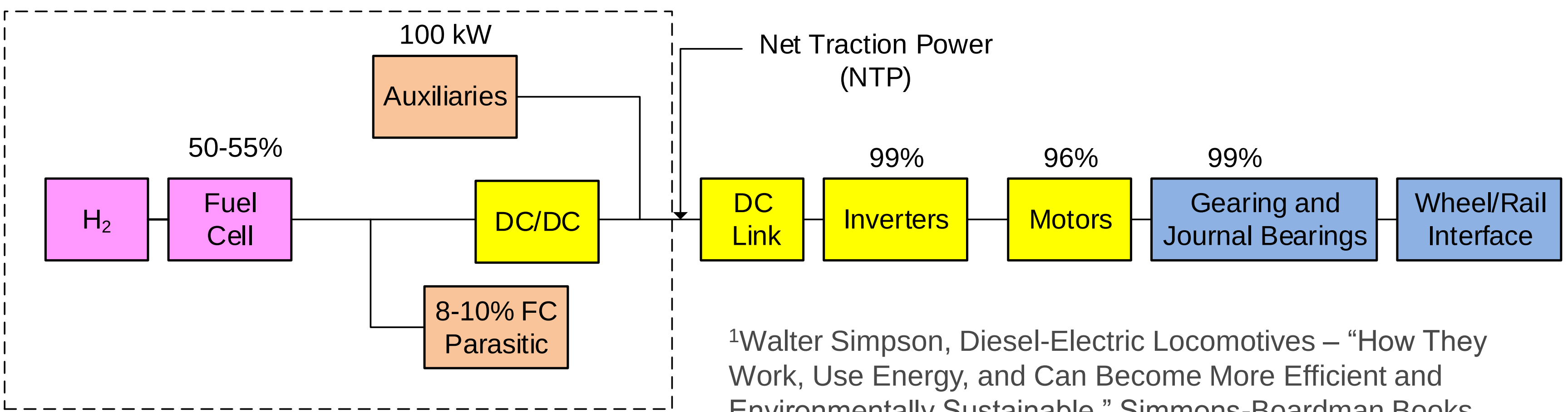


Fuel Cell Locomotive: Performance



Walter Simpson, Diesel-Electric Locomotive, ISBN 9780911 282693

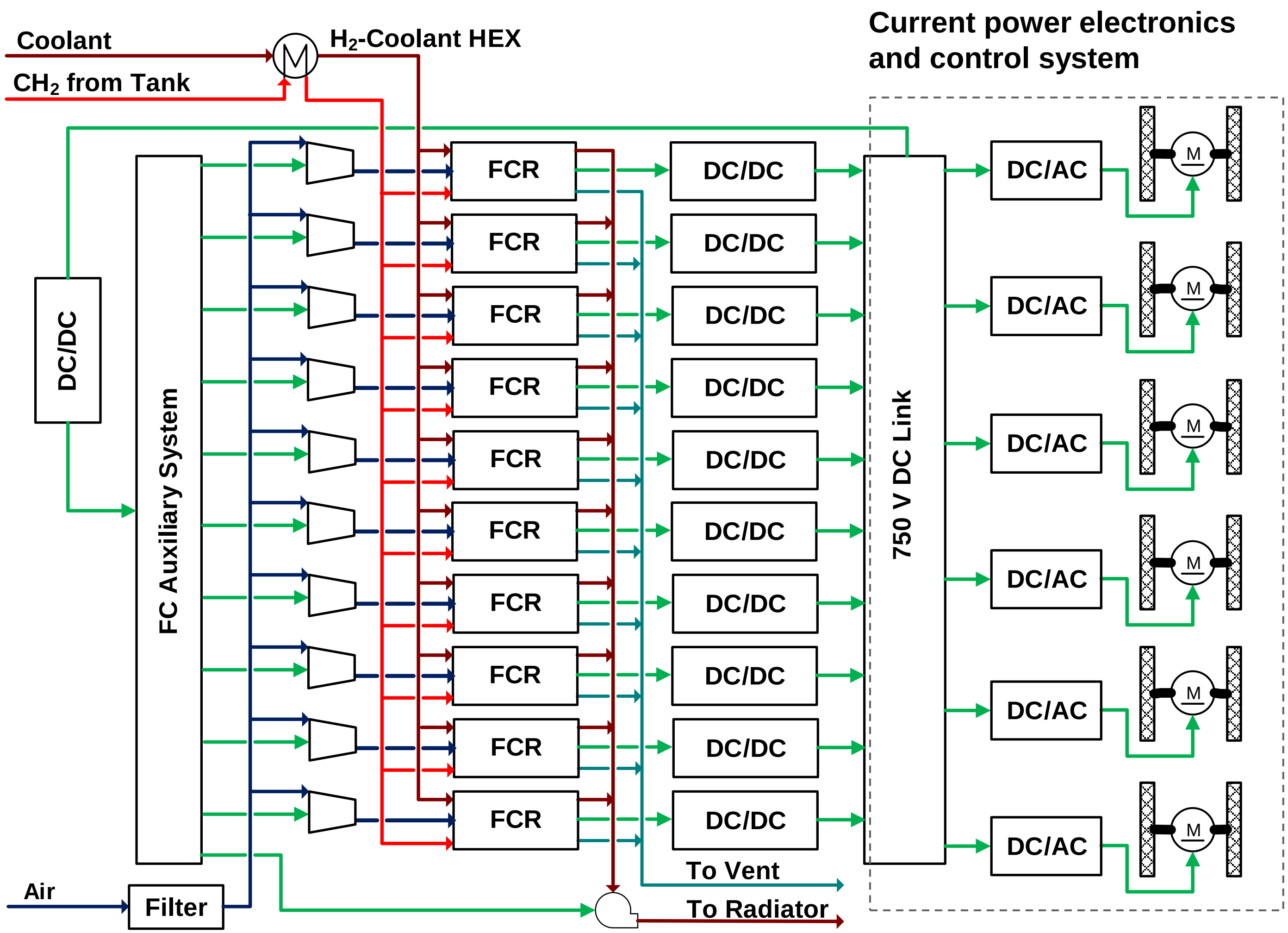
Replacing diesel engine in an electromotive with FCS is made easier by the existing electric drive. Alternator and rectifier are replaced with a DC/DC converter, offering 2-3% gain in efficiency.



[1]Walter Simpson, Diesel-Electric Locomotives – “How They Work, Use Energy, and Can Become More Efficient and Environmentally Sustainable,” Simmons-Boardman Books, Omaha, NE (2018)

Fuel Cell Locomotive: Modular Concept

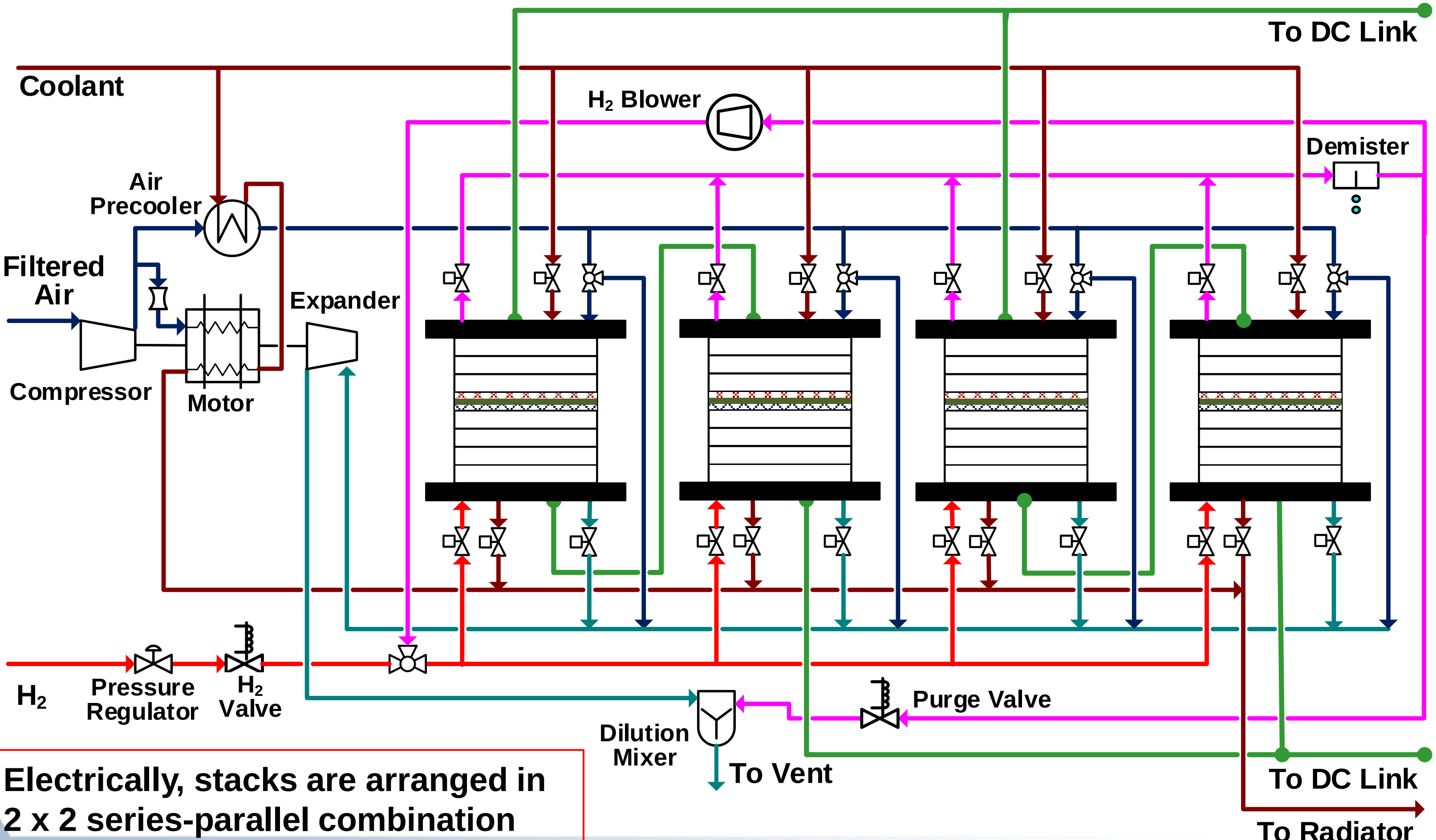
A fuel cell module (FCM) combines 10 fuel cell racks (FCR) to form a 3.2 MW_e power system. FCM shares a common coolant circuit but the FCRs have separate air and H_2 systems. Possible to have the same 750 V DC link as in diesel-electric.



Fuel Cell Locomotive: Rack Concept

A 320-kW$_e$ FCR consists of 4x100 kW$_e$ stacks with common air and H_2 systems.

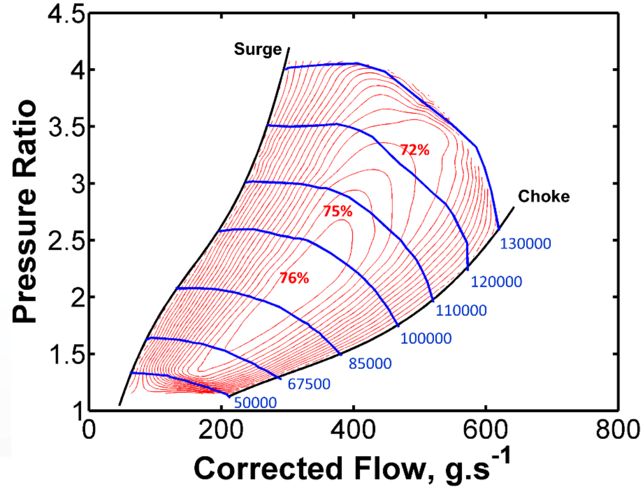
- Cathode: 0.25 mg/cm^2 Pt loading in a-Pt/HSAC; membrane: TBD; anode: TBD
- Air system with expander; anode system with recirculation blower
- Rated power: 2.5 atm, 87^{o}C, 0.7 V
- Control valves for startup/shutdown, cold start and OCV control

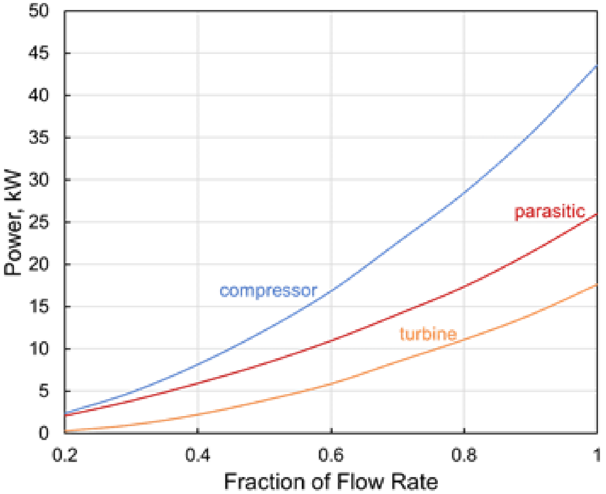


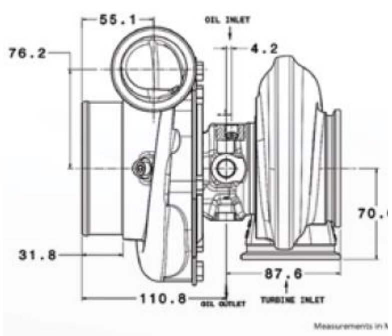
Electrically, stacks are arranged in 2 x 2 series-parallel combination

Air Management for Fuel Cell Rack

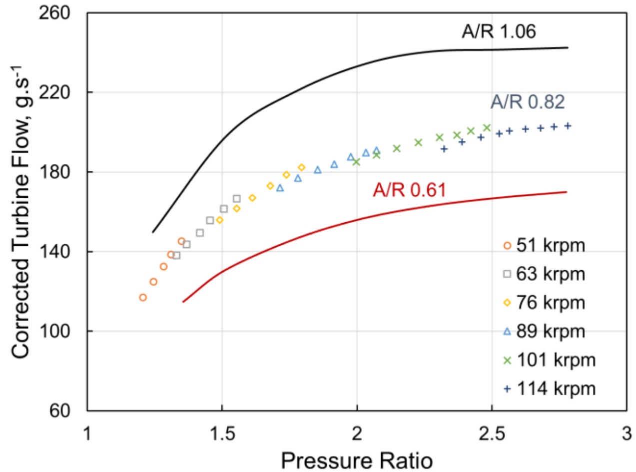
Garrett GTX3582R
GEN II Turbocharger

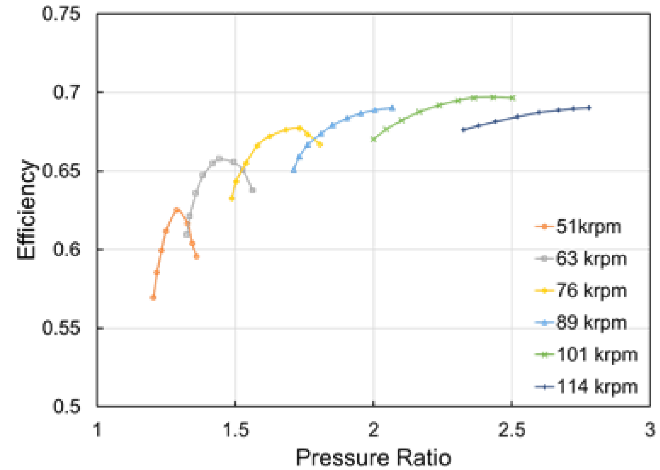






A/R: Inlet cross-sectional area / center to center radius



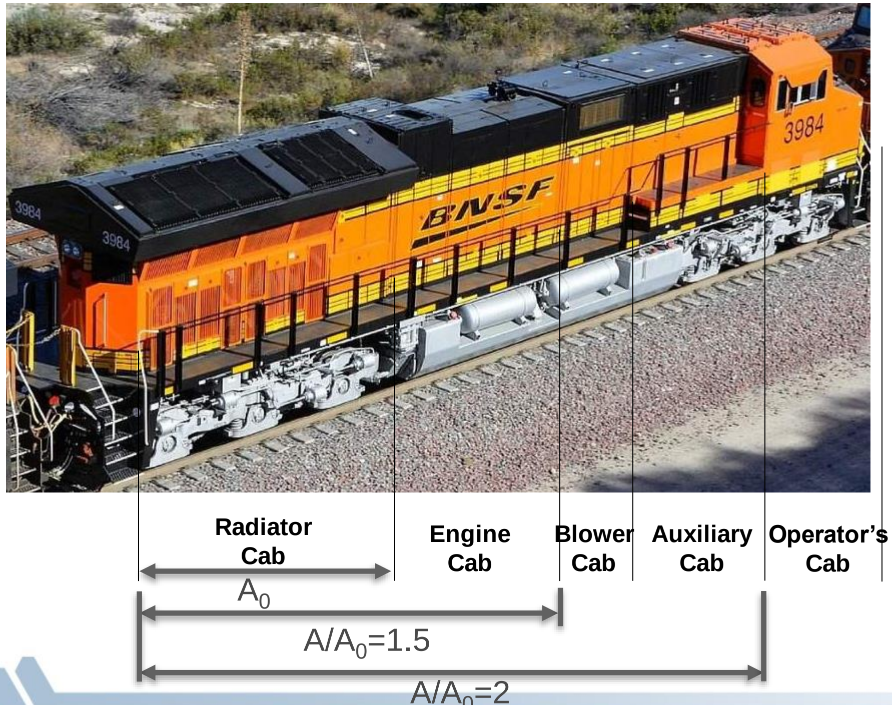


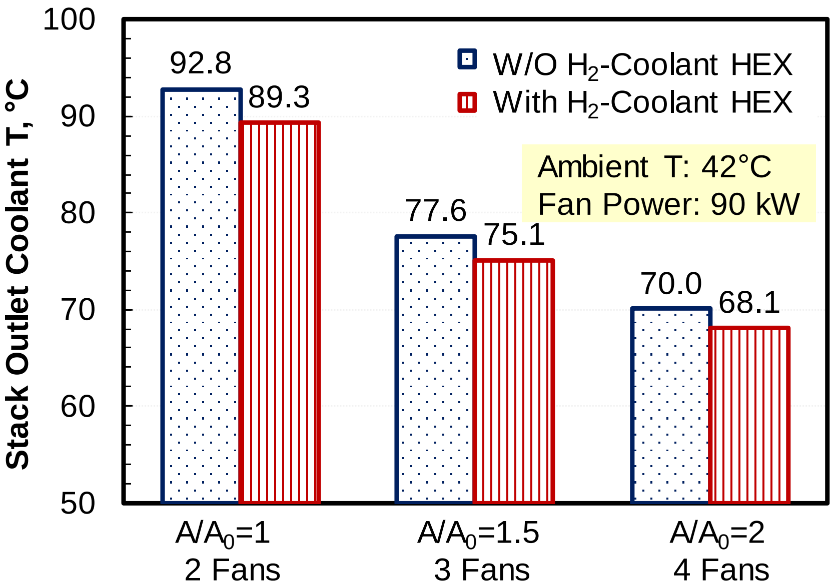
A truck supercharger can serve as the air management system for FCR.

- **At rated power, compressor consumes 45 kW; 25 kW_e net parasitic CEM power**

Fuel Cell Locomotive: Heat Rejection

- **ET/ES locomotives have radiators on the roof, and radiator fans underneath providing forced draft.**
- **Fuel cell locomotive thermal management is challenging because of lower operating temperatures, requiring 2X heat transfer area.**
- **Cryogenic H_2 from tender car absorbs 3% of waste heat and lowers the stack coolant temperature by 2-3°C**



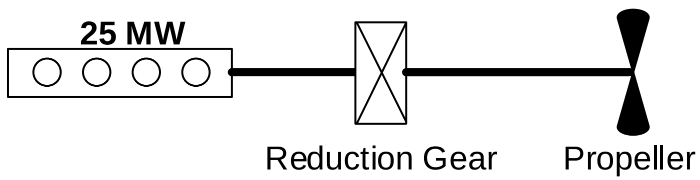


Diesel Powertrain for Feeder Container Ship

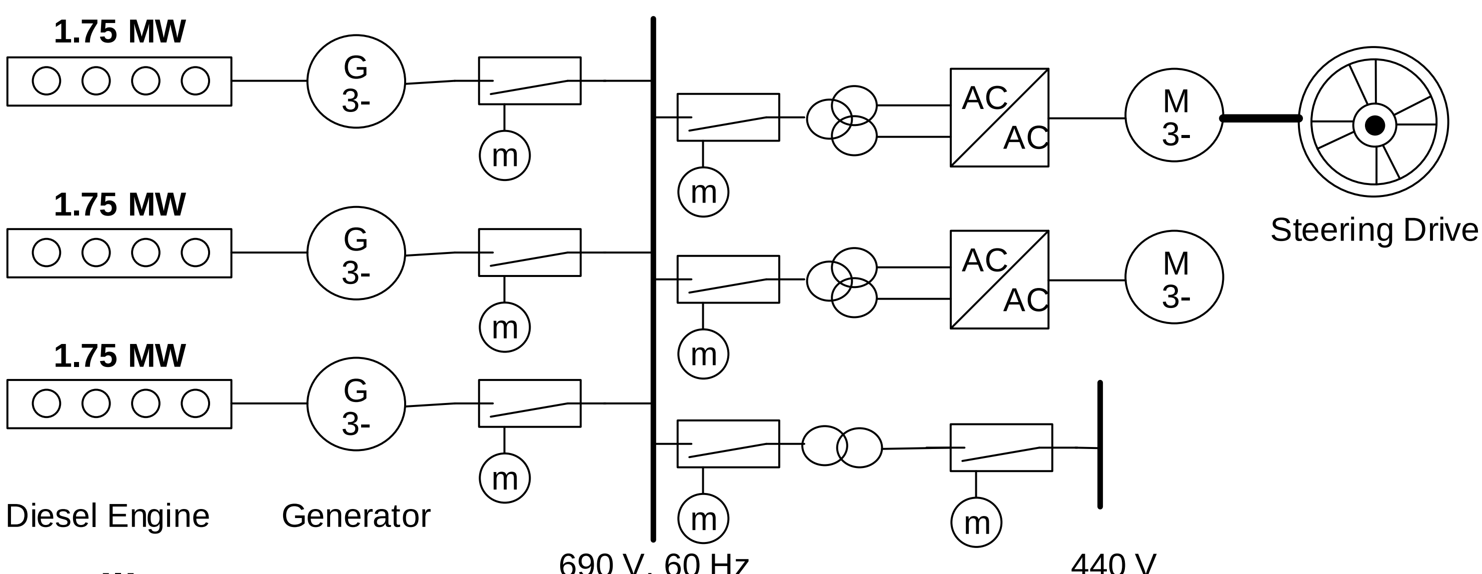
Approach: FCS for Maritime

Isla Bella LNG Container Ship

- Main Dimensions: 233(L)X32(W)X10(D)m
- Performance: 2100-TEU (36,571 T)
- Engine: 25-MW main, 3x1.75-MW auxiliary
- Service life: 25 years



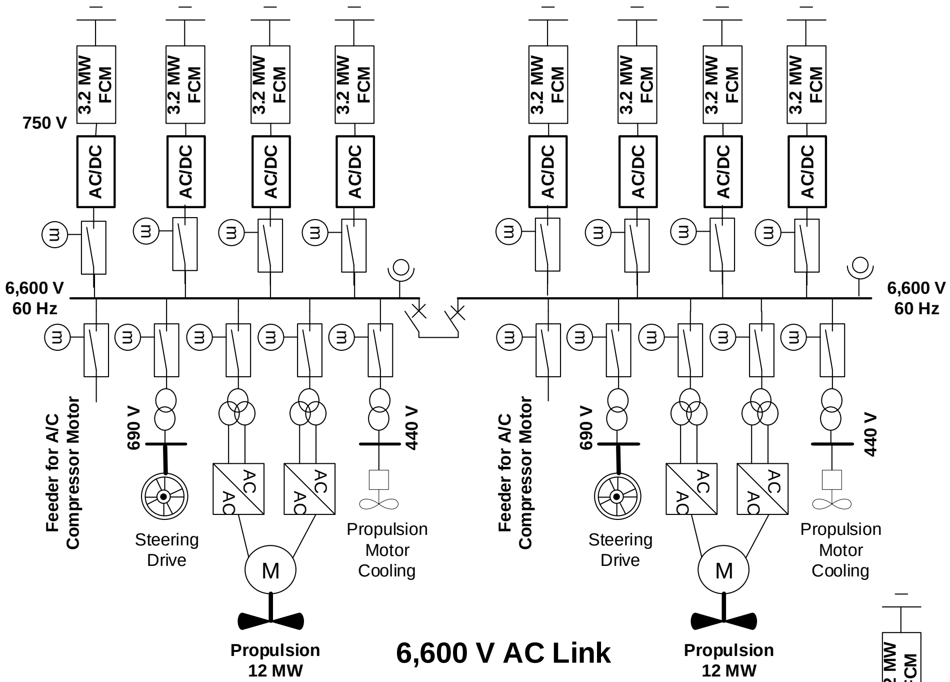
Primary Mover and Propulsion



Auxiliary Genset

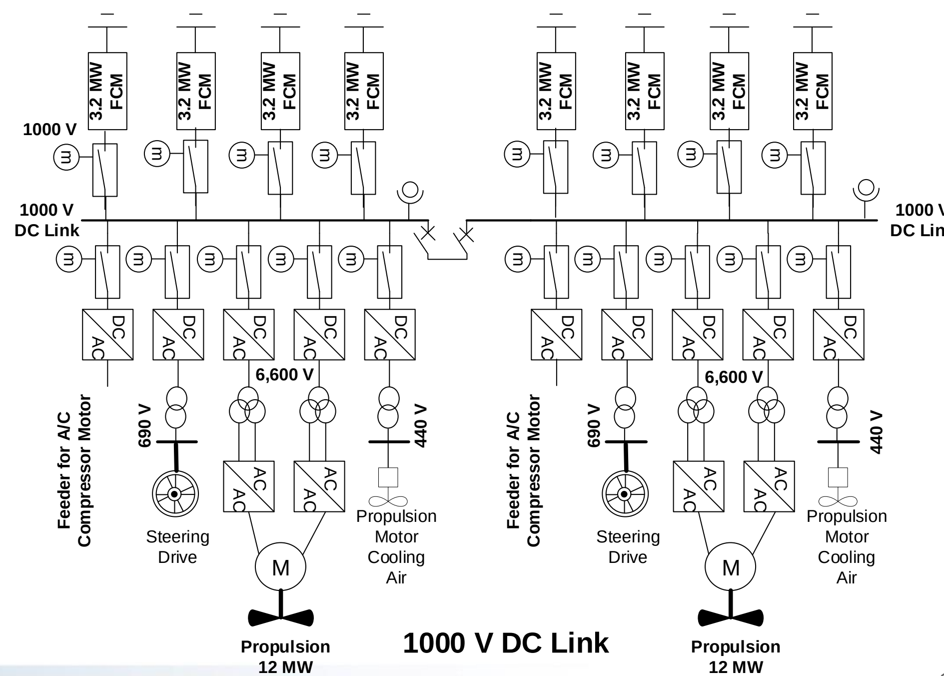
Fuel Cell Electric Propulsion System

Accomplishments: FCS for Maritime



FCS Container Ship

A 26-MW FCS replaces 25-MW propulsion engine and 3 x 1.75 MW$_e$ auxiliary genset

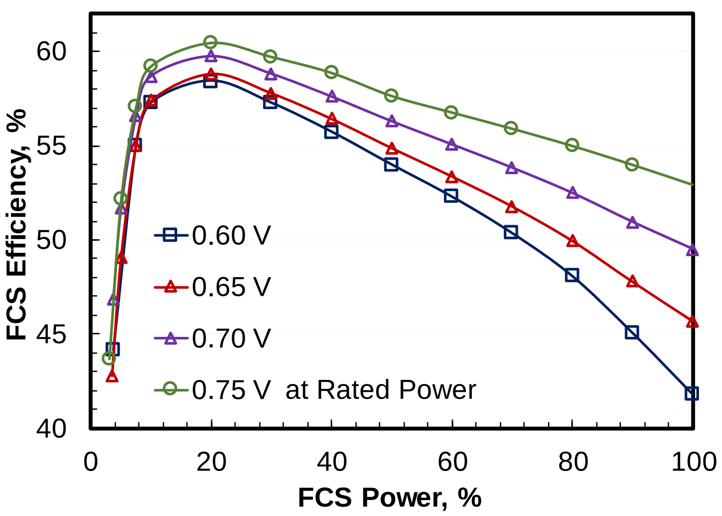


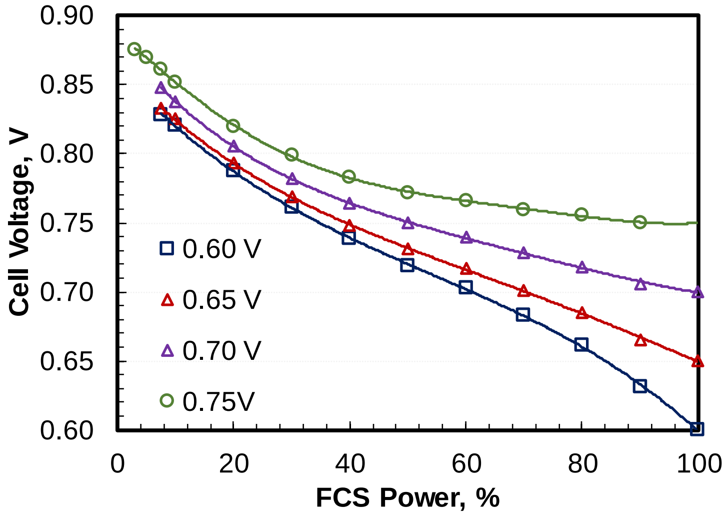
Two Configurations

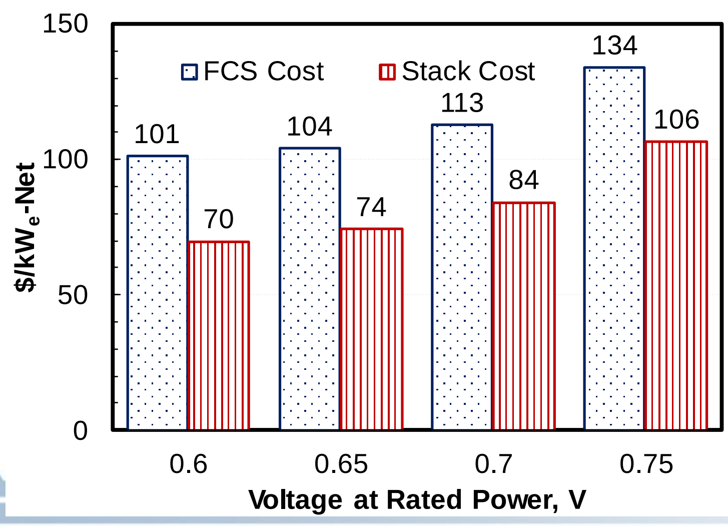
- 6,600 VAC vs 1000 VDC
- Same AC motors & speed control
- Main factors: safety and cost

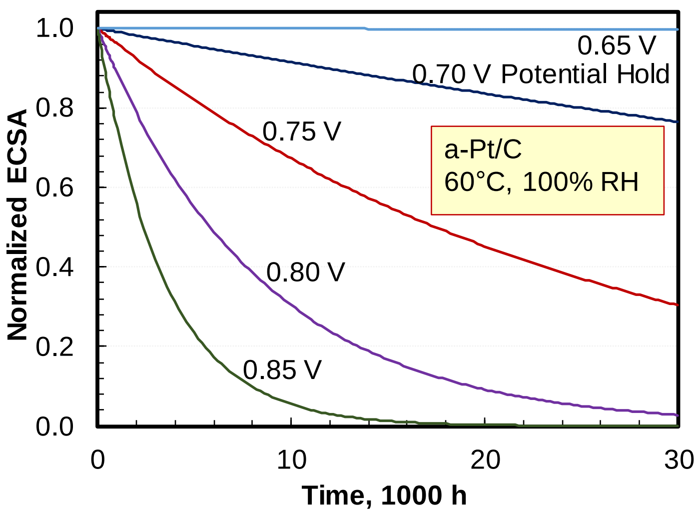
FCS Performance and Durability

- **Fuel cells operating at lower temperatures have higher power density and better durability**
- **Systems designed with higher cell voltage have higher efficiency, higher initial cost, and lower durability**





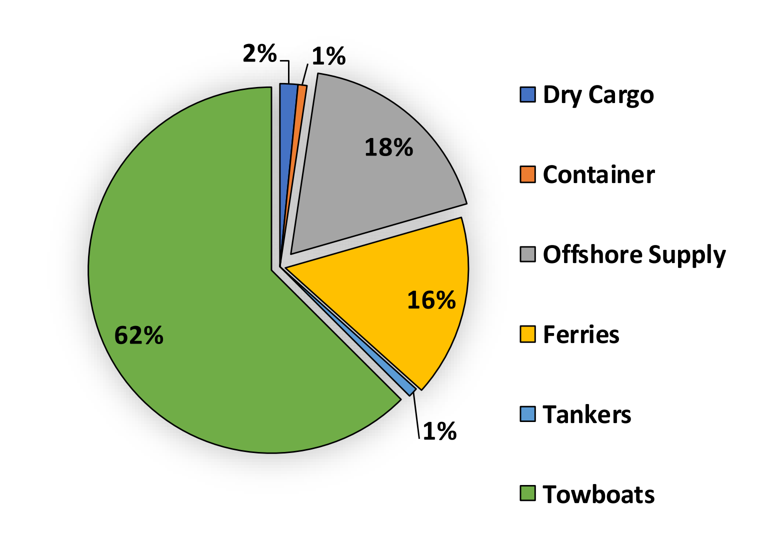




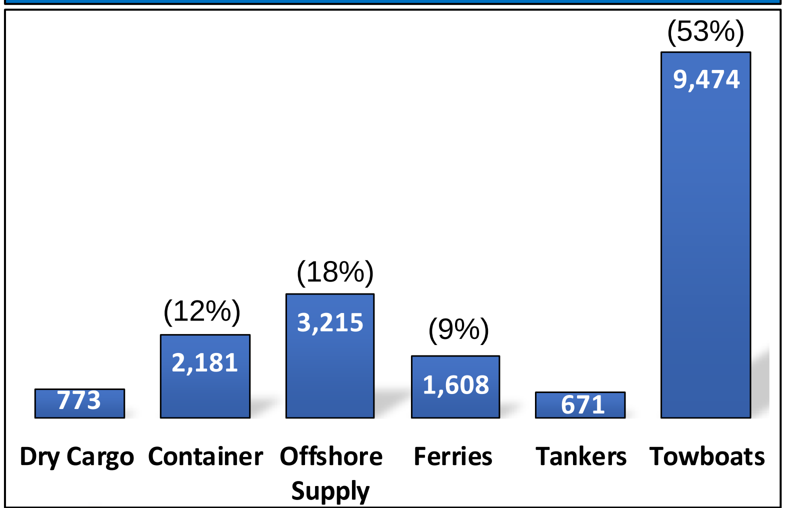
Application of FCR and FCM Concepts to 440 kW_e – 6 MW_e Maritime Fuel Cell Systems for Ferries and Tugboats

Waterborne Transportation Lines[1] of the U.S.

U.S. Flagged Vessels by Type 2018 (9,310)

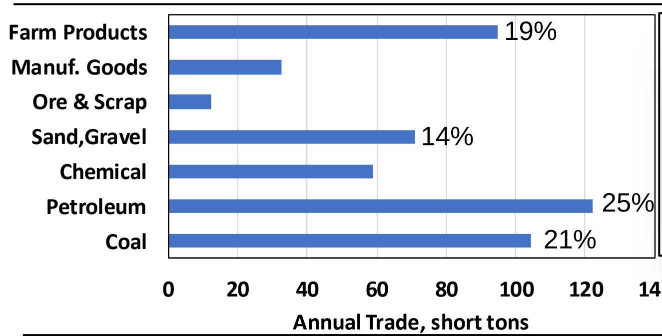


Total Engine Power by Vessel Type (~18,000 MW)



U.S. Merchant Fleet

- A total of 9,310 self propelled vessels as of 2018
- Majority of fleet consists of towboats (62%)
  - Push boats: 3,357 for barge movement (inland river system)
  - Tugboats: 2,463 (pulling ships to dock)
- Total engine power by vessel type dominated by towboats (53%)
- ~1,500 ferries in operation as of 2018. 119 million passengers and 25 million vehicles per year[2]
  - NY and WA top two states for passenger boarding (60%)
  - WA top state for vehicle boarding (45%)



Mississippi River Push-boat

70% of U.S. waterborne domestic trade by inland traffic (mainly Mississippi river). Petroleum and Coal main trade (46%) followed by farm products (19%)

[1]Source: U.S. Army Corps of Engineers. Excludes fishing and recreational vessels
[2]Source: National Census of Ferry Operators

Duty Cycles – RoPax Ferry

Mid-size RoPax Ferry
Cars: 124-150, Passengers:1,500

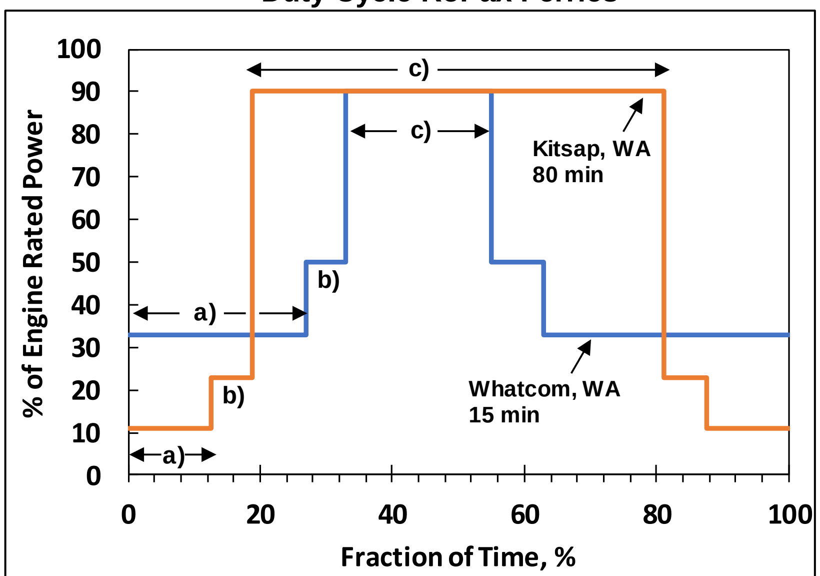
Small RoPax Ferry
Cars: 16-28, Passengers:100-150

Whatcom scenario applied for a 22 car ferry (150 pax) as potential upgrade of Whatcom Chief[1]

Ferry Line County	Bremerton-Seattle Kitsap, WA	Washington Island Door, WI	Washington Island Door, WI	Washington Island Door County, WI	Lummi Island Whatcom, WA
Name	MV Tokitae	Arni J. Richter	Robert Noble	Washington	Whatcom Chief
Length (m)	110.0	31.7	27.4	30.4	30.4
Beam (m)	25.4	11.6	10.9	11.2	13.4
Draft (m)	5.5	3.0	2.4	2.7	3.3
Gross Tonnage	N/S	92	97	82	129
Propulsion	2xMTU	2 CAT 3508B	2 CAT C18	2 CAT C18	2 Engines
Engine Rated Power (kW)	2250	750	341	365	180
Generator Capacity (kW)	4x300	N/S	N/S	N/S	2x35
Capacity - Cars	144	18	19	21	16
Capacity - Passengers	1,500	149	149	149	100
One way trip time (min)	80	30	30	30	15

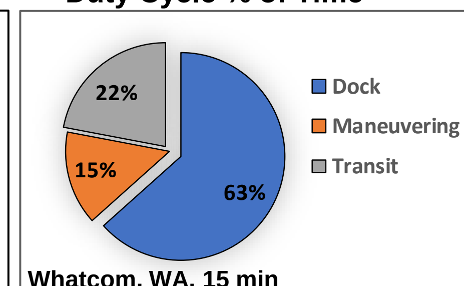
N/S: Not Specified

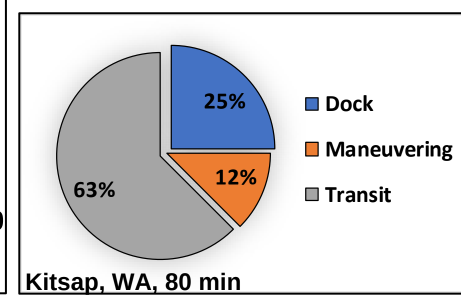
Duty Cycle RoPax Ferries



a) Dock load/unload, b) Maneuvering from dock, c) Transit

Duty Cycle % of Time





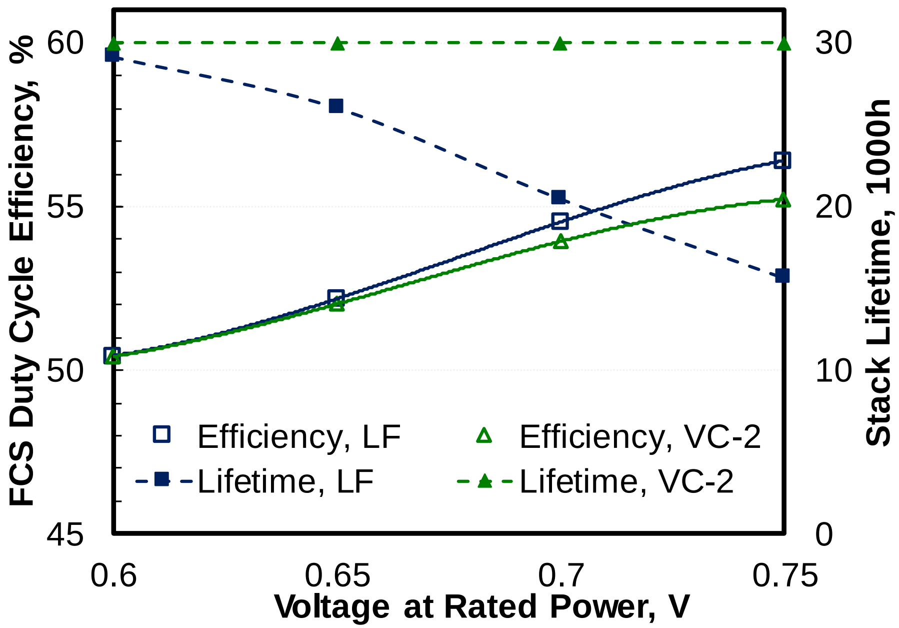
[1]*Elliot Bay Design Group. (2018). Lummi Island Ferry System – Task 4.1 – Vessel Alternatives Analysis, 17098-03M.*

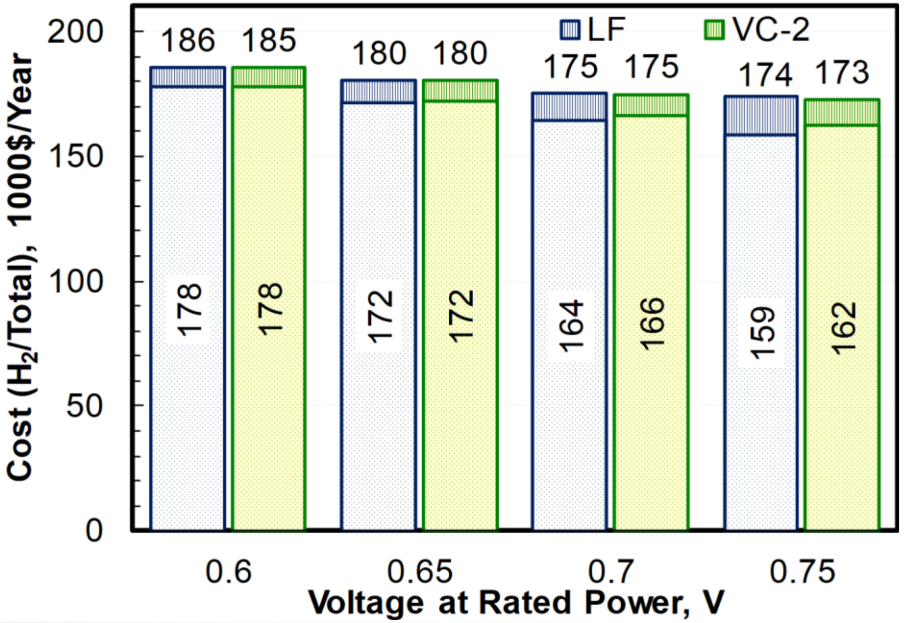
Small RoPax Ferry: Annualized Cost of FCS and Hydrogen

440 kW_e FCS, 70 kW_e Auxiliary Load

Duty cycle consistently has loads above 40%: 44% loading; 58% departure; 92% transit; 58% arrival; 44% unloading

- Voltage Clipping 1 (VC-1), the highest efficiency mode of operation, is not applicable, i.e., same as LF
- Small efficiency penalty with VC-2, the highest durability mode of operation, 30,000-h, except for FCS with 0.75 V at rated power
- Small difference in annualized cost for LF and VC-2: saving in capital cost offset by up to 3,000 $/year higher fuel cost
- TCO smallest for FCS sized for 0.75 V at rated power, 16,000 $/year saving compared to FCS sized for 0.6-V at rated power
- Future work: discrete stack sizes, sustainable manufacturing volume



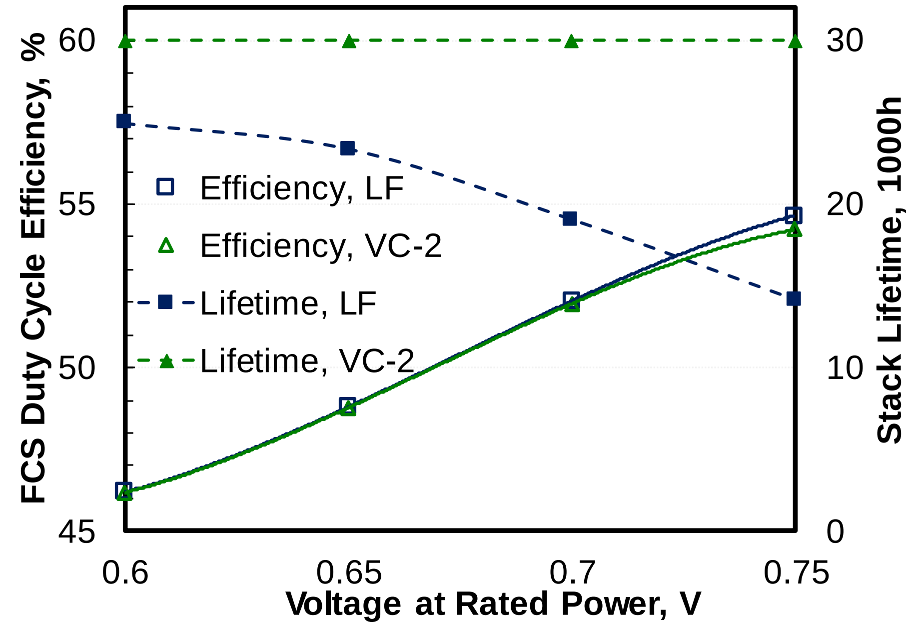


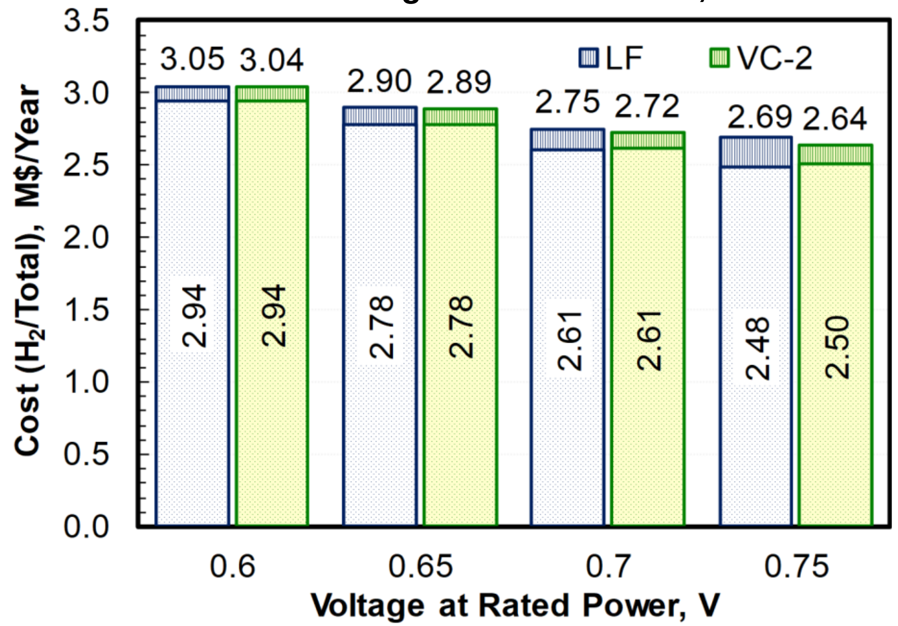
Medium-Sized RoPax Ferry: Annualized Cost of FCS and Hydrogen

5.54 MW_e FCS, 900 kW_e Auxiliary Load

Duty cycle consistently has loads above 25%: 25% loading; 36% departure; 92% transit; 36% arrival; 44% unloading

- Voltage Clipping 1 (VC-1), the highest efficiency mode of operation, is not applicable, i.e., same as LF
- Small efficiency penalty with VC-2, the highest durability mode of operation (30,000-h)
- Annualized saving with VC-2 compared to LF operating mode: 10,000-50,000 $/year.
- TCO smallest for FCS sized for 0.75 V at rated power, 400,000 $/year saving compared to FCS sized for 0.6 V at rated power



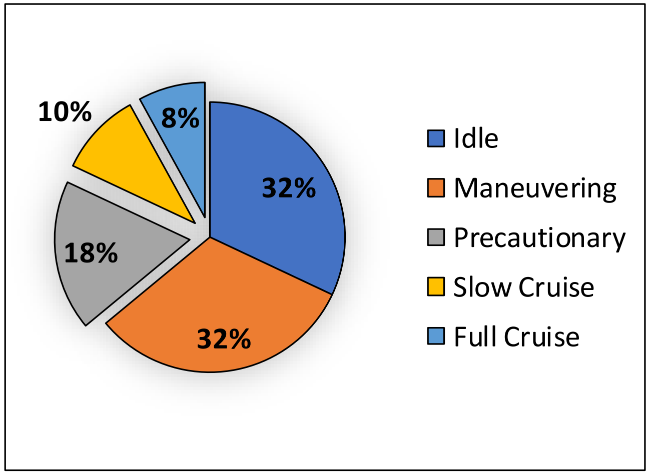


Duty Cycles – High Speed Ferry

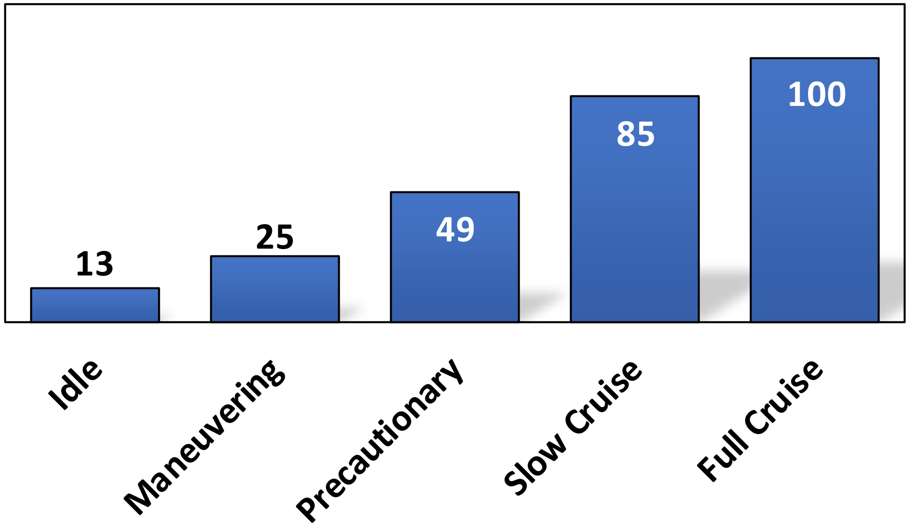
M/V Seastreak – NJ/NY/Highlands

Type	High Speed Passenger Ferry
Length (m)	42.9
Breadth (m)	10.5
Draught (m)	2.0
Service Speed (knots)	38
Maximum Speed (knots)	42
Total Propulsion Power (kW)	5,625
Engine	MTU 16V4000
Number of Engines	2
Engine Rated Power (kW)	3,440
Aux. Power (kW)	190
Distance (nm)	18
Trip Duration (min)	60
Passengers	600

Fraction of Time (High-Speed Ferry)



Engine Load (% of Rated Power)



Duty cycle similar to ISO E5 cycle for ferries (emissions test)

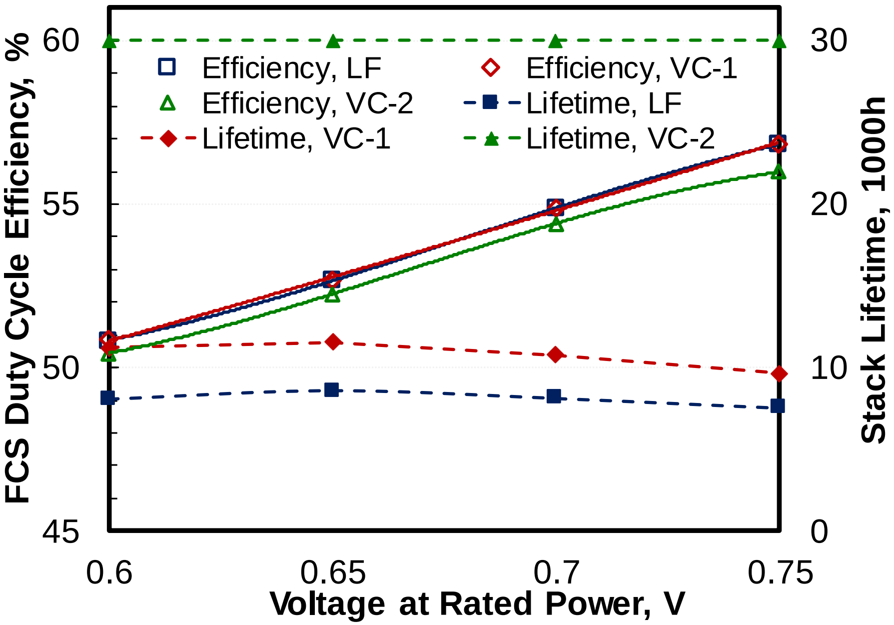
Duty cycle matches range and time for trip

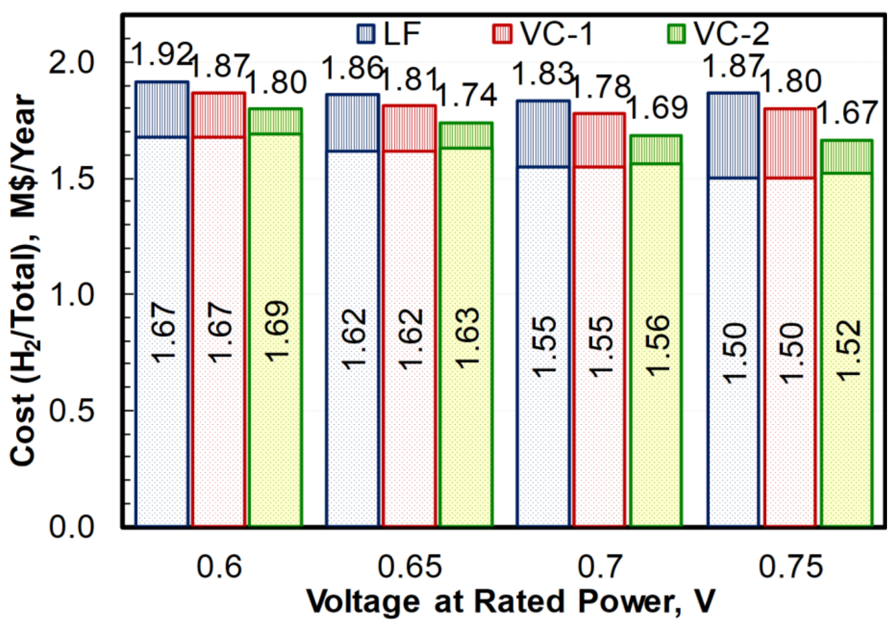
High-Speed Passenger Ferry: Annualized Cost of FCS and Hydrogen

6.13 MW_e FCS, 190 kW_e Auxiliary Load

Duty cycle: 15% idle; 27% maneuvering; 49% precautionary; 84% slow cruise; 98% full cruise

- Up to 1% point efficiency gain with VC-1 mode of operation
- Lowest cost option for LF: FCS sized for 0.7 V at rated power
- Lowest cost option for VC-1: FCS sized for 0.7 V at rated power
- Annualized costs for VC-2<VC-1<LF: costs dominated by fuel cost but lowest for operating mode with smallest annualized stack cost (longest life)
- TCO smallest for VC-2 with FCS sized for 0.75 V at rated power, 130,000 $/year saving compared to FCS sized for 0.6-V at rated power

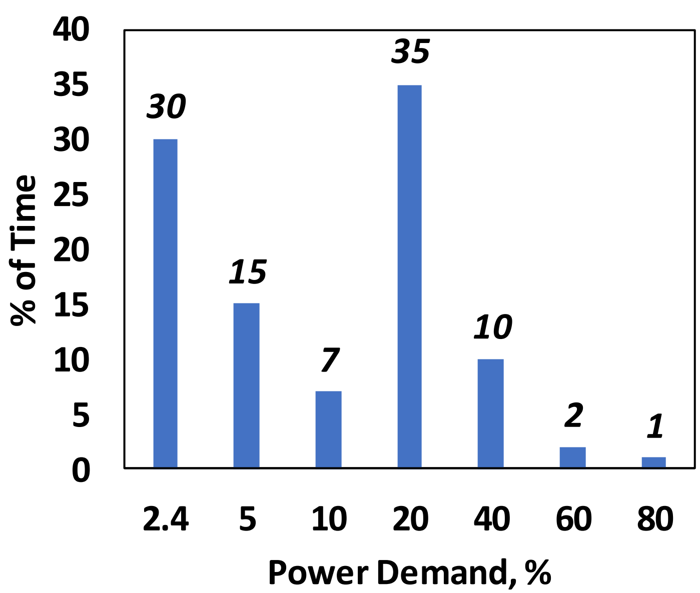




Duty Cycles[1] – Tugboats

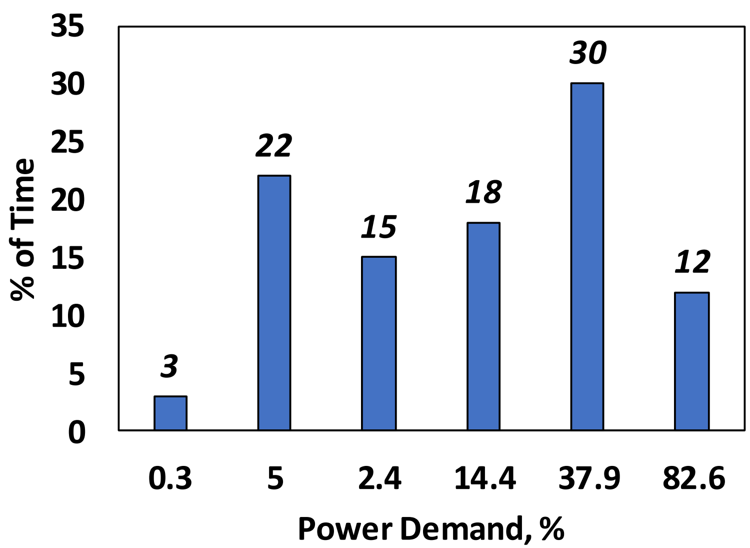
Harbor Tug

Mode ID	Task	Service	Time %	Load %
1	Stand-By	Idle	15	5
2	Transit Low	Transit	30	2.4
3	Transit High	Transit	7	10
4	Assist	Towpull	1	80
5	Assist	Towpull	1	60
6	Assist	Towpull	9	40
7	Assist	Towpull	26	20
8	Barge MV	Towpull	1	60
9	Barge MV	Towpull	1	40
10	Barge MV	Towpull	9	20



Ocean-going Tug

Mode ID	Task	Service	Time %	Load %
1	Stand-By	Idle	22	5
2	2 kts	Transit	3	0.3
3	4 kts	Transit	15	2.4
4	6 kts	Transit	18	14.4
5	8 kts	Transit	30	37.9
6	10 kts	Transit	12	82.6



[1]Boyd, E. and Macperson, D. Using Detailed Vessel Operating Data to Identify Energy-Saving Strategies, ITS 2014, Germany

Harbor Tug: Annualized Cost of FCS and Hydrogen

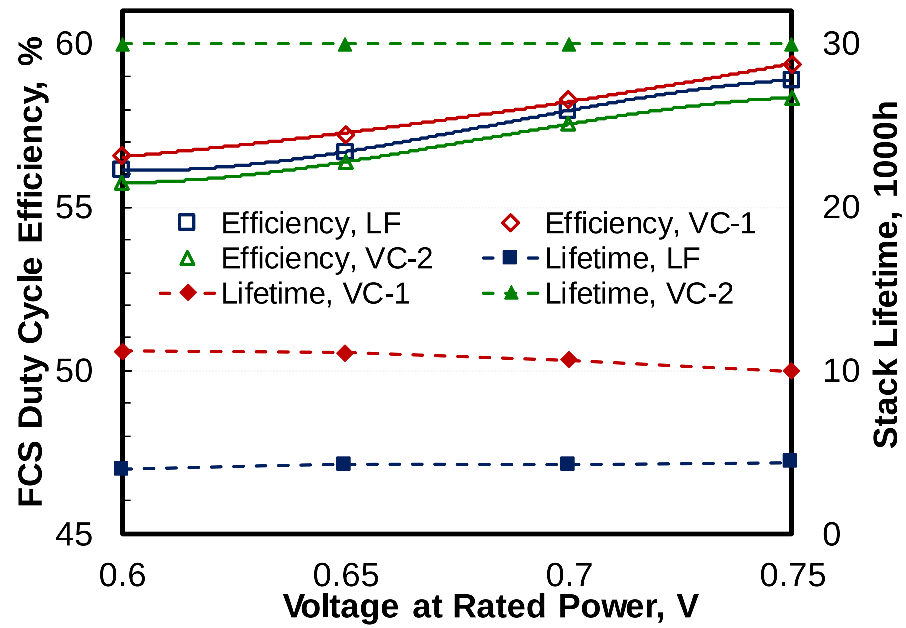
3.8 MW_e FCS, 200 kW_e Auxiliary Load

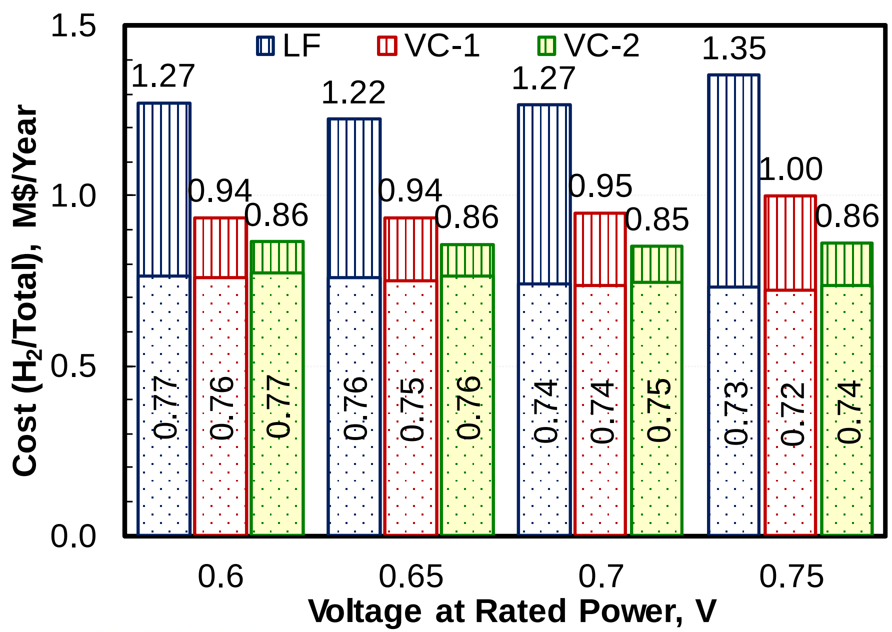
Duty cycle: 15% idle; 7-30% transit; 20-80% towpull

- Up to 2% point efficiency gain with VC-1 mode of operation
- Lowest cost option for LF: FCS sized for 0.65 V at rated power
- Lowest cost option for VC-1: FCS sized for 0.6-0.65 V at rated power
- Lowest cost option for VC-2: FCS sized for 0.7 V at rated power

Annualized costs for VC-2<VC-1<LF

- LF: Fuel cost ~ annualized FCS cost
- VC-1: Fuel cost > annualized FCS cost
- VC-2: Fuel cost >> annualized FCS cost
- TCO smallest for VC-2 with FCS sized for 0.7 V at rated power, 420,000 $/year saving compared to LF, 100,000 $/year saving compared to VC-1





Technical Accomplishments: Summary

1. Fuel Cell Systems for Rail

- Formulated a concept of heavy-duty fuel cell racks (FCR), nominally 320-kW_e for 0.7 V cell voltage at rated power. A FCR consisting of 4x100 kW_e stacks, and common air and fuel management systems. The stacks can be standardized for deployment in different heavy-duty applications such as rail and maritime.
- Formulated a concept of combining FCRs to build larger fuel cell modules (FCM), e. g., a 3.2 MW_e FCS for freight trains.
- Investigated the issue of thermal management and showed the need to enlarge the radiator heat transfer area by 50-100%.

2. Fuel Cell Systems for Maritime

- Applied the concept of heavy-duty FCRs and FCMs to maritime applications, including a 25 MW_e system for small container ships, and electrification of the propulsion system.
- Developed models for performance, durability and cost of fuel cell systems with different cell voltages at rated power.

3. Applications of FCR and FCM Concepts to 440 kW_e – 6 MW_e Maritime FCS for Ferries and Tugboats

- Proposed operational concepts for load following (LF), voltage clipping for maximum efficiency (VC-1) and voltage clipping for maximum lifetime (VC-2)
- Determined the best operational method and stack size (cell voltage at rated power) for least annualized fuel and FCS cost.

Proposed Future Work

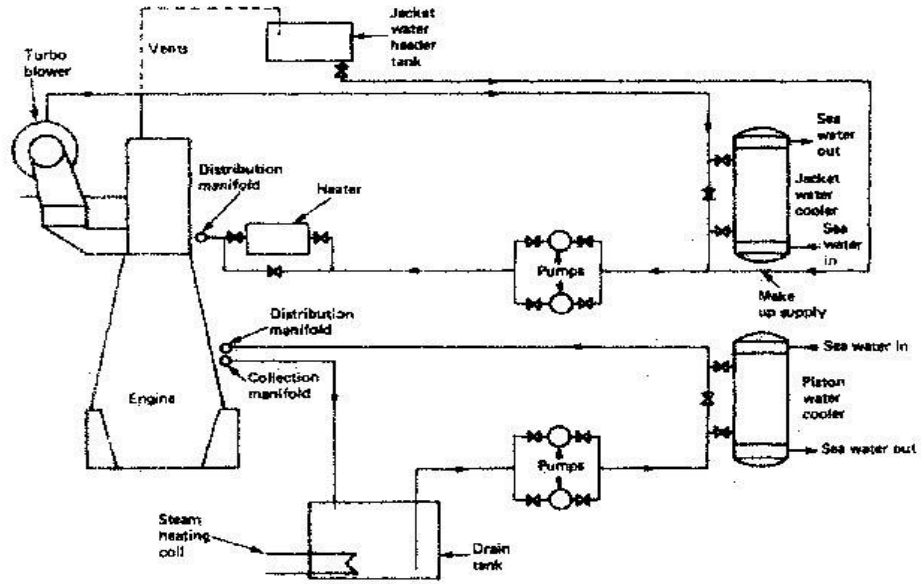
1. **Heavy-Duty Fuel Cell Stacks and Systems**
   - Further develop the concept of standardized stacks for use in fuel cell racks (FCR) and fuel cell modules (FCM)
2. **Fuel Cell Systems for Rail**
   - Investigate heat rejection, performance, durability and cost of fuel cell systems for passenger trains, yard switchers and freights.
2. **Fuel Cell Systems for Maritime**
   - Investigate performance, durability and cost of fuel cell systems for ferries, tugboats and small container ships.
3. **Applications of FCR and FCM Concepts to TCO Studies**
   - Collaborate with the on-going projects on TCO of fuel cell rail applications
   - Collaborate with the on-going projects on TCO of fuel cell maritime applications

Any proposed future work is subject to change based on funding levels

Backup Slides

Cooling of Ship's Slow-speed Diesel Engine-1

- Two separate systems: one for cooling the cylinder jackets, cylinder heads and turbo-blowers; the other for piston cooling. Both have a sea-water-circulated cooler.
- The hot cylinder jacket cooling water: 1) for cylinder jackets, cylinder heads and turbo-blowers; 2) a header tank allows for expansion and water make-up in the system; 3) A heater for warming of the engine prior.
- The piston cooling system: 1) limit any contamination from piston cooling glands within the system only; 2) a drain tank; 3) the vents led to high points in the machinery space.
- Turbo blower pressure: 2 atm



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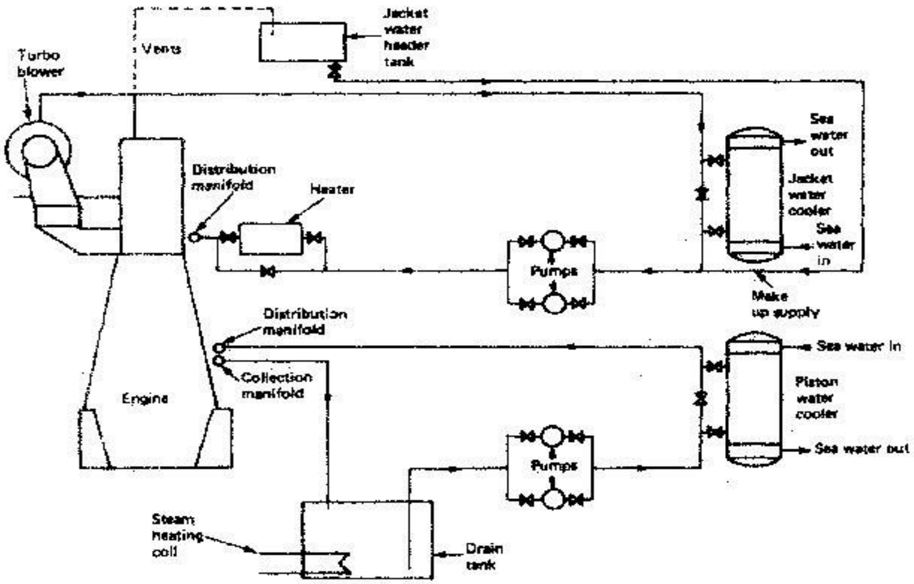
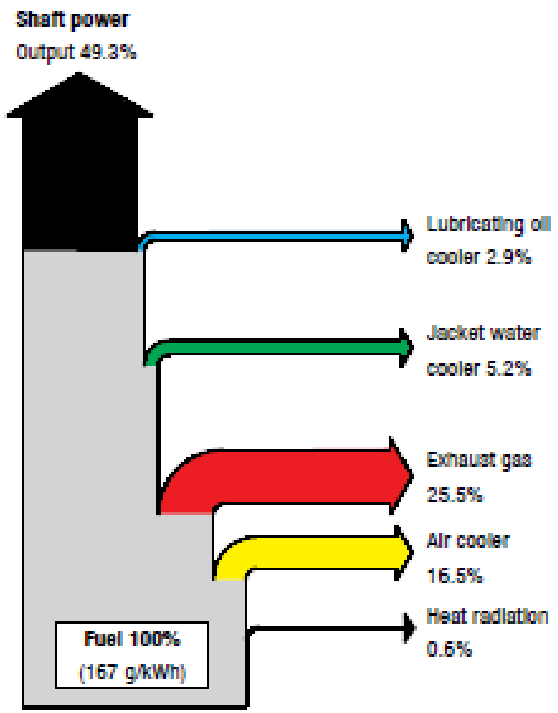


FCS for Maritime: System Efficiencies



MAN Diesel

- **Shaft Power: 49.3%**
- **Coolant Load: 24.6%**
  Air Cooler 16.5%
  Jacket water cooler 5.2%
  Lubricating oil cooler 2.9%