Chapter 11

SHIPS

1. Summary

We find that the overall saving generated by our individual ship and recreational boat *Conventional Wisdom* technology portfolio amount to an instantaneous potential saving of 0.21 M bbl/day of residual oil versus the EIA projected 2025 baseline. This represents 0.48 Quads saved per year, or a reduction of 31.2% of EIA's projected 2025 use of 1.53 Quads, at a cost of $0.12 per gallon of saved residual fuel. The instantaneous savings generated by our *State of the Art* technology portfolio are nearly double, at 0.38 Mbbl of crude per day, or 0.87 Quads, i.e., a 56.5% reduction, at an average cost of saved energy (CSE) of $0.23 per gallon of saved residual oil. Accounting for stock turnover, the savings become 15.2% and 28.2% for the *CW* and *SOA* technologies, respectively.

2. Detailed Assessment and Results

In sum, we find that the overall saving generated by our individual ship and recreational boat conventional technology portfolio amount to an instantaneous potential saving of 0.21 M bbl/day of residual oil versus the EIA 2025 baseline. This represents 0.48 Quads saved per year, or a reduction of 31.2% of EIA's projected 2025 use of 1.53 Quads. These savings are very similar to the savings generated by those in the Clean Energy Futures report [1]. We base our cost estimates on those for the truck industry. Our approximate estimate of average costs for the savings produced by the *Conventional Wisdom* technology portfolio is therefore $0.12 per gallon of saved residual oil. The savings generated by our *State of the Art* technology portfolio are nearly double, at 0.38 Mbbl of residual oil per day, or 0.87 Quads, i.e., a 56.5% reduction, at an average cost of saved energy of $0.22 per gallon.

Brief overview of industry energy use: Domestic and foreign shipping and recreational boating consume about 6 percent of U.S. transport energy use in 2000 [1, Appendix C-3]. By volume, more than 95% of U.S. imports and exports are carried by ships [2]. Worldwide, about 44,000 cargo ships with a combined capacity of 215,715 MW, burn about 200 of a total of 284 million metric tons (70%) of all marine fuel to move containers, general cargo, fuel, and bulk, with 14% being combusted by military ships, and the rest by non-cargo vessels for passenger transport, fishing, tugging, and research [2]. U.S. waterborne commerce represents between 22% and 24% of the total ton-mile of cargo movements in recent years, rivaling truck and rail modes each with about 25-29% of annual cargo ton-mile movement [2]. The Clean Energy Futures report notes that domestic shipping consumes about one quarter of freight shipping energy, and carries about 1.1 billion tons of cargo annually on about 41,000 ships [1]. Recreational boating consumes mostly gasoline; freighters consume residual fuel oil and diesel, with residual fuel taking a three quarters share in domestic shipping and dominating foreign long-haul shipping.

Internationally, 98 percent of freighters are powered by diesel engines burning marine residual fuels, although the 2 percent of ships that are powered by steam-electric propulsion are the largest ships—tankers, bulk carriers, and some container ships—and carry 17 percent of the gross tonnage [1]. Steam-powered vessels will be replaced with diesel-powered ships within the next 10 years, so any examination of future shipping energy use can focus exclusively on diesel engines [1]. In terms of energy conservation, although domestic land-based residual fuel consumption has decreased significantly over the past two decades, marine transportation fuel consumption has not changed much, either internationally or domestically [2].

<u>Overview of methodology</u>: We first quantify the potential reductions in fuel use from individual ship technologies, basing our estimates for conventional technologies off the CEF advanced scenario. The CEF report's individual ship efficiency improvements total 30%. To reproduce their overall 30% savings, we have adjusted to 15% CEF's gain from larger ships and to 8% the possible propulsive and engine improvements. The use of larger ships, though offering significant fuel savings, may be less attractive to ship purchasers because of port limitations and, perhaps, the greater capital risk inherent in such ships. We use both these levels for our *Conventional Wisdom* technology portfolio. Only in our *SOA* portfolio do we assume that adoption of larger ships will reduce fuel burn by 30% and that propulsion efficiency will improve by the full 22 percentage points. These savings are additional to the EIA 2025 baseline. We assume the domestic shipping efficiency gain is representative of the fleet gain, and we make this assumption due to the absence of an explicit efficiency measure for the international fleet in the EIA data.

While it is reasonable to expect that some of these savings will be eaten up by demands for increased speed (performance) [3], we do not explicitly account for this marginal component of fuel per ton-mile consumption because it is very hard to predict. While we assume that the EIA forecasts for U.S. marine transport fuel use are not materially affected by recent estimates indicating that worldwide marine fuel use may in fact be nearly twice the quantities assumed by EIA [4], we note that this assumption could turn out to be incorrect. If the assumption indeed were incorrect, the savings figures may have to be scaled by a factor approximately equal to (actual use 2000/EIA use 2000). The remaining methodology and assumptions are noted in Table 11-1.

<u>Discussion of efficiency-enhancing measures</u>: We first consider the reduction potential for *ship system power demand per unit ton-distance traveled*. We use as a basis for our *Conventional Wisdom* technology portfolio the CEF report [1]. It notes that there are a number of measures that can be taken to improve ship efficiency, including:

1. Propeller maintenance (<5% improvement in fuel use)
2. Anti-fouling paint (34%)
3. Weather routing (4%)
4. Adaptive autopilot (2.5%)
5. Changes in hull form (3%)
6. Larger ships (to 30% for doubling size)
7. Fuel switching (reduction in greenhouse gases)

With the exception of our slightly lower gain from coating measures and our savings from more efficient ship APUs, our overall saving from the *Conventional Wisdom* technology portfolio is approximately equal to that of the CEF report. Total power demand savings from the *SOA* technology portfolio is slightly less than doubled the cumulative total resulting from the Figure 11-1.

In terms of the reduction potential for *propulsion system fuel supply per unit of power supplied*, diesel marine power plants are already very efficient relative to non-marine diesel power plants, primarily due to the large capacities involved of range 5MW to 100MW [3], and very uniform and high load factors. Older diesel engines may have efficiencies of about 35 percent peak or 28 percent at part load [1]. Modern diesels are more likely to have efficiencies of about 46–47 percent peak or 36 percent at part load [1]. Assuming that most freighters use their engines at peak load during the greater part of their journeys, the diesel drivetrain aboard a modern freighter may obtain greater than 40 percent efficiency, for example at a 45 percent engine efficiency, and with a 97 percent reduction gear and shafting, the yield is 42 percent efficiency from engine to propeller [1].

In terms of net gains in our two technology portfolios, we assume the conventional portfolio propulsive gains are the same as CEF's. By inference, the CEF report baseline engine-to-propeller shaft fuel efficiency is around 42%, which also agrees with CEF's example calculation. To achieve a 30% fuel burn reduction per ton-mile including the demand-side measures as listed above implies an approximate improvement of about 8%, to about 50% engine-to-shaft efficiency by 2025. We note that the best diesels sold today are at over 50% efficiency in the biggest classes, so while we adopt the implicit CEF figures for our *CW* scenario, we adopt their 22 percentage point potential propulsive gain as representative of our *SOA* propulsive technology portfolio.

In terms of gains from fuel switching, the U.S. military and MARAD, the Maritime Administration within DOT, have both focused attention on fuel cells as a less polluting and more efficient alternative to current marine power plants. The Clean Energy Futures report notes the following design studies that have identified various potentials for propulsive fuel use reduction:

- Coast Guard cutter conversion from diesel electric to Molten Carbonate fuel cell system using a diesel fuel reformer; the estimated fuel cell system efficiency is 54 percent, coupled with weight reduction from removal of exhaust stacks and sound isolation bedplate required for diesel engines, yielding much improved efficiency
- Navy design study converting from gas turbine generator to PEM fuel cell with diesel reformer, yielding 30 percent fuel reduction
- MARAD study replacing medium-speed diesels with molten carbonate fuel cells using natural gas, yielding 17 percent decrease in fuel use; adding a steam turbine bottoming cycle to the fuel cells boosts system efficiency to 64 percent. [1]

While the CEF report notes that overall efficiency superiority of fuel cells over diesel systems is still to be confirmed, [2] does outline five factors that may favor marine transportation as a cost-minimizing mode for hydrogen or other alternative fuel. The CEF report notes that recent studies of PEM fuels cells for highway use have questioned whether fuel cells coupled with fuel reformers (in this case, methanol and gasoline) will be as efficient as modern diesel systems. Further, to convert these results to a marine context, it notes that diesel fuel reforming should be no more efficient than gasoline reforming, and marine diesels are spared some of the transmission losses incurred in highway duty cycles. Also, although molten carbonate/natural-gas systems probably yield a more definitive efficiency advantage, reliance on natural gas as a fuel might not be attractive to freight carriers without extensive fuel infrastructure development.

However, marine transportation may ultimately be favored as the sector that first makes the switch to gaseous fuels such as hydrogen. First, large nonpassenger ships offer a relatively small cargo loss factor in ensuring storage of gaseous fuels. Second, due to rigorous training and licensing, ship operations and management may, at minimal exposure to the public, be particularly well suited to adopting alternative fuels more safely and at lower costs than other sectors. Third, a highly centralized refueling infrastructure implies transition investments can be low per unit of energy delivered—most U.S. marine fuel is delivered from 30 major fuel providers in the top 20 ports for waterborne commerce. Fourth, net improved environmental performance may be greater in the less regulated industries such as international and domestic shipping, and converting ships to hydrogen could reduce emissions of traditional pollutants significantly if that were to become a priority. Finally, because of the scale of each ship propulsion system, each ship uses tailored designs with generally similar power systems built one at a time, which makes the process of innovation more effective than for mass-produced vehicles such as automobiles [2].

<u>Discussion of costs of savings</u>: The CEF report presumes that many ships will adapt some of these measures as a matter of course, on the basis of fuel savings and without need of new government policies. Fuel switching is less likely to be adopted without government support of fuel infrastructure development. We therefore assume that fuel switching will only occur in the period after 2025.

While cost estimates for technology improvements in marine transport do exist, e.g., [5], they are few and far between. We therefore used as basis for our costs our examination of the CSE for Heavy Trucks in the *CW* and *SOA* technology portfolios. We found that the *CW* CSE was about 30% of the pretax cost of diesel fuel ($1.00/gal in 2003 dollars), paying for a 5% saving over the *BAU* case. For the CSEs for marine freight and other ships we assumed the same percentages applied because we were unable to locate a credible source that treated the range of technologies and options that we considered. The savings and implementation fractions based on the CEF study are sufficiently modest not to warrant too many further questions. For the *SOA* truck analysis we found about 75% of the cost of fuel covered the average CSE.

A major conservatism on cost warrants brief elaboration. We assume the ship system demand-side improvements described above. We calculate the effect on fuel burn from these measures before considering the effect of power plant improvements, also detailed above. Reductions in energy demand from demand-side improvements such as hull shape, coatings and propeller efficiencies, would reduce the need for brake power at the propeller shaft, therefore engine size, and thus engine cost, *ceteris paribus*. While this proper system-level integration gives rise to a cost savings per ton-mile from the reduced engine cost, we have as a conservatism not accounted for this cost reduction.

REFERENCES

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1 Interlaboratory Working Group. 2000. Scenarios for a Clean Energy Future (Oak Ridge, TN: Oak Ridge National Laboratory and Berkeley, CA: Lawrence Berkeley National Laboratory), ORNL/CON-476 and LBNL-44029, November. Available online at http://www.ornl.gov/sci/eere/cef/

2 Corbett, J.J., “Marine Transportation and Energy Use,” in *Encyl. of Energy*, vol. 3, 2004, pp. 745-758.

3 McKesson, C.B., “Alternative Powering for Merchant Ships: Task 1 – Current and Forecast Powering Needs,” California State University – Long Beach, 2000. Available online at http://www.ccdott.org/Deliverables/2000/task2.9.1/task2.9.1_3.pdf

4 Corbett, J. J., and H. W. Koehler, “Updated emissions from ocean shipping,” J. Geophys. Res., Vol. 108 (D20), 4650, 2003.

5 Genovesi, K. and L. Browning, "Incremental Cost Estimates for Marine Diesel Engine Technology Improvements," Engine Programs and Compliance Division Office of Mobile Sources, U.S. Environmental Protection Agency, EPA420-R-98-021, September 1998. Available online at http://www.epa.gov/otaq/regs/nonroad/marine/ci/fr/r98021.pdf

Table 11-1: Summary of ship fuel-use reductions: Technical Potential and Stock Turnover

	Baseline	CEF comparison	RMI *CW* (low est.)	RMI *SOA* (high est.)	Units	Notes
EIA 2025 use (baseline)	#### ####				M bbl/day of residual oil Quads	 (Includes 0.39 Quads recreational boating)
Instantaneous Pot. Savings		30.8% 0.21 0.47	31.2% 0.21 0.48	56.5% 0.38 0.87	% saved off EIA baseline M bbl/day of residual oil saved Quads saved	
Savings w/ RMI stock turnover			15.6% 0.10 0.24	28.2% 0.19 0.43	% saved off EIA baseline M bbl/day of residual oil saved Quads saved	
2025 Use w/ RMI stock turnover		0.46 1.06	0.46 1.05	0.29 0.67	M bbl/day of residual oil used Quads used	
Average CSE (2000$)			$0.12	$0.23	$/gal residual oil (based on RMI truck analysis)	

Details of ship fuel use reductions: Technical Potential

		Ind. meas	Post-meas	Ind. meas	Post-meas	Ind. meas	Post-meas	**Source**	**Notes**
Measure		avg %	%		%		%		
Baseline			100%		100%		100%		
Logistics, weather routing, & autopilot		-6.5%	93.5%	-6.5%	93.5%	-5.0%	95.0%		Based on similar study for logistics operational improvements in airtravel system.
Hull-shape		-3.0%	90.7%	-3.0%	90.7%	-5.0%	90.3%	1	High-tensile steel applied in structural areas, reduces weight (1% effect on fuel). Changes in design, materials.
Larger ships		-15.0%	77.1%	-15.0%	77.1%	-30.0%	63.2%	7	We use CEF total potential in SOA, and 1/2 that in CEF and CW to re-produce the 30% CEF total savings
Coating & anti-fouling paint		-3.5%	74.4%	-2.7%	75.0%	-5.3%	59.8%	2,3	Issues are largely environmental. Biomimetic skins based on shark-skin, already in use by swimmers, also known as Riblet coatings, are v advanced, makes it very smooth. As-is drag reduction of about 8%. The long range goal of doubling riblets' drag reduction capability to 15-16 percent would translate into a five percent reduction in fuel costs.
Hotel-loads		0.0%	74.4%	-2.5%	73.2%	-6.3%	56.1%	4	
Propeller		-5.0%	70.7%	-4.0%	70.2%	-10.0%	50.5%	1,5	Ducted propeller, waterflow correction devices, assumes PAX Scientific for SOA
Engine		-8.0%	65.0%	-8.0%	64.6%	-22.0%	39.4%	6	Diesel engines will be choice, but low speed diesels already very thermodynamically efficient (171g/kWh / 60-65% to shaft energy). Better load-matching and thermal integration (e.g. bottom-cycles) expected, as hotel loads go to gas turbines and waste heat use improves further. CEF notes MARAD study of 64% thermodynamic efficiency obtained (including bottoming cycle). We assume baseline new engine, gear, and shafting efficiency of 42% (CEF) and assign 8% to CW and 22% gain to SOA.
Other		0.0%	65.0%	0.0%	64.6%	0.0%	39.4%		
EIA reduct'n			4.2%		4.2%		4.2%		
Use vs. *BAU*			**69.2%**	***CW***	**68.8%**	***SOA***	**43.5%**		
Reduction			**30.8%**		**31.2%**		**56.5%**		

Details of ship fuel use reductions: Stock Turnover

Ship turnover			20	20	years	See note 8 below
Begin year			2005	2005	AC	
Yrs to diff to 100% of new			10	10	years	
Begin stock turnover			2015	2015	AC	
End stock turnover			2035	2035	AC	
% turnover by 2025			50%	50%		
Reduct'n w/ stock turnover			**15.6%**	**28.2%**	% saved of baseline use	

Source	References for table
1	Spyrou, Andrew G., *Energy and Ships — The Effects of the Energy Problem on the Design and Efficient Operation of Future Merchant Ships*, Lloyd's of London Press LTD 1988.
2	http://oea.larc.nasa.gov/PAIS/Riblets.html
3	http://www.elasmo-research.org/education/white_shark/scales.htm — used by winning boat of Kevin O'Connor, Americas Cup.
4	*CG-59 USS Princeton Report to U.S. Navy*, Rocky Mountain Institute, 2001, on http://www.rmi.org/sitepages/pid955.php: Assuming US Navy hotel loads are 4X those of civilian transport fleet, and that gas turbines for propulsion is unique to Navy, applying 1/4 of 10-25% savings from ref. 6. These savings are derived from: $6 M worth of diesel-like turbine fuel per yr, propulsion gas turbines use ~$2–3 M to make up to 2.5 MW of electric power, the rest for 58.8 MW propulsion. Retrofitting motors, pumps, fans, chillers, lights, and potable water systems ~20–50 % saved electricity (~$1-1.5M), or ~10–25 % of total fuel use (possibly ~50–75% if combined with virtual trailshfting propulsion and other electric generation measures).
5	www.paxscientific.com
6	RMI diesel engine analysis for section on Heavy Trucks, supplemented by general diesel engine expertise.
7	Clean Energy Futures Report assumes doubled ship size gives 30% efficiency improvement.
8	Encyclopedia of Energy, 2004, p 753: ".. conversion from sail as measured by number of ships took approximately 50 years to complete." Also, "The effective fleet conversion of vessel tonnage to higher performing combustion systems took less than 20 years." Since what we are proposing is mostly a case of the latter, with a few exceptions like hull tweaks, we use 20 years as the *SOA* turnover for ships unless the article indicates differently. We assume an incremental 10 years to fully work all technologies into new sales.