Economic viability of bulk cargo merchant sailing vessels

Lead author and alphabetically listed co-authors:
Sergio E. Perez[1,2], perezs@usmma.edu, Chang Guan [1,3], Alexander Mesaros[1,2], Atil Talay[1,2]
US Merchant Marine Academy, Kings Point, NY[1]; Department of Marine Engineering[2]; Department of Marine Transportation[3]

ABSTRACT

We update and extend a MARAD (U.S. Maritime Administration) report which concluded that commercial ships using sail power were not economically viable when compared with engine-powered vessels. We find that, using current fuel prices, the opposite is true: bulk carriers using the wind as a primary source of power have a substantially lower Required Freight Rate (RFR) than engine-driven vessels. The routes considered are between U.S.-China, U.S.-Europe, U.S.-Africa and U.S.-Australia.

We found that, based on past and predicted fuel prices and foreign construction/crewing, bulk cargo sailing vessels of 15, 30 and 45 kDWT have substantial economic advantage over conventional motorized vessels, while emitting 10% of the pollutants. Using our Baseline Cost Estimate (a best estimate based on sailing vessel construction costs 20% higher than equivalent motor vessels) and recent 10-year average fuel prices, sailing vessel Required Freight Rate would be between 21% and 40% lower than the equivalent motor-vessel, depending on the vessel and route.

The sailing vessels studied here have Dynarig quadrilateral fabric sails, and auxiliary engines to be used only when sailing speeds dip below 6 knots. These vessels would include the largest sailing ships ever built.

We found that the advantage of the sailing vessel is quite resistant to higher-than-predicted construction costs: increasing the estimated construction costs of the sailing vessel to as much as 50% greater than motor vessel costs still resulted in sailing vessel superiority.

In addition, for all the vessels on all the routes, we found that fuel prices would have to dip below about $40-$50/barrel in order for the motor vessel to outperform the sailing ship economically – this is well below the predicted and historical values for high-sulfur fuels. Decreasing the speed of the motor vessel from 15 to 10 knots resulted in increased advantage of the sailing ships.

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For motor and sailing vessels manufactured and crewed by U.S. personnel using the Federal Ship Financing Program, the Baseline estimate also results in sailing vessel superiority, but the margin for error in the vessel price estimates becomes much smaller.

Due to the height of the masts, the vessels considered here would be unable to access many U.S. ports. Telescoping or folding masts need to be developed to overcome this restriction. It remains to be seen whether this can be done within the sailing vessel acquisition cost limit established in this work of 50% greater cost than the motor vessels.

Background

The ramming and eventual sinking of the 433-foot (132 m) cargo sailing vessel Preussen by a steamship in 1910 could not have been a better metaphor for the demise of the merchant sailing ship. Despite the reliability and success of the German Laeisz Lines in transporting cargo between Europe and the West coast of South America, the fate of the sailing vessel was sealed when steamships became reliable and fuel widely available [35].

But now, a century later, the pendulum may be swinging back towards wind-powered vessels. We are not referring to engine-powered vessels with auxiliary sails, but a return to sails as the principal means of propulsion – sailing vessels far larger than the giant Preussen and almost as large as today's largest cargo ships. These would be the biggest sailing vessels ever constructed, with masts as high as 100 m and automated control of sails. We consider only bulk carriers in our analysis since their cargo does not require the higher speeds of engine-driven vessels.

As we will show in this article, fuel prices over the last 10 years have been high enough to give bulk carrier sailing ships a substantial economic advantage over motor-driven vessels. The variability of fuel prices may periodically give the advantage to motor-driven vessels, but it appears to us that the better economical alternative is by-far the sailing vessel.

In addition to economic considerations, ships emit significant emissions that affect people near ports and coastlines as well as those hundreds of miles inland [10]. The world shipping community, through MARPOL (International Convention for the Prevention of Pollution from Ships), established in 1997 Annex VI to address air pollution from ships. Quite recently, measures from Annex VI have been adopted, limiting sulfur content of marine fuels to 0.5% [23]. Clearly, the reduction of air pollution from ships is an important goal of the marine industry.

In addition, MARPOL has instituted mandatory energy efficiency measures aimed at reducing greenhouse gas (GHG, mostly consisting of carbon dioxide) emissions from ships. Cargo shipping is the most energy-efficient method of transport [32], and is responsible for a relatively small portion (2.9%) of world-wide global anthropogenic greenhouse gas emissions. Out of 36,573 million metric tons of GHG emissions produced yearly, 1,056 million are attributed to ships [18]. Nevertheless, GHG emissions from ships need to be addressed due to the importance of mitigating climate change on many fronts.

The 1975 Report to MARAD

In a 1975 report to the U.S. Maritime Administration (MARAD) [39], the authors studied the economic viability of U.S.-made vessels for the transport of bulk goods (such as grains, coal, iron ore) over 4 round-trip routes: New York-Liverpool, Baltimore-Monrovia, Cape Flattery-Shanghai and San Francisco-Sydney. They compared their results to U.S.-made steam-powered motor vessels, for ships of 15 kDWT, 30 kDWT and 45 kDWT, and found that the motor vessels had lower required freight rates (RFR, or the freight rate required to cover all yearly costs). The ships considered by the authors were preliminary designs, consisting of what the authors referred to as the "first loop of a design spiral".

The authors used resistance curves from Series 60 motor vessel hull forms [34] to estimate the resistance of the sailing vessels, as well as Dynarig sailing rig force coefficients and Mariner hull leeway force coefficients from [36] to generate speed polar curves for each vessel. Pre-set sailing vessel voyage tracks based on average wind directions were established and adhered to. Average crossing speeds and variances were calculated for each voyage and season using multiple runs of a Monte-Carlo scheme (along the pre-set tracks) that randomly selected local wind speed and direction based on statistical weather data. This procedure did not permit changes in course when the Monte Carlo algorithm imposed a change from the average wind conditions, and thus had to result in poorer sailing performance/greater engine use than might be possible in an actual ship with the ability to respond to changes in the weather.

The vessels considered ranged in length from 175 to 250 meters. The steam vessels used for comparison were to be driven by turbines burning Bunker C, an inexpensive residual fuel that would be illegal today without sulfur-removing scrubbers, while the sails were to be made of Dacron polyester, a ubiquitous sail material then and still today. The sailing ships were to have relatively small auxiliary engines (600, 1000 and 1200 BHP for 15 kDWT, 30 kDWT and 45 kDWT vessels) for supplying electric power, for limited maneuvering to and from port and for supplementing wind power if sailing speeds were to drop below 6 knots. The authors of the report expressed concern that the relatively small power and high windage of the sailing vessels would require sailing vessels to avoid entering or leaving port at times of high winds.

The sailing rig proposed in [39] is similar to the Dynarig concept first proposed by engineer Wilhelm Prolss in the 1960's (today, this type is sometimes referred to as a Falcon Rig). The Dynarig has been shown to be about twice as efficient as conventional square rigger ships [11]. The rig consists of quadrilateral sails suspended in tension from curved yards, with the capability of automated sail furling around vertical cylinders attached to the mast. On each mast are five separate sails which are mounted very close to each other, approximating one high-aspect ratio wing (a high aspect ratio wing is long and thin, and produces less drag than a short and wide wing). Please see Figure 1.

The sails are furled using a series of cables coming down to an electric motor on the deck. Figure 1 shows the 45 kT vessel. Each mast is made of three vertical, hollow steel sections (spars) arranged in a tripod configuration, with a single leading spar and two trailing spars. The tripod arrangement gives the mast sufficient strength without supporting wires (stays), enabling unobstructed deck space for loading and unloading of cargo. There are 5 or 6 masts (depending on vessel size), with total sail areas of 8180, 12920 and 16638 square meters for the 15 kT, 30 kT and 45 kT vessels.

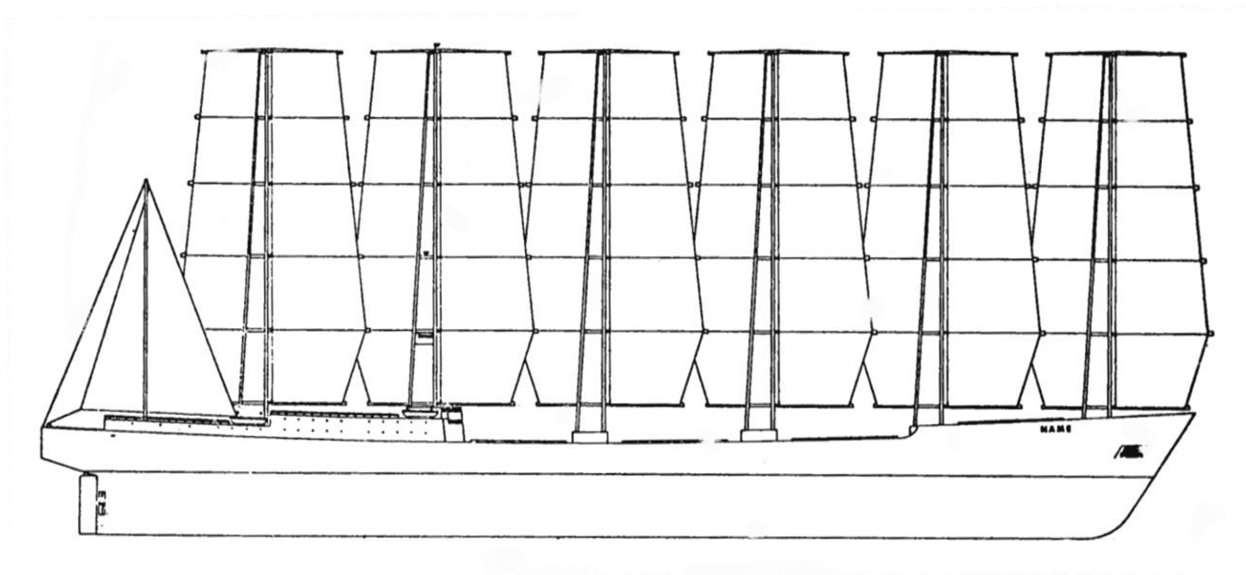

Figure 1. 45 kDWT sailing vessel. Note the tripod masts. On each mast are 5 sails that furl onto cylinders attached to the forward tripod leg of the masts. The sails slide along channels in the yards (these are the members perpendicular to the mast, 6 of them on each mast), and together, all 5 sails on each mast work in unison as a single high-aspect ratio wing. A housing for a motor is located at the base of each mast for furling and trimming the sails. Reliable push-button sail-furling is now common in sailing yachts. Image taken from [39].

Other past work

The Dynarig concept has been used in several yachts in recent years, the most famous of which is arguably the 88 m Maltese Falcon. This vessel was built in 2006 as a private yacht, with rotating single-spar carbon fiber masts strong enough to preclude the use of tripod masts and at the same time permit a slot running almost the entire length of the mast to house the furled sails [11]. Carbon fiber has greater strength than steel, and is extremely corrosion resistant. However, it must be noted that the Maltese Falcon reportedly cost roughly U.S. $150 million in 2006, which at the time was 2-3 times more expensive than some of the world's largest cargo ships [1].

In a 1981 report to MARAD [21], the authors considered U.S.-built, sail-assisted vessels up to 38,000 DWT (sail-assisted involves the engines being the primary source of propulsion; the engines are always engaged to move the ship). The authors found that rigid wing sails gave the best combination of cost, performance, reliability and safety, followed by unstayed cat rigs (a cat rig is a conventional sail as found in most recreational sailboats, but with only one sail located behind the mast; unstayed refers to the mast standing without need of supporting wires). Sail-assisted propulsion was found to give modest improvements in RFR (Required Freight Rate) as compared to motor-only cruising, with decreasing sail advantage with increasing vessel size. The 2,000-ton DWT sailing vessel demonstrated RFR improvements of $0.45/ton (cat rig) and $1.04/ton (rigid sail) over the motor vessel, while the 38 kT sailing vessel had improvement for the rigid wing of $0.23/ton, and no improvement for the cat rig.

During the 1970's and 1980's there was much activity in sail-assisted propulsion of merchant ships, sparked by high oil prices. For example, the Usuki Pioneer, a 27,500 DWT bulk carrier built in 1985, operated successfully for eight years using sail assisted motoring until an accident in port damaged the sails. This vessel had rigid, foldable sails designed by JAMDA (Japan Marine Machinery Development Association) and reportedly achieved 10%-30% fuel savings while transporting wood and grain between Japan and the U.S. West Coast. The 1984 built bulk carrier Aqua City, a 31 kDWT bulker, was retro-fitted with relatively small rigid sails of similar design; 16 other vessels had similar sails installed [14]. But the momentum of the sail-assisted concept was lost when fuel prices dropped. Recently, sail-assisted propulsion has been making a comeback. A full review of sail-assisted technology is presented in Chou[5].

The authors in [14] conducted a comprehensive design and economic analysis of a 50,000 DWT sailing vessel with Dynarig type sail with rotating masts, twin screws, bow thruster and collapsible masts, with a construction cost 20% greater than the equivalent motor vessel. The author found that at then-current prices there was no benefit to the use of sails. [15] followed up his design [14] with a study of a 50,000 DWT tanker that used rigid sails with a complex arrangement of adjustable wing shapes that simulated flaps and slats on aircraft. The result was a wing that generates almost twice the lift as a fabric sail, but with twice the drag, allowing smaller masts and sail area but requiring greater engine use. The author calculated the sailing vessel to be 23% more expensive than equivalent motor vessels and found no economic advantage to using wind power, based on fuel prices at the time. [16] predicted economic advantage of a 50 kDWT autonomous, hybrid vessel with the same wing sails from [14], for year 2025 operation. Operational savings compared to a motor-driven ship ranged from 3% to 25%, depending on the route and vessel speed, using a fuel cost of $126/barrel. The vessel was quite complex, with photovoltaic solar collectors, fuel cell, lithium-ion energy storage in addition to the rigid sails. The vessel was also designed to extract wind power from the ship's propellers when an excess in wind energy is available. The cost of this vessel was estimated as 24% higher than an equivalent engine-driven vessel.

Recently there has been attention given to a variety of proposed projects involving the use of sails as the principal power source for merchant vessels, for example the Oceanbird 7,000-car RORO by Wallenius Marine and the Ecoliner 8,000 DWT cargo ship by Oceanco.

There are numerous large motor-sail and sailing ships operating today, for example the modern-square-rigged vacation ship Club Med 2 (194 m LOA and 2400 square meters of sail area) and the traditional square-rigged Coast Guard Eagle training vessel (90 m LOA and 2070 square meter sail area), but they are all either private yachts, training vessels or cruise liners. There appear to be no merchant vessels in operation that measure over 100 m and use the wind as the primary source of power.

Smaller cargo ships exist in a niche green-transport market that may or may not be economically sustainable, for example vessels such as Tres Hombres (LOA 32 m LOA and 40 DWT) of Fairtransport, Inc., and the wooden Ceiba (under construction at this time, 250 DWT).

Methods:

We use the sailing vessel speeds, routes and fuel-use strategy from [39] to re-assess economic viability of 3 bulk carrier sailing vessel sizes: 15,000 DWT, 30,000 DWT and 45,000 DWT, using the fuel, construction and crewing prices of today.

We consider four round-trip voyage paths, each consisting of one leg with cargo and the other without: NY-Liverpool (6200 nautical miles round trip), Baltimore-Monrovia (8200 NM), San Francisco-Sydney (10,500 NM), Cape Flannery-Shanghai (12,800 NM). While these voyages may not necessarily be representative of current popular transit routes and practices, they serve as a basis for comparison between the sail and engine-driven ships in a variety of directions across two oceans. Voyage directions are measured along the course taken by the engine-driven ships.

The fuel-use strategy for the sailing vessel in [39] is to engage the auxiliary diesel engine for maneuvering and under light-wind conditions, so that a 6-knot speed can be maintained while under power-assisted operation. The engine is disengaged once the vessel is able to move at 6 knots under sail power alone. This strategy was found to eliminate much of the transient-time variability inherent in wind-powered propulsion. Table 1 shows average sailing vessel speeds and variances from [39].

The fuel-use strategy results in average voyage speeds of about 10 knots and use of the engine for approximately 50% of the distance traveled in summer, and as low as about 20% during seasons with higher wind speeds. On average, adopting this strategy results in sailing ship fuel consumption per cargo ton of about 1/10th that of the engine-driven vessel.

	15 kT	**30 kT**	**45 kT**
LOA (m)	**175.3**	**220.1**	**250.0**
Beam (m)	**20.1**	**25.4**	**29.0**
Draft (m)	**10.1**	**12.0**	**13.7**
Displ (tons)	**20,000**	**39,750**	**59,250**
Air draft (m)	**71**	**83**	**92**
Sail Area (m^2)	**8,180**	**12,920**	**16,638**
Engine Power kW	**447.4 (600 HP)**	**745.7 (1000 HP)**	**894.8 (1200 HP)**
Fuel Tankage (tons)	**200.0**	**250.0**	**275.0**
***Crew Size**	**22**	**23**	**24**
Average Vel (knots)	**9.2**	**9.8**	**10.5**
Average % Variance in Velocity	**7%-9%**	**7%-9%**	**7%-9%**
***Estimated Build Cost (USD)**	**$12.5 M**	**$27.6 M**	**$31.4 M**

Table 1. Features of the Asian-built sailing vessels used for this report, with updated construction costs including bow thrusters and sulfur-abatement scrubbers. Items marked with an asterisk are changed/updated from [39].

We investigate additional factors not considered in [39]: higher fuel costs, vessel construction in Asian shipyards, the use of bow thrusters and sulfur-abatement scrubbers, slow (10 knot) steaming for the motor vessels as well as normal speeds, and larger departures from "best estimate" costs (as high as

50%, as compared to 5% for the 1975 report). In addition, we use a "Fuel Parity Price", a new method for comparing wind-powered ships with conventional vessels. Table 1 shows the features of the proposed sailing ships considered in this report.

There were 9 costs considered in our analysis: fuel, insurance, crew, port, maintenance/repair, stores and lubes, vessel construction, financing and overhead.

There is a larger uncertainty in estimating the construction and operating costs of large merchant sailing vessels, as compared to motor vessels. Sailing ships of this size have never been constructed before (the Preussen was 433 ft in length (132 m), while the 45 kT sailing vessel is 820 ft (250 m)). In addition, there is limited operational experience with sailing vessels this size. One of the largest sailing vessels in operation today is the Royal Clipper cruise ship, with a length of 439 ft (134 m) and a draft of 5.6 m. The Preussen was about the same length, but had a draft of 8.3 m, allowing it to use sails 30% larger than the cruise ship.

The authors of [39] considered 3 scenarios: an "Operational" estimate based on their most reasonable estimate, as well as "Optimistic" and "Pessimistic" estimates based on reasonable departures from the Operational scenario. Using these different estimates resulted in a required freight rate (RFR) for the sailing vessels that varied by slightly less than +-5% from the Operational values.

We establish a "Baseline Scenario", representing our most reasonable estimate, based on sailing vessel construction cost 20% greater than the equivalent motor vessel. We felt that the +-5% RFR variation presented in [39] was too small given the uncertainties involved; in addition to the Baseline scenario, we consider sailing vessel construction costs that differ from the motor vessels by factors of 1.5 and 2. Furthermore, we consider Asian and U.S. vessel construction and operation, as well as slowing the motor vessel to 10 knots from the 15 knots assumed in [39].

We use [22] to estimate the majority of the operating costs for motor vessels, which compares average operating costs of U.S. and foreign-flag vessels. We established that the average bulker in 2010 was 68 kDWT [3], and scaled operating costs from [22] down to our vessels in proportion to DWT.

In the paragraphs below, we describe in more detail how costs are estimated. All estimates are made for foreign-crewed and constructed vessels, unless expressly specified.

COST ESTIMATES

Ship Construction costs: Vessel construction costs of motor-vessels were determined from recent Asian shipyard construction values, obtained from individuals familiar with this topic: <u>15 kDWT</u>: $10,000,000 USD; <u>30 kDWT</u>: $23,000,000 USD; <u>45 kDWT</u>: $26,000,000 USD. We add $100K, $200K and $300K to the cost of these vessels for installation of bow thrusters, and $1M, $1.25M and $1.5M USD for sulfur scrubbers, based on estimates in [25] and [9]. Sailing vessels construction costs were assumed to be 20% greater than the engine-driven vessels.

Construction in U.S. shipyards is also considered in this report, with construction costs 4 times the foreign yard values (people with knowledge in this field specify 3-5 times greater cost for U.S. construction).

The cost of the sails is included in the construction cost of the ship, and is important for calculating maintenance costs, as a 2-year sail life span is assumed. Table 2 shows Asian manufactured sail prices, based on a value of 0.113 USD/gram. This is a conservative estimate, as prices surveyed were as low as 17% below this figure.

Vessel	Sail Area (square m)	Cost (US $)
15 kT	8180	240,000
30 kT	12920	379,000
45 kT	16638	489,000

Table 2. Sail costs, based on Asian manufacture.

Fuel Prices: We found that the most important factor in determining economic viability was fuel price, due to its historical variability and outsized effect on economic viability (fuel accounts for well over of 50% of total expenses for motor vessels).

We note that there is some ambiguity in terms used to describe fuels. In some reports, the term HFO (or heavy fuel oil, used to denote products composed of the residue of distillation of crude oil) is being replaced by HSFO (high sulfur fuel oils, with sulfur content between 1% and 3.5%). IFO 380, which is a blend of mostly residual fuel with a small fraction of distillate fuel and therefore not a true residual fuel, is sometimes referred to as HFO and HSFO, presumably because the distillate content is so low. IFO 380 is the least expensive fuel listed on fuel price tracking sites, and reportedly one of the more common fuels used by ships before the new sulfur rules came into effect. In this report we use IFO 380 prices for comparing sailing and engine-driven ships. In addition, when interpreting fuel prices extracted from a variety of recent information sources, we consider HFO and HSFO to be IFO 380.

Fuel prices are in a particularly high state of flux at the time of this writing. At the beginning of 2020, new regulations by the IMO calling for a reduction in the sulfur content of ship fuel oils to 0.5% came into effect, down from 3.5%. Ship owners have a choice of using fuels with low sulfur content and using less-expensive, high sulfur fuels requiring installation of scrubbers.

These new regulations were accompanied by an increase in fuel prices, as expected, but were soon followed by a precipitous price drop due to Covid 19 reduction in demand [27].

Industry predictions are that by late 2021 VLSFO (Very Low Sulfur Fuel Oil) prices will rise over $500 per metric ton [31]. Prior to the Covid pandemic, [30] reported year 2025 predictions by IHS Markit of $560/tonne for MGO (Marine Gas-Oil), $730 per tonne for LSFO (Low Sulfur Fuel Oil) and $400/tonne for HFO (or $63/barrel based on a density of 991 kg/m^3).

Due to the relatively low price of HSFO compared to other fuels, some shipping companies are installing expensive scrubber systems to enable the use of this fuel and still remain within IMO guidelines. For this reason, we use the HSFO average price over the last ten years for our Baseline estimate, as well as the $63/barrel 2025 prediction by IHS Markit. The lower the price of the fuel, the greater the advantage for the motor-driven vessel over the sailing vessel.

We use the Rotterdam HSFO average price for years 2010-2019, at a price of $72.24/barrel. Figure 3 shows HSFO prices since 2004, obtained from [2]. Figure 3 also shows the lowest price attained by IFO 380 in Rotterdam in April of 2019 during the pandemic.

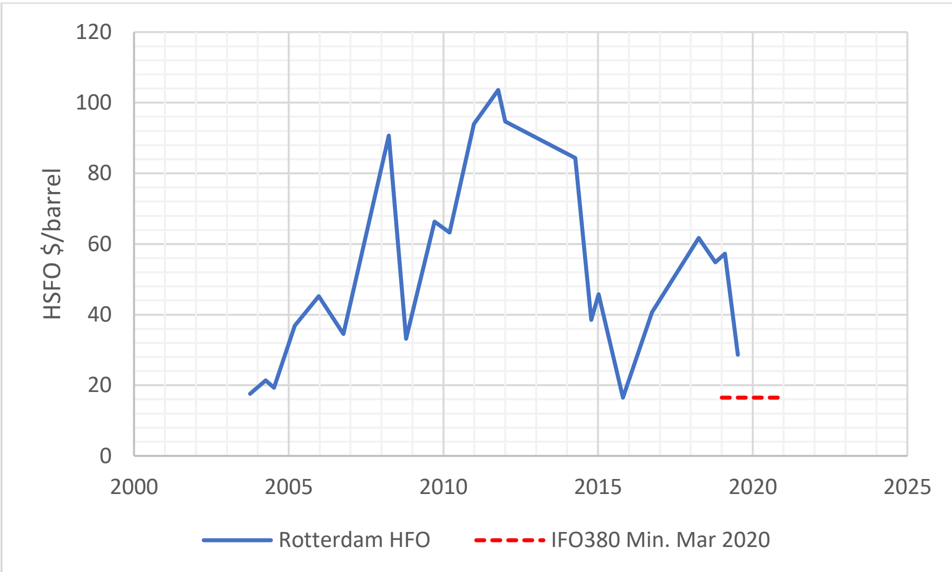

Figure 3. Historical Rotterdam HSFO fuel prices, with IFO 380 low at the onset of the Covid pandemic.

Figure 3 demonstrates the tremendous variation in fuel prices that can occur, from slightly below $20/barrel to over $100/barrel.

The fuel consumption figures used in [39] have been reduced by 20% for our report due to improvements in engine efficiencies since then [37].

Crew Costs: Crew costs were calculated using [22], which showed daily average wages (covering salaries, overtime, transportation and benefits) of $11,490 and $2,013 for U.S. flag and foreign bulk carriers. These figures were adjusted upwards for inflation to 2020 by multiplying by a factor of 1.1. Staffing levels were determined from ITF Annex 5 [19]. Crew sizes for sailing vessels were increased by one person over the motor vessels to accommodate additional duties related to maintaining the sails and their associated hardware. Table 1 shows the sailing vessel staffing levels.

Insurance Rates: [22] lists average bulker daily insurance rates of $1,527 and $745 for U.S. and foreign flag vessels, with an average bulker ship size of 62.8 kDWT [3]. These figures were scaled down to our vessels in proportion to the DWT of each vessel.

Sailing vessel insurance rates are likely to be greater than motor vessel rates by as much as about 20% [39], due to sailing vessels seeking out routes with greater winds and thus presumably greater levels of risk. Because of this, we increased sailing vessel insurance costs by 20% over engine-driven vessels. It is possible that the smaller amount of fuel carried by the sailing vessel could drive insurance rates lower due to reduced likelihoods of fire or oil spills.

Maintenance and repair: [22] lists average daily maintenance and repair costs for foreign and US flag bulker ships of $1,736 and $3,019 per day. These were scaled down to our three engine-driven vessels in proportion to DWT. The maintenance and repair costs of the sailing vessels were estimated by summing three quantities: the same M&R costs as the equivalent motor vessel, the costs associated with maintaining the sails, taken to be the same as the yearly maintenance costs of the engine ($6000*(SHP/1000)^2/3 ([39]) adjusted for inflation by multiplying by the average of the increase in labor and steel costs since then (4.6), and the cost of purchasing new sails amortized over 2 years (in other words, a 2-year life is assumed for the sails).

Overhead Costs: these were calculated by $3.33 times DWT ([39]), and adjusted for inflation as described above.

Stores and Lubes: Store and Lube costs were taken from [22] as $638 (foreign flag) and $1,362 (U.S. flag), the majority of which is lubrication for the engines. These were for the average bulker, with estimated 16,512 HP ([39] and [22]. Stores and Lubes values for our ships were calculated by scaling [22] values in proportion to ship engine power. Since sailing vessel engines are on less than ½ of the time, we used ½ the motor vessel costs for the sailing ship.

Ports Costs: From [29], the average cargo ship paid $76,370 per port visit in 2016/2017. We established that the average bulker vessel is 62.8 kDWT [3], and we scaled the average fee in proportion to DWT.

Financing charges: We use an interest rate of 8%, assuming a 10-year loan for sail and motor vessels as per current trends. For U.S.-built ships, the Federal Ship Acquisition Program current rate of 1.6% is used, over ten years [26].

COMPARISON STRATEGY

We compare required freight rates (RFR, the price that must be charged per ton of cargo, in order to meet all costs associated with owning and operating a vessel) between sail and motor vessels. RFR was calculated by summing all yearly costs and dividing by the total cargo carried per year.

Since sailing vessels of the size proposed have never been built, and even the smaller range of vessels considered has not been constructed or operated for cargo transport in over a century, there is some uncertainty in predicting construction prices, beyond what might normally be encountered in the design of conventional vessels.

When fuel prices are very high, sailing vessels obviously have the economic advantage over motorized vessels. The opposite is true when fuel prices are very low, and somewhere in-between there is a fuel price that results in equal RFR for the sailing and motor vessels. We refer to this as the “Fuel Parity Price”, and we use it to compare the economic viability of the vessels. Fuel prices over the Parity Price result in advantage for sailing vessels, while those below favor motor vessels. We feel the Fuel Parity Price is an important parameter for determining the viability of sailing ships since it is independent of current fuel prices.

We also use a “Baseline Estimate” for comparing sail and motor vessel freight rates, determining costs as described above, with 20% higher construction costs for the sailing vessel over the engine-driven vessel. Fuel cost of USD $72.24/barrel were used (the average over the last ten years for HSFO) for the Baseline Estimate.

We compare the sailing vessel against a motor vessel using the least expensive fuel alternative (IFO 380 with scrubbers to remove sulfur). The sailing vessel is assumed to use the same fuel, with scrubbers for the auxiliary engine.

Results:

Required Freight Rate

Figures 4a-4c show Baseline Estimates for Required Freight Rate for 15, 30 and 45 kDWT vessels, for the voyages studied in this work, using the 10-year average fuel price of $72.24/barrel. The plots show that the sailing vessel RFR is 21%-40% lower than for engine-driven vessels. In addition, the advantage of the sailing vessel can be seen to increase with voyage length (distance between ports increases from left-to-right on the plots) and to decrease with vessel cargo capacity.

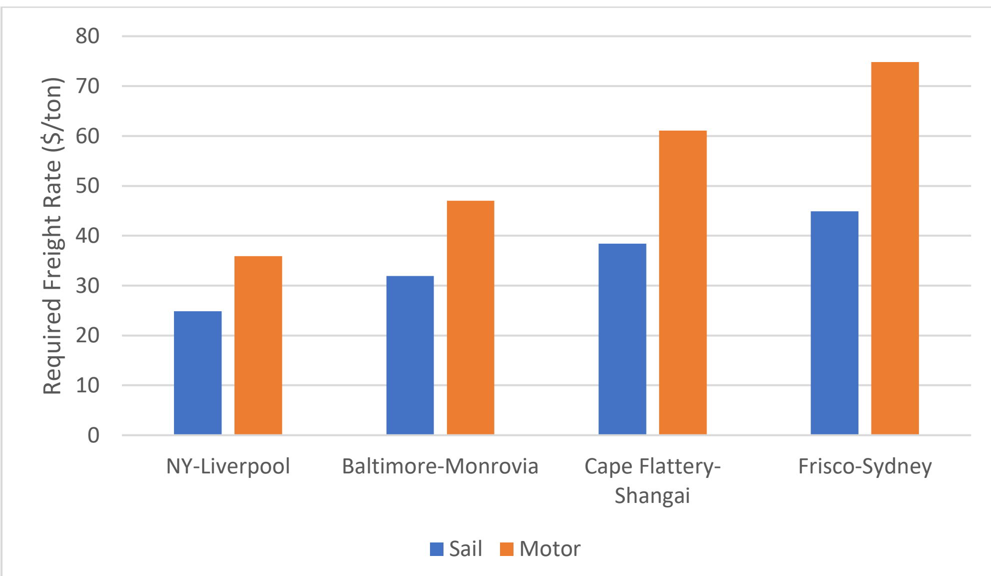

Figure 4a. 15 kDWT vessel Required Freight Rate (RFR).

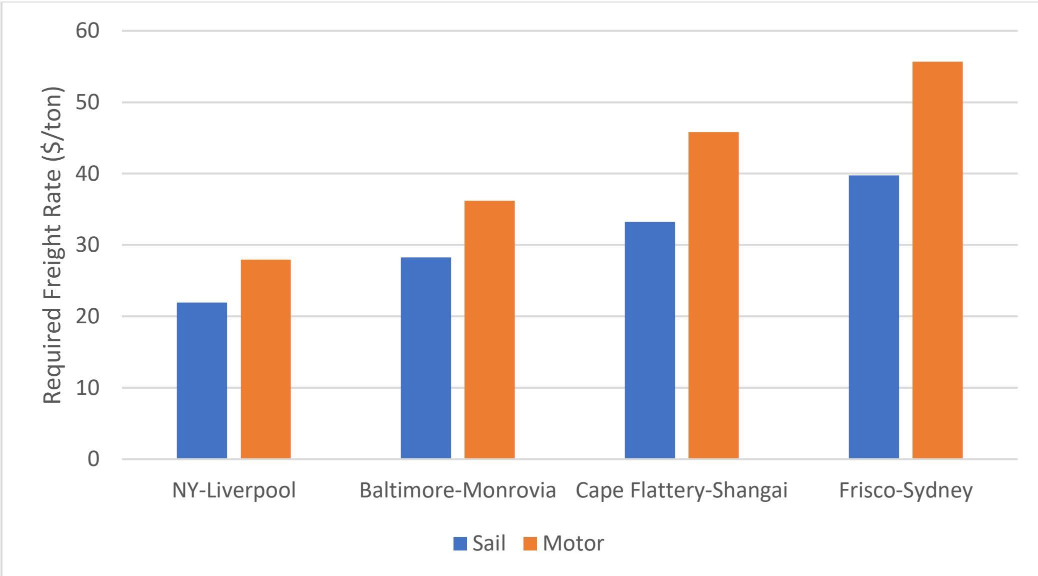

Figure 4b. 30 kDWT vessel Required Freight Rate (RFR).

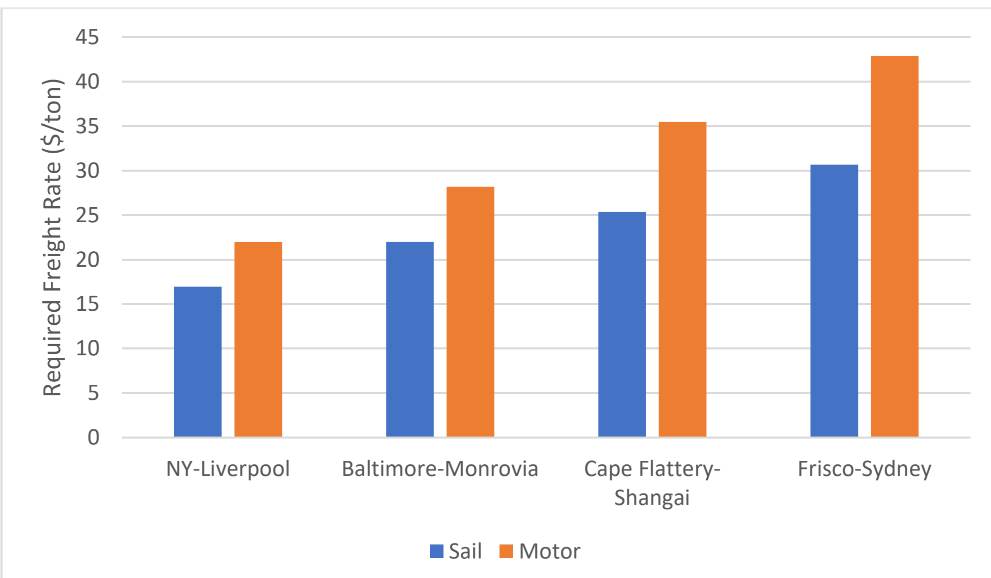

Figure 4c. 45 kDWT vessel Required Freight Rate (RFR)

The RFR was found to vary almost linearly when plot against voyage length, despite the differences in the routes, as demonstrated in Figure 5 for the 30 kDWT vessel. The plot also shows that for voyage round-trip distance less than about 3000 NM, the engine-driven vessel is more economical than the sailing vessel. At these shorter distances, a shift from motor-assisted sailing to sailing-assisted motoring might be more economical, as found in [21]. This is a topic that should be pursued further in future work.

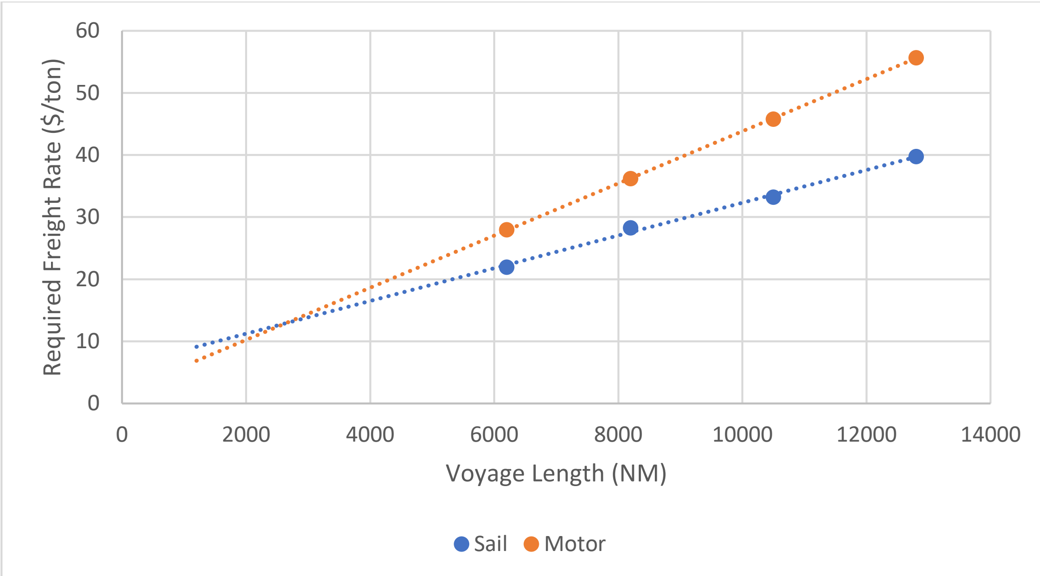

Figure 5. The plot shows that the Required Freight Rate (RFR) is linear with distance, despite the routes being different. Plot is for the 30 kDWT vessel.

Cost Breakdown

Figure 6a and Figure 6b show total cost percentages for the 30 kT motor and sailing vessels on the Baltimore-Monrovia run. Figure 6a shows that fuel costs are by-far the largest expense for the motor vessels, followed by costs of paying off the loan for the ship. For the sailing vessel, Figure 6b shows the largest costs are due to servicing the loan, followed by maintenance and repair.

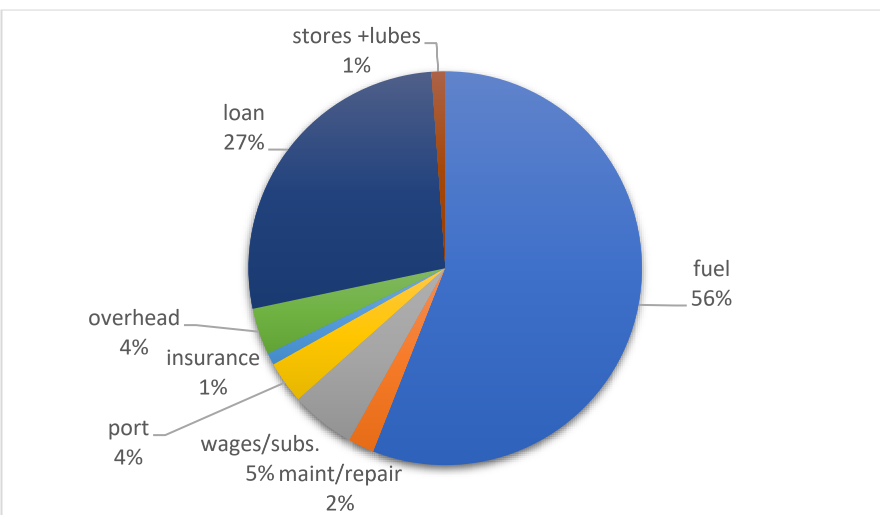

Figure 6a. 30 kT engine-driven vessel with foreign build, Baltimore-Monrovia run.

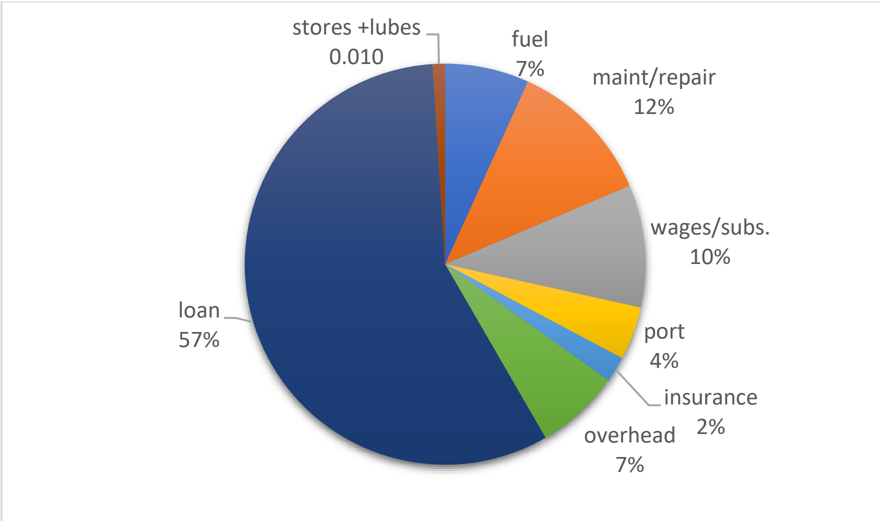

Figure 6b. 30 kT Sailing vessel with foreign build, Baltimore-Monrovia run

One very important result is that the 15 kT sailing vessel is less expensive to operate than the 30 kT engine-driven vessel, over all the routes considered. For example, Figure 4a shows that the 15 kT sailing vessel has a RFR of $24/ton on the NY-Liverpool run, while the 30 kT motor vessel RFR for the same voyage is $27.96/ton. The same result occurs for the 30kT sailing vessel and the 45 kT engine-driven ship. It also appears that the 15 kT sailing vessel is very close in Required Freight Rate to the 45 kT motor vessel, especially at the longer voyages.

Sensitivity Studies

We have already alluded to the fact that sailing ships of the sizes considered here have never been constructed. There is thus a possibility that cost estimates may be inaccurate, and we now explore the effects of underestimating some of the factors influencing economic viability.

<u>Effects of sailing vessel purchase cost</u>

As described earlier, for each of the ship sizes and journeys considered there is a “Parity Fuel Price” which results in equal freight rates between the sail and motor vessels. Figures 7a-7c show the Parity Fuel Price for the 15 kT, 30 kT and 45 kT sailing vessels using the assumptions listed above, but with 3 different construction costs: 1.2, 1.5 and 2 times the engine-driven vessel costs. Fuel prices greater than the Fuel Parity value result in sailing vessel advantage. The plots show that, based on the predicted HSFO year 2025 price by IHS Markit of $63/barrel as well as the 10-year average HSFO price of $72.24/barrel, the 15 kT sailing vessel construction prices can go as high as twice the motor vessel cost and still result in sailing vessel advantage for all the voyages considered. For the 30 kT and 45 kT sailing vessels, construction costs can go as high as about 1.5 times motor vessel costs.

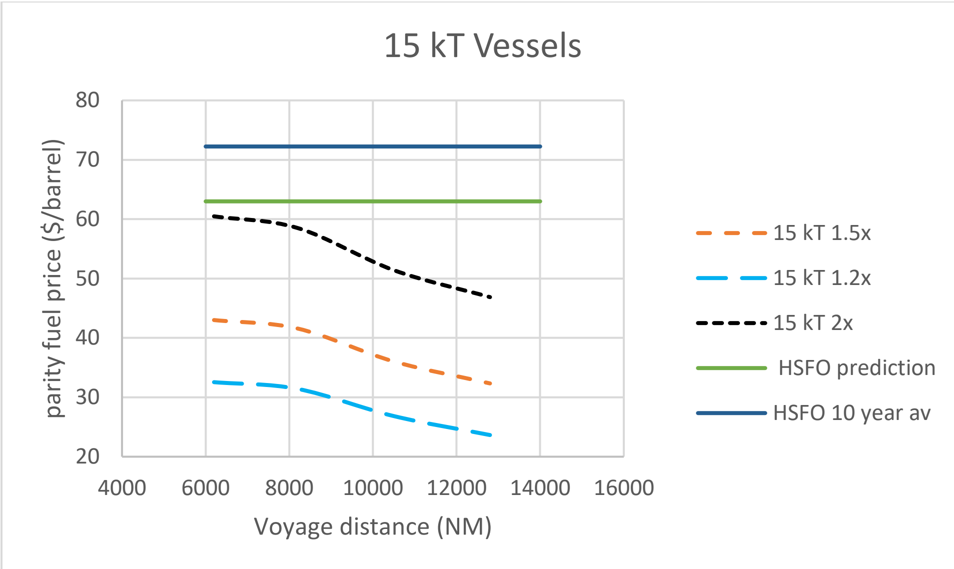

Figure 7a.

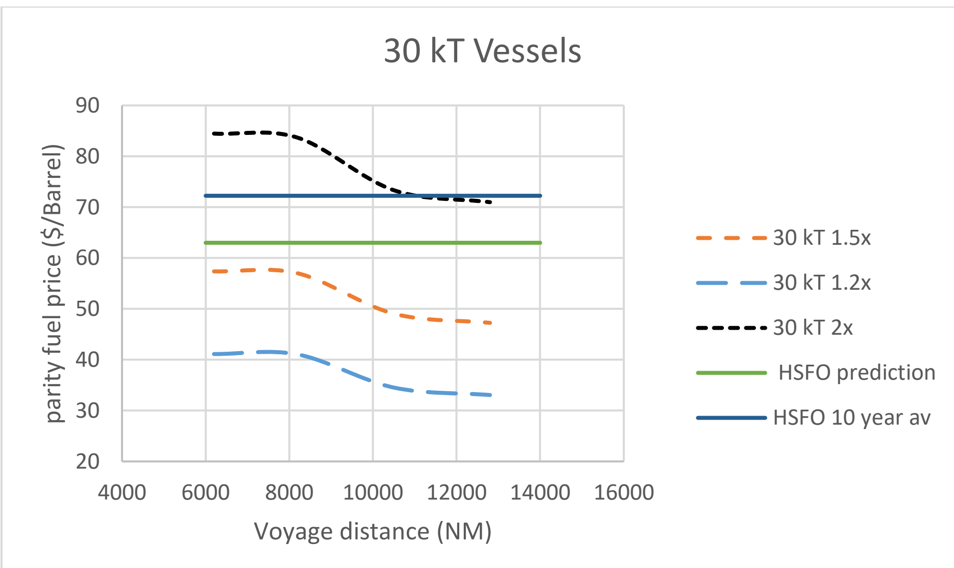

Figure 7b.

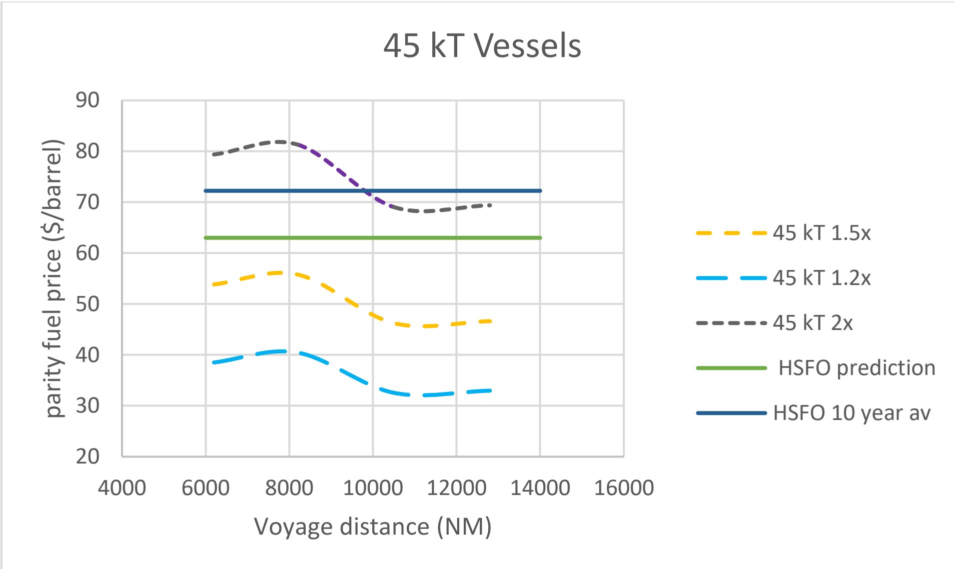

Figure 7c.

Figures 7a-7c: Parity fuel prices for 15 kT (Fig. 7a), 30 kT (Fig. 7b) and 45 kT (7c) vessels, with 1.2 times higher build costs than motor vessels (long-blue dashes), 1.5 times higher build costs (medium-length-orange dashes) and 2 times higher build costs (short-black dashes). The green solid lines represent the predicted IHS Markit HSFO fuel price for year 2025, and the solid blue lines are the 10-year average HSFO fuel price. Areas over the dashed lines represent sailing vessel advantage, and areas below show motor vessel advantage.

Effect of U.S. Construction and Crew

For comparison with U.S. construction and crewing, we present in Figure 8 the parity plot for the 15 kT vessel with U.S. construction and financing at 1.6% and 20 years. Construction costs are estimated as 4 times foreign, and the personnel costs 5.7 greater [22]. The plot shows that the greater overall cost of the vessels tends to decrease the advantage of the sailing ships, making them more susceptible to construction cost overruns, shifting the plots upward on Figure 8, as compared to Figure 7a. Nevertheless, the baseline parity price (based on 1.2 times the construction costs) is below the 10-year HSFO fuel average, but not below the $63 IHS Markit 2025 prediction (except for the longer voyages).

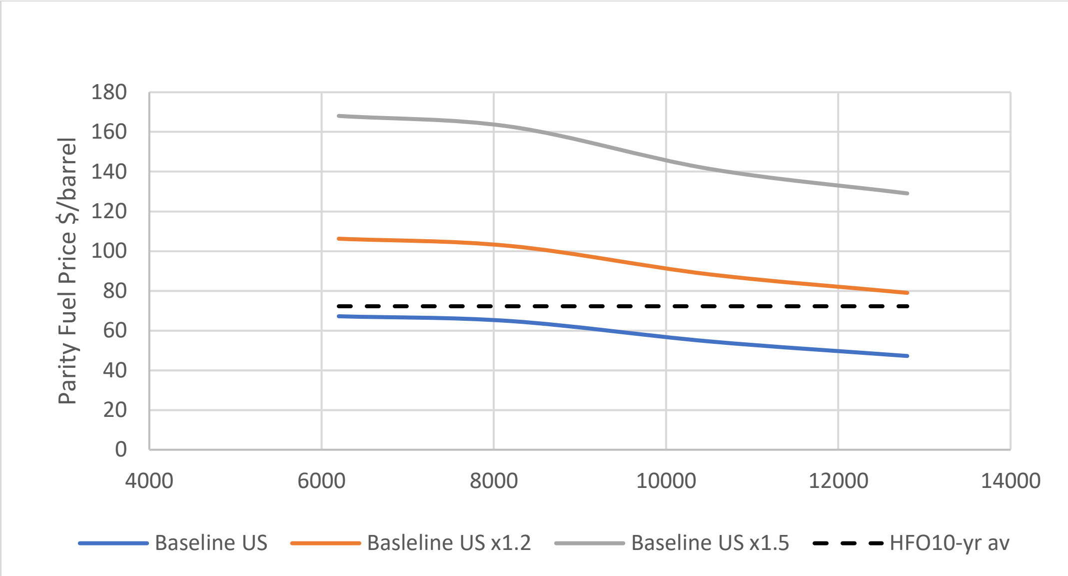

Figure 8. Fuel parity prices for sailing vessels constructed in the U.S., with U.S. crews. The baseline price refers to sailing vessel construction cost at 1.2 times the motor vessel cost. Areas over the solid lines represent sailing vessel advantage, and areas below show motor vessel advantage.

Effect of Interest Rates

The effects of varying the interest rate for ship financing are shown for the 15 kT foreign vessel in Figure 9, beginning with the baseline rate of 8%, to a maximum of 24%. Figure 9 shows that the interest rate is not as important as other factors considered in this report for determining economic viability.

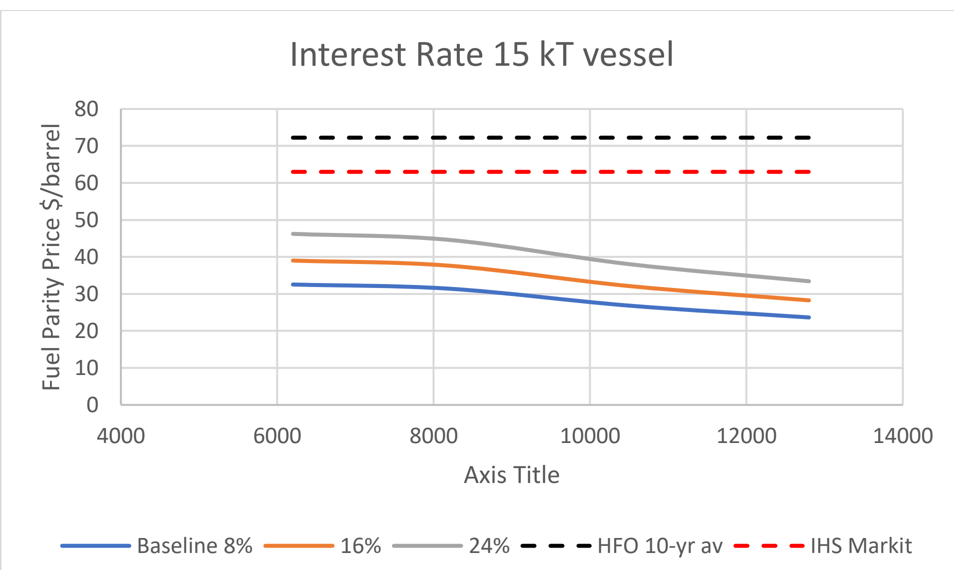

Figure 9. Effect of increased interest rates for ship loans. Areas over the solid lines represent sailing vessel advantage, and areas below show motor vessel advantage.

Effect of Crew Size

The effect of the crew size is seen in Figure 10, for the 15 kT vessel. The motor-vessel crew size is held constant at 20, while the sailing vessel crew is allowed to vary from 22 to as high as 28. Clearly the lower the crew size the better, but the effect, at least within the range considered is relatively small.

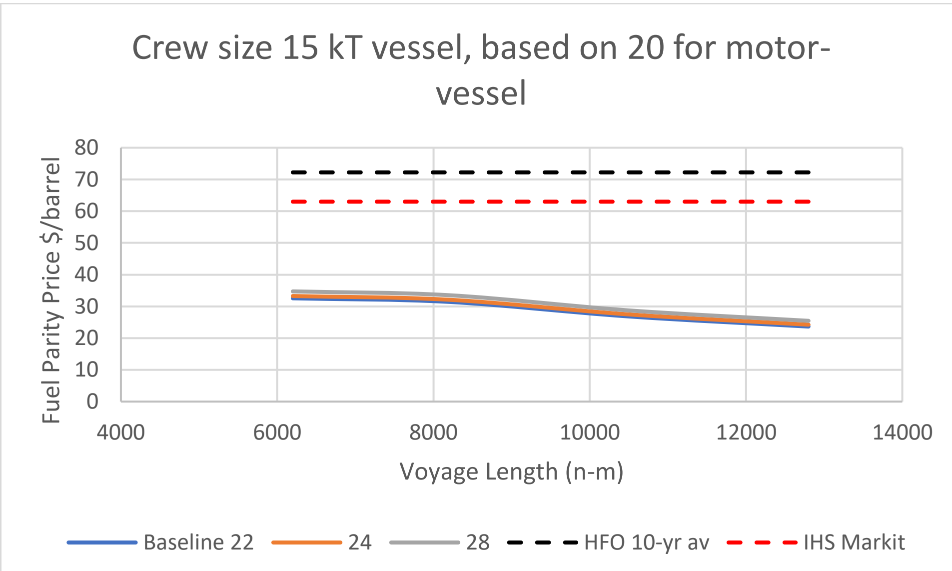

Figure 10. Effect of crew size on fuel parity price. The crew size appears to be relatively insensitive to crew size. The engine-driven vessel crew size was held constant at 20. Areas over the solid lines represent sailing vessel advantage, and areas below show motor vessel advantage.

Effect of Maintenance and Repair Costs

The effect of underestimating maintenance and repair costs for the 15 kT vessel is shown in Figure 11 below. Maintenance and repair (M&R) costs refer to mechanical components of the ship as well as the sails. Underestimating these costs is a scenario that is very possible, as the sails of the 30 kT and 45 kT vessels would be by-far the largest ever used. The authors in [39] set an expected 4-year life for the sails, but we feel a 2-year life span is more realistic. The replacement of the sails is included in the baseline maintenance costs as half of the sail cost every year. It appears from Figure 11 that excursions beyond about 3 times the Baseline sailing vessel maintenance and repair estimates will still result in economic advantage for the sailing vessel.

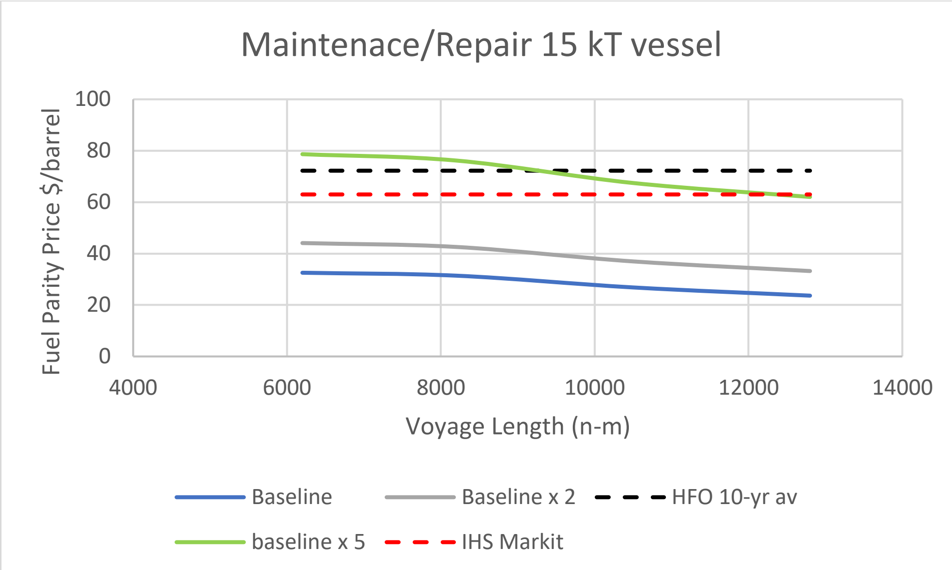

Figure 11. Effect of increased maintenance and repair costs for the 30 kT vessels. Areas over the solid lines represent sailing vessel advantage, and areas below show motor vessel advantage.

The plot shows that excursions up to about 3 times the baseline Maintenance and Repair will still result in sailing vessel advantage.

Effect of Motor-vessel speed

The results above involve 15 knot motor-vessel speeds. In this section we investigate the effect of lowering the motor-vessel speed. Figures 12 shows the effect of lowering the speed of the 30 kDWT motor vessel to 10 knots. The results for the 15 and 45 kDWT vessels are very similar.

In general, slowing the motor-vessel from 15 to 10 knots gives a greater advantage to the sailing vessel, driving the parity prices up. This occurs because the reduced speed results in fewer tons of cargo per year, and lower motor vessel speed than the sailing ship in the case of the larger vessels. The reduction in fuel consumption is not enough to overcome the decrease in total cargo carried.

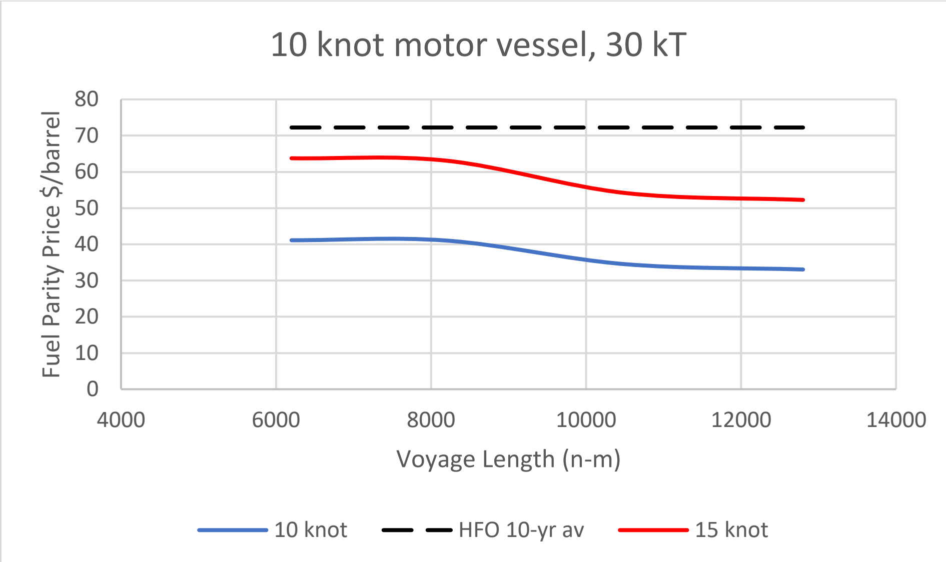

Figure 12. The solid red line is the fuel parity price for the 15 knot motor vessel and the baseline sailing vessel. Areas over the solid lines represent sailing vessel advantage, and areas below show motor vessel advantage. The solid blue line is the 10 knot motor vessel and the baseline sailing vessel. The fuel parity price is shifted up by slowing the motor vessel to 10 knots, giving a greater advantage to the sailing vessel.

Effect of Sail Prices

Figure 13 below shows polyester prices since 1987, which may reflect the price of Dacron (Dacron is a synthetic polyester fabric intended to show here possible variation in Dacron prices. We do not have historical Dacron prices available and use polyester fabric as a proxy for Dacron). The figure shows that the price has varied a maximum of about 63% of the mean. The sail costs are $240K, $379K, and $489K for the 15, 30 and 45 kT sailing vessels, which are a relatively small portion of the ship construction costs of $10, $23 and $26 million USD. Sail prices are not then likely to have a significant effect on our results, as the effect of total costs on economic viability has been shown above to be quite resistant to increased construction and maintenance costs.

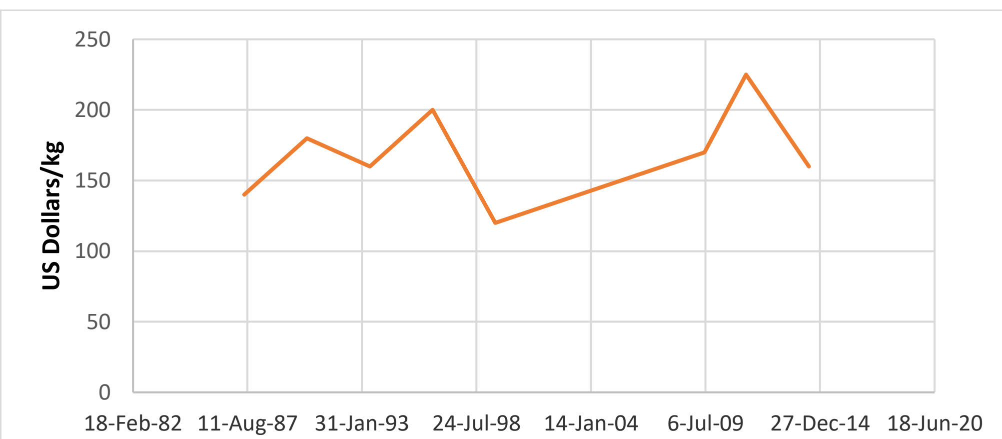

Figure 13. Historical polyester cloth prices.

Article may be cited as: Perez, S; Guan, C; Mesaros, A; Talay, A, Economic Viability of bulk cargo merchant sailing vessels, Journal of Merchant Ship Wind Energy, 17 August 2021.

Other important factors to consider in future studies

Carbon-Fiber Masts

Since the publication of [39], advances have been made in the field of composite materials, specifically carbon fiber. Masts made of carbon fiber are now not unusual in sailing yachts, and typically cost 3-4 times more than more common aluminum yacht masts [33]. The greater strength of carbon fiber permits single-sparred masts with slots in them to house the furled sails – an impossibility at the time of the development of the Dynarig [11].

We feel that using carbon fiber masts may be useful in reducing the windage of the sailing ships, leading to improved sailing performance. In addition, if draft of the sailing vessels is reduced, as will be discussed below, it may be difficult to achieve vessel stability without lightening the rig.

Air and Water Draft

One of the key findings in [39] and [21] was that draft restrictions in U.S. ports limit the carrying capacity of sailing vessels to about 45 kDWT, due to the need of greater draft for satisfactory sailing performance. Motor-driven vessels of the same draft (45 feet) would be limited to 70-80 kDWT. However, the authors of [39] noted that the use of moveable surfaces (such as retractable centerboards or leeboards/daggerboards used on some sailboats) could achieve the same side forces as fixed-keel vessels.

Centerboards and leeboards are not just for small boats, and are fairly common in larger sailing vessels. Sailing Yacht Mirabella 5 for example, a 77.6 m super-yacht with 2385 square meter sail area, is to the best of our knowledge the largest existing sailing vessel with a centerboard, permitting a draft of 3.8 m. When the centerboard is deployed for sailing, the draft increases to 10.2 m. Ancient Chinese sailing ships with leeboards are reported to have measured between 61-76 m (200-250 ft) in length [6].

A centerboard may achieve greater efficiency than a fixed keel – by going deeper, a centerboard with a high aspect ratio (depth/width) could achieve the same lift as a fixed keel, with lower induced drag force [38]. However, the stability of the vessel may be compromised if the center of gravity is raised when draft is reduced. This is a topic that has to be considered in further research, to enable sailing vessels to access as many ports as possible.

The mast height of even the smallest vessel considered here (15 kDWT) of 71 m can just pass underneath the Verrazano Narrows Bridge. Masts of these heights would prevent access of the vessels considered in this report to many U.S. ports. Telescoping or folding masts need to be incorporated into the sailing rig design, so that the sails can clear air drafts of about 37 m. At this point it is not clear if this can be accomplished within the cost limits found in this report of sailing vessel construction costs of 1.5 times motor vessel construction costs. The masts considered here are quite large, and the requirement to permit sail reefing and removal complicates the folding or telescoping of a mast.

Engine Power

The sailing vessels proposed might be susceptible to sudden high winds due to thunderstorms, as well as more likely moderately-high-sustained winds while maneuvering to and from port. Motor vessels of the same cargo capacity have many times more powerful engines, with greater ability to overcome such challenges.

We calculated that engine sizes of 4082 HP, 5395 HP and 6828 HP would provide sufficient power for the three sailing vessels to make way against 50 knot winds at vessel speeds of 6 knots with sails furled, increasing the cost of each ship by approximately $328K, $379K and $463K for the 15 kT, 30 kT and 45 kT vessels. The increases would result in relatively insignificant increases in manufacturing costs of about 3% and less, much lower than the cushion of 1.5 times the baseline found earlier in this work. The engine sizes suggested are 6.8, 5.4 and 5.7 times the power selected in [39], which accounted only for moving the vessel at 6 knots under ideal conditions.

The greater capabilities of the installed engines would be used only in emergency situations, so that the amount of fuel carried by the sailing ships would not need to be significantly increased, preventing the need for larger fuel tanks that would reduce cargo-carrying capacity.

We feel that increasing the power of the sailing vessels is essential for ensuring the safety and insurability of the sailing vessels, and should be a part of any future design, probably with the inclusion of side-thrusters and twin screws. [14] suggested using twin-screws with 7000 total horsepower (5400 kW) and a single bow thruster for a similar 50,000 DWT sailing vessel as used in this study.

Routes

Although the routes used provide useful comparisons between engine-driven and sailing vessels, further analysis should be performed involving more routes in liner and tramp shipping.

In addition, the transfer of goods between two points may involve multiple transport modes and intermediate storage of cargo. This process may be disrupted or complicated by the greater variability in sailing vessel crossing times inherent to dependence on the wind [39[. This is a topic that should be addressed in future studies.

Sailing Vessel Speed

Due to their lower speed, the sailing-ships considered carry less yearly cargo than the engine-driven vessels. Although the sailing vessels have a lower Required Freight Rate in order to cover all costs, the reduced yearly cargo can affect profits, which were not considered in [39] nor in this study. There were 9 costs considered in our analysis: fuel, insurance, crew, port, maintenance/repair, stores and lubes, vessel construction, financing and overhead. Further studies of sailing-ship viability should include a variety of possible business models.

Conclusions and Discussion

The vessels in this study are inspired by the large square-rigged merchant ships used in the 1900's by the P-series ships of the Laiesz lines. However, the vessels considered here are far larger, with sails that can be furled and adjusted by the touch of a button, using Dynarig setups that are twice as efficient as the square riggers of old [11]. The vessels considered here would be the largest sailing vessels ever constructed, with lengths up to 250 m.

We analyzed bulk trade sailing vessels using wind energy as the primary source of energy, and considered only fabric sails. The vessel designs, performance and method of economic analysis are the same as used in a feasibility study of merchant sailing ships [39], which found that sailing vessels were not economically viable. Today, with higher fuel prices, the opposite is found to be true.

We have determined that, based on past and predicted HSFO fuel prices and foreign-flag ships, bulk cargo sailing vessels of 15, 30 and 45 kDWT appear to have substantial economic advantage over foreign-flag motorized vessels. This is due to use of 10% of the fuel of the motor vessels while still maintaining sailing average speeds of about ten knots. The advantage results in the 15 kDWT sailing vessels requiring lower Required Freight Rate (RFR) than 30 kDWT motor vessels. The same applies to the 30 kDWT sailing vessels and the 45 kDWT engine-driven vessels.

Using our Baseline Cost Estimate (a best estimate that assumes 20% higher sailing ship construction costs than equivalent motor vessels) and the recent 10-year average price for HFO, the sailing vessel Required Freight Rate would be 21%-47% lower than the motor-vessel, depending on the vessel and route considered.

We found that the advantage of the sailing vessel is quite resistant to increased costs. For example, increasing the estimated total costs of operating and owning the sailing vessel by a factor of 1.5 times the Baseline estimate still resulted in economic superiority for the sailing vessel. This is because fuel costs dominate total expenses for the motor vessel, and play only a small portion of the sailing vessel's expenses.

Using Baseline estimates with 20% higher sailing ship construction costs than engine-driven vessels, fuel prices would have to dip below about $30-$40/barrel in order for the motor vessel to economically outperform the sailing ship. For sailing vessels 1.5 times the cost of the engine-driven vessel, the fuel price would need to be below about $40-$50/barrel for motor-vessel superiority. The predicted HFO price by IHS Markit [30] is $63/barrel. The recent 10-year average of HFO is $72/barrel.

Reducing the speed of the motor vessel from 15 to 10 knots resulted in an increased advantage of the sailing ship, with the exception of the shorter voyages combined with 1.5 times Baseline cost. This is due to the fact that the motor vessel still burns a much greater quantity of fuel than the sailing ship, and with the decreased speed carries less yearly freight.

We found that factors such as insurance and interest rates, maintenance costs, sail costs and crew size were not as important in establishing economic superiority as fuel price and ship acquisition costs, although they could conceivably tip the scales either way if the motor and sailing vessels were close in total operating costs.

For motor and sailing vessels manufactured and crewed by U.S. personnel, the Baseline estimate also results in sailing vessel superiority. However, sailing vessel construction costs cannot go larger than a factor of about 1.1 times baseline cost, beyond which the advantage goes to the motor-vessels.

Several improvements to the current sailing vessel design are discussed in [39], and may be realizable while remaining within the safety cushion of 1.5 times Baseline estimated costs:

1) The sailing vessels are limited to a maximum of approximately 50 kDWT by draft considerations in ports, since the sailing vessels require high draft for good sailing performance. However, this restriction may be circumvented through the use of movable leeboards or centerboards, such as are used in some large yachts today.
2) Maneuvering these large sailing ships with the relatively small auxiliary engines proposed in [39] could be unsafe under high wind conditions of motor-only cruising, such as in transiting to and from port areas. However, engines with roughly 6 times greater power would only result in overall cost increase by about 3% and would give maneuverability consistent with normal motor vessels.
3) The mast sizes proposed are not feasible given air draft restrictions found in many U.S. and foreign ports. Telescoping or folding masts, or some other solution, need be incorporated into the sailing rig design.

Upon analysis it appears that bulk cargo vessels with sails as the principal power source could provide not only lower operating costs, but also much lower emission levels, by virtue of greatly decreased fuel consumption. More detailed design and economical studies should be pursued.

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APPENDIX: RFR runs, foreign-vessel crews and construction, 10-year average fuel price, USD

NY-Liverpool 15 kT

fuel price per barrel 72.24
crew size motor,sail 20 21
tons transport/yr motor,sail 233200 165900
loan interest rate % 8
loan period years 10
----
all costs in $, to be multiplied by 1000
vessel cost motor, sail 11000 13000
sail cost USD. US, 240.545476
fuel $/year motor,sail 5195.92889 353.173333
maint $/yr motor,sail 142.501963 533.399495
wages $/yr motor, sail 672.517043 706.142896
lube $/yr motor, sail 113.63495 56.817475
port $/yr motor, sail 293.664 202.464
insurance $/yr motor, sail 64.9502389 77.9402866
overhead $/yr motor, sail 254.745 254.745
----
tot operating $/yr motor,sail 6737.94208 2184.68249
capital cost $/yr motor, sail 1639.32438 1937.38335
total $/yr motor,sail 8377.26646 4122.06584
motor RFR, sail RFR $/ton 35.923098 24.8466898

****
NY-Liverpool 30 kT

fuel price per barrel 72.24
crew size motor,sail 21 22
tons transport/yr motor,sail 471000 343200
loan interest rate % 8
loan period years 10
----
all costs in $, to be multiplied by 1000
vessel cost motor, sail 24250 28850
sail cost USD. US, 379.952513
fuel $/year motor,sail 7186.54222 460.195556
maint $/yr motor,sail 285.003927 877.94136
wages $/yr motor, sail 706.142896 739.768748
lube $/yr motor, sail 151.0748 75.5374
port $/yr motor, sail 586.5984 417.3312
insurance $/yr motor, sail 129.900478 155.880573
overhead $/yr motor, sail 509.49 509.49
----
tot operating $/yr motor,sail 9554.75272 3236.14484
capital cost $/yr motor, sail 3613.9651 4299.50075
total $/yr motor,sail 13168.7178 7535.64559
motor RFR, sail RFR $/ton 27.9590612 21.9570093

****

NY-Liverpool 45 kT
fuel price per barrel 72.24
crew size motor,sail 22 23
tons transport/yr motor,sail 707800 535000
loan interest rate % 8
loan period years 10
----
all costs in $, to be multiplied by 1000
vessel cost motor, sail 27500 32700
sail cost USD. US, 489.291365
fuel $/year motor,sail 8256.76444 497.653333
maint $/yr motor,sail 427.50589 1179.26709
wages $/yr motor, sail 739.768748 773.3946
lube $/yr motor, sail 183.91655 91.958275
port $/yr motor, sail 876.6144 651.168
insurance $/yr motor, sail 194.850717 233.82086
overhead $/yr motor, sail 764.235 764.235
----
tot operating $/yr motor,sail 11443.6557 4191.49716
capital cost $/yr motor, sail 4098.31094 4873.26428
total $/yr motor,sail 15541.9667 9064.76144
motor RFR, sail RFR $/ton 21.9581332 16.9434793

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Baltimore-Monrovia 15 kT

fuel price per barrel 72.24
crew size motor,sail 20 21
tons transport/yr motor,sail 179900 128600
loan interest rate % 8
loan period years 10
----
all costs in $, to be multiplied by 1000
vessel cost motor, sail 11000 13000
sail cost USD. US, 240.545476
fuel $/year motor,sail 5345.76 379.928889
maint $/yr motor,sail 142.501963 533.399495
wages $/yr motor, sail 672.517043 706.142896
lube $/yr motor, sail 113.63495 56.817475
port $/yr motor, sail 229.824 156.864
insurance $/yr motor, sail 64.9502389 77.9402866
overhead $/yr motor, sail 254.745 254.745
----
tot operating $/yr motor,sail 6823.9332 2165.83804
capital cost $/yr motor, sail 1639.32438 1937.38335
total $/yr motor,sail 8463.25757 4103.22139
motor RFR, sail RFR $/ton 47.0442333 31.9068538

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Baltimore-Monrovia 30 kT

fuel price per barrel 72.24
crew size motor,sail 21 22
tons transport/yr motor,sail 367400 264900
loan interest rate % 8
loan period years 10

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all costs in $, to be multiplied by 1000
vessel cost motor, sail 24250 28850
sail cost USD. US, 379.952513
fuel $/year motor,sail 7443.39556 508.355556
maint $/yr motor,sail 285.003927 877.94136
wages $/yr motor, sail 706.142896 739.768748
lube $/yr motor, sail 151.0748 75.5374
port $/yr motor, sail 461.1072 322.1184
insurance $/yr motor, sail 129.900478 155.880573
overhead $/yr motor, sail 509.49 509.49

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tot operating $/yr motor,sail 9686.11486 3189.09204
capital cost $/yr motor, sail 3613.9651 4299.50075
total $/yr motor,sail 13300.08 7488.59279
motor RFR, sail RFR $/ton 36.2005442 28.2695084

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Baltimore-Monrovia 45 kT

fuel price per barrel 72.24
crew size motor,sail 22 23
tons transport/yr motor,sail 557800 408200
loan interest rate % 8
loan period years 10

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all costs in $, to be multiplied by 1000
vessel cost motor, sail 27500 32700
sail cost USD. US, 489.291365
fuel $/year motor,sail 8625.99111 567.217778
maint $/yr motor,sail 427.50589 1179.26709
wages $/yr motor, sail 739.768748 773.3946
lube $/yr motor, sail 183.91655 91.958275
port $/yr motor, sail 694.944 497.952
insurance $/yr motor, sail 194.850717 233.82086
overhead $/yr motor, sail 764.235 764.235

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tot operating $/yr motor,sail 11631.212 4107.8456
capital cost $/yr motor, sail 4098.31094 4873.26428
total $/yr motor,sail 15729.523 8981.10988
motor RFR, sail RFR $/ton 28.1992165 22.0017391

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Cape Flattery-Shanghai 15 kT

fuel price per barrel 72.24
crew size motor,sail 20 21
tons transport/yr motor,sail 141400 105300
loan interest rate % 8
loan period years 10

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all costs in $, to be multiplied by 1000
vessel cost motor, sail 11000 13000
sail cost USD. US, 240.545476
fuel $/year motor,sail 5570.50667 353.173333
maint $/yr motor,sail 142.501963 533.399495
wages $/yr motor, sail 672.517043 706.142896
lube $/yr motor, sail 113.63495 56.817475
port $/yr motor, sail 182.4 127.68
insurance $/yr motor, sail 64.9502389 77.9402866
overhead $/yr motor, sail 254.745 254.745

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tot operating $/yr motor,sail 7001.25586 2109.89849
capital cost $/yr motor, sail 1639.32438 1937.38335
total $/yr motor,sail 8640.58024 4047.28184
motor RFR, sail RFR $/ton 61.1073567 38.435725

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Cape Flattery-Shanghai 30 kT

fuel price per barrel 72.24
crew size motor,sail 21 22
tons transport/yr motor,sail 292400 222000
loan interest rate % 8
loan period years 10

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all costs in $, to be multiplied by 1000
vessel cost motor, sail 24250 28850
sail cost USD. US, 379.952513
fuel $/year motor,sail 7625.33333 449.493333
maint $/yr motor,sail 285.003927 877.94136
wages $/yr motor, sail 706.142896 739.768748
lube $/yr motor, sail 151.0748 75.5374
port $/yr motor, sail 370.272 269.952
insurance $/yr motor, sail 129.900478 155.880573
overhead $/yr motor, sail 509.49 509.49

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tot operating $/yr motor,sail 9777.21743 3078.06341
capital cost $/yr motor, sail 3613.9651 4299.50075
total $/yr motor,sail 13391.1825 7377.56416
motor RFR, sail RFR $/ton 45.7974779 33.232271

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Cape Flattery-Shanghai 45 kT

fuel price per barrel 72.24
crew size motor,sail 22 23
tons transport/yr motor,sail 447100 349200
loan interest rate % 8
loan period years 10

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all costs in $, to be multiplied by 1000
vessel cost motor, sail 27500 32700
sail cost USD. US, 489.291365
fuel $/year motor,sail 8888.19556 508.355556
maint $/yr motor,sail 427.50589 1179.26709
wages $/yr motor, sail 739.768748 773.3946
lube $/yr motor, sail 183.91655 91.958275
port $/yr motor, sail 560.88 424.6272
insurance $/yr motor, sail 194.850717 233.82086
overhead $/yr motor, sail 764.235 764.235

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tot operating $/yr motor,sail 11759.3525 3975.65858
capital cost $/yr motor, sail 4098.31094 4873.26428
total $/yr motor,sail 15857.6634 8848.92286
motor RFR, sail RFR $/ton 35.4678224 25.340558

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San Francisco-Sydney 15 kT

fuel price per barrel 72.24
crew size motor,sail 20 21
tons transport/yr motor,sail 116100 90300
loan interest rate % 8
loan period years 10

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all costs in $, to be multiplied by 1000
vessel cost motor, sail 11000 13000
sail cost USD. US, 240.545476
fuel $/year motor,sail 5650.77333 379.928889
maint $/yr motor,sail 142.501963 533.399495
wages $/yr motor, sail 672.517043 706.142896
lube $/yr motor, sail 113.63495 56.817475
port $/yr motor, sail 151.392 109.44
insurance $/yr motor, sail 64.9502389 77.9402866
overhead $/yr motor, sail 254.745 254.745

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tot operating $/yr motor,sail 7050.51453 2118.41404
capital cost $/yr motor, sail 1639.32438 1937.38335
total $/yr motor,sail 8689.8389 4055.79739
motor RFR, sail RFR $/ton 74.8478803 44.9146998

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San Francisco-Sydney 30 kT

fuel price per barrel 72.24
crew size motor,sail 21 22
tons transport/yr motor,sail 241800 186000
loan interest rate % 8
loan period years 10
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all costs in $, to be multiplied by 1000
vessel cost motor, sail 24250 28850
sail cost USD. US, 379.952513
fuel $/year motor,sail 7759.11111 508.355556
maint $/yr motor,sail 285.003927 877.94136
wages $/yr motor, sail 706.142896 739.768748
lube $/yr motor, sail 151.0748 75.5374
port $/yr motor, sail 308.9856 226.176
insurance $/yr motor, sail 129.900478 155.880573
overhead $/yr motor, sail 509.49 509.49
----
tot operating $/yr motor,sail 9849.70881 3093.14964
capital cost $/yr motor, sail 3613.9651 4299.50075
total $/yr motor,sail 13463.6739 7392.65039
motor RFR, sail RFR $/ton 55.6810335 39.7454322

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San Francisco-Sydney 45 kT

fuel price per barrel 72.24
crew size motor,sail 22 23
tons transport/yr motor,sail 372100 288000
loan interest rate % 8
loan period years 10
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all costs in $, to be multiplied by 1000
vessel cost motor, sail 27500 32700
sail cost USD. US, 489.291365
fuel $/year motor,sail 9064.78222 567.217778
maint $/yr motor,sail 427.50589 1179.26709
wages $/yr motor, sail 739.768748 773.3946
lube $/yr motor, sail 183.91655 91.958275
port $/yr motor, sail 470.592 350.208
insurance $/yr motor, sail 194.850717 233.82086
overhead $/yr motor, sail 764.235 764.235
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tot operating $/yr motor,sail 11845.6511 3960.1016
capital cost $/yr motor, sail 4098.31094 4873.26428
total $/yr motor,sail 15943.9621 8833.36588
motor RFR, sail RFR $/ton 42.8485946 30.6714093

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San Francisco-Sydney 45 kT

fuel price per barrel	72.24	
crew size motor,sail	22	23
tons transport/yr motor,sail	372100	288000
loan interest rate %	8	
loan period years	10	

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all costs in $, to be multiplied by 1000

vessel cost motor, sail	27500	32700
sail cost USD. US,	489.291365	
fuel $/year motor,sail	9064.78222	567.217778
maint $/yr motor,sail	427.50589	1179.26709
wages $/yr motor, sail	739.768748	773.3946
lube $/yr motor, sail	183.91655	91.958275
port $/yr motor, sail	470.592	350.208
insurance $/yr motor, sail	194.850717	233.82086
overhead $/yr motor, sail	764.235	764.235

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tot operating $/yr motor,sail	11845.6511	3960.1016
capital cost $/yr motor, sail	4098.31094	4873.26428
total $/yr motor,sail	15943.9621	8833.36588
motor RFR, sail RFR $/ton	42.8485946	30.6714093

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