EFFICIENT APPLICATION RANGE OF ELECTRIC CARGO SHIPS

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SUMMARY

This paper scrutinizes the common belief that electric vessels are economically disadvantageous. To achieve this, data from the most known all-electric cargo ships (available on the internet) was gathered and missing information was estimated, to put together a sample selection. Sample vessels' parameters including principal dimensions, speed and battery capacity were used to calculate their relative cargo transport efficiency. Different routes and speeds were used, as electric ships' efficiency was compared to that of fuel-powered vessels. Electric ships were shown to be about 50% more profitable on short routes and equally as profitable on medium routes (if they were slow steaming), the reasons being reduced crew, lower maintenance requirements and higher propulsion efficiency. However, at long routes and/or high speeds oil-powered ships currently dominate because otherwise a big part of cargo space would be allocated to transporting batteries, whose energy density is much lower than fuel among other reasons. This paper derives an electric ship's design guidelines and provides guidance on decision-making as to whether to adopt an electric propulsion ship on a given route.

NOMENCLATURE

B	Breadth of a ship (m)
C	Battery capacity (kWh)
Cb	Block coefficient
T	Draught of a ship (m)
T_c	TEU capacity of a ship
TEU	Twenty-foot Equivalent Unit
Dw	Deadweight (metric tons)
D	Displacement (metric tons or kN)
E	Efficiency parameter (USD/metric ton)
Fr	Froude's number for ships
L	Length of a ship (m)
LOA	Length Over All of a ship (m)
N	Power (kW)
η	Propulsive coefficient
R	Range of a ship (m)
l	Ship's relative length (l)
v	Speed (knot [1,852 m/h], m/s)
μ	Kinematic viscosity, (m^2/s)
t	Time (hours)
R_T	Towing Resistance (kN)
WPR	Weight-to-Power Ratio
S_w	Wetted surface area (m2)

1. INTRODUCTION

All-electric ships have already been around and popular for a while. Ever since the world's first electric boat was launched by Boris Semyonovich von Jacobi in St. Petersburg in 1839 (Engineering and Technology History Wiki, n.d.), electric boats have remained passenger boats. The usage of batteries only penetrated the cargo fleet as auxiliaries to combustion engines. The reason is, that batteries could not, and still can't, provide as much energy for a long time as fuel can because of their energy density, which is defined as the amount of energy stored in a unit of mass of an energy source (battery or fuel).

However, with developments in battery technology as well as combustible fuel's environmental impact awareness on the rise, all-electric cargo vessels are emerging as a new sub-division of electric vessels.

As they are a new type of vessel, there is a certain degree of ambiguity in their design principles. Different companies experiment with various battery types and vessel architectures. This paper aims to analyse the existing projects and shed some light on the reasoning behind their design so that future designs of such vessels would be devised with an understanding of all the factors involved.

2. LITERATURE REVIEW

In recent years, the broad topic of on-ship battery technology and all-electric ships has gained increased interest in the scientific community as well as the broad public. Some of the most important and relatable publications should be mentioned.

In 2018, the European Maritime Safety Agency (EMSA) commissioned DNV GL to perform a study on the use of electrical storage systems in shipping, with the objective of providing an overview of the technology, research, feasibility, regulations and safety of battery systems in maritime applications. Their finding is presented in a large report, that explores dozens of battery types and examines specifically how they fit for marine applications. (European Maritime Safety Agency, 2020). It is a comprehensive guide for choosing battery type. However, almost all current vessels are using Li-Ion batteries as the trusted and tested technology.

A 2020 study on passenger electric ships (Anwar, 2020) includes a compilation of data including battery technology type, battery usage as well as principal particulars. The data is very useful, but the paper did not touch on the engineering aspect of said ships.

Another article titled "Developments in Electric and Green Marine Ships" provides information on currently commercially available battery packs and some methods for power consumption calculation. (Koumentakos, 2019) The author proves, that solar energy is not enough to power a cargo ship and that batteries have to be charged onshore, and argues, that electric ships are economically viable if the travel distance is not long.

An important development for the unification of batteries is the introduction of the E-Powerbox, a 20-feet container stuffed with batteries, a control device and insulation from shocks. that can be loaded to recharge the ship in minutes. It was developed at the EU's Connecting Europe Facility's request and the technology will be piloted by a Dutch company Port Liner on their river-going all-electric container vessels. (RINA, 2018) Other companies were quick to follow. A similar container from another manufacturer is shown in Fig. 1.

Figure 1. SKOON battery container.
Source: https://skoon.world

3. METHOD

The data for this paper was gathered around the internet. Chiefly, on shipping and shipbuilding companies' websites, scientific papers, news outlets etc.

In total, data on 8 electric and 68 oil ships was used in this study. The data was collected with due diligence, but in several cases, the numbers are approximate or disputed, such cases are marked red. Only when the approximate data fit well with generic values it was accepted.

Data analysis with help of different naval architecture methods specified in each section was performed on the sampled data. All the calculations were performed in Excel. Approximation was done with the least-squares method.

3.1 DATA PREPARATION

The aggregated datasheet for electric vessels is shown in Table 1. The raw data collected included length overall, breadth, draught, deadweight, design TEU, range, installed propulsion power and battery capacity as well as battery type. The values marked orange were calculated according to the reliable methods described below. Red values were approximated from photos (dimensions) and taken as generic (speed, capacity).

3.2 SPEED CALCULATION

It was proven, that generally, slow steaming is an efficient method to cut operational costs. (Gurning, et al., 2017) In this study, both maximum speed and economic speeds are considered, but for most ships, only maximum speed data is available. The economic speed was calculated as follows:

Firstly, block coefficient Cb was calculated from the principal particulars. Displacement was found as deadweight divided by utilisation coefficient, assumed 0.77, which is slightly bigger than the average of the coefficient, all-electric ships don't have an engine room, thus at least 2% of the ship's displacement goes to deadweight. The exact deadweight was known for all ships but PortLiner EC110.

It is known well known, that different companies assume different container loads when specifying their ship's TEU capacity based on planned cargo. From PortLiner EC52 data, it is evident they count a TEU as weighing 11 ton. Yara Birkeland counts their container as weighing 26.6 ton, which is about the maximum TEU load when carried on a ship. When carried on trucks or trains, the allowed weight is lower, 20 and 23 tonnes respectively (UK P&I Club, 2010). For the purpose of just comparison of freight rates in further calculations, all ships had their deadweight expressed in "*Normal*" TEUs, weighing 20 metric tonnes.

Secondly, the optimal Froude number was calculated with the following expression, derived from the empirical formula for cargo ships (9.67) (V.V.Ashik, 1985):

$$Fr = \frac{0.99 - C_b}{1.2} \tag{1}$$

It is worth noting that depending on wave conditions on the route as well as the on the ship purpose the empirical formulae differ, the difference only amounts to ± 0.03Cb at the same Fr number (Solomentsev & Lee, 2013), therefore it is not practical to use different formulae for the different ships and routes in this paper.

Table 1: Aggregated data of electric ships

Type	Name	LOA	Breadth	Draught	Deadweight	Displacement	Design TEU	Normalised TEU	Speed max	Speed ECO	Range	Trip time	Trip time at eco	Installed EPS	Battery capacity	Battery type	Fr max	Cb
		L, m	B, m	T,m	Dw, t	D, t			v, kn		R, nm	t, h		P, kW	C, kW*h			
Cont	PortLiner EC52	52	6.7	2	400	519	36	20	9	9.62	135.0	15	14.0	112	1680	VRFB	0.20	0.72
Cont	PortLiner EC110 11.45m	110	11.5	3.5	3080	4000	280	154	10.2	5.58	143.0	14	25.6	480	6720	Li-Ion	0.16	0.88
Cont	PortLiner EC110 15m	110	15	3.5	3850	5000	350	192	10.2	7.74	143.0	14	18.5	480	6720	Li-Ion	0.16	0.84
Cont	Yara Birkeland	80	15	6.3	3200	4156	120	160	13	7	30	2.3	4.3	1800	8000	Li-Ion	0.24	0.54
Bulk	Zhongtiandianyun 001	50	11	3	1000	1299		50	7	7.98	50	7.1	6.3	204	1458	Li-Ion	0.16	0.77
Bulk	GSIC Ship	70.5	13.9	3.3	2000	2597		100	6.9	8.8	43.2	6.3	4.9	320	2400	Li-Ion	0.13	0.78
Cont	China Smart Energetics Innovation Center Ship	65	10	2.5	1000	1299	64	50	10	8.61	135.0	13.5	15.7	534	7208	Li-Ion	0.20	0.78
Tank	e5Consortium tanker (when not using fuel)	62	10.3	4.15	1300	1688		65	11	7	64.2	5.8	9.2	600	3500	Li-Ion	0.23	0.62

As the Length and Cb of a ship are already known, this optimal Froude number is used to determine at which speed the resistance would be as low as possible while the speed remains as fast as possible - the ship's economic speed,

$$v = Fr\sqrt{gL}, \tag{2}$$

where v is ship speed in m/s.

3.3 RESISTANCE CALCULATION

The data only contained installed maximum power, without specifying how much of it is actually required under normal sailing conditions. To find the required power, every ship's is total calm water resistance was calculated by an approximate method.

$$P = \left(R_T * \mathrm{v}\right) K / \eta,\ kW, \tag{3}$$

where R_T is total calm water resistance;

K = 1.2 – sailing conditions factor for seagoing vessels;

η = 0.7 – propulsive coefficient.

$$R_T = 1.1\left(R_f + R_0\right),\ kN \tag{4}$$

As the ships are relatively slow, the dominant part of the resistance is due to friction, so it is calculated more precisely:

Table 2: Comparison of factual relative length, m to proposed by formulas

№	l_{koh}	l_{nog}	l_{fact}
1	4.55	4.68	6.32
2	4.09	3.90	6.99
3	4.33	4.35	6.49
4	4.25	4.21	4.86
5	4.36	4.40	4.48
6	4.45	4.54	5.01
7	4.43	4.51	5.82
8	4.25	4.21	5.09

$$R_f = C_{F0}\frac{\rho}{2}S_w \mathrm{v}^2, kN \tag{5}$$

Wetted surface area, a formula for large C_b

$$S_w = \mathrm{LT}\left(1.36 + 1.13C_b\frac{\mathrm{B}}{\mathrm{L}}\right), m^2 \tag{6}$$

Prandtl–Schlichting friction resistance coefficient (Schlichting H, (1941) /42)):

$$\mathrm{C}_{F0} = \frac{0.455}{\left(lgRe\right)^{2.58}} \tag{7}$$

Reynolds number:

$$Re = V\mathrm{L} / \mu \tag{8}$$

Residual resistance (Voitkunski Y.I., 1988):

$$R_0 = C_R\frac{\rho \mathrm{v}^2}{2}S_w,\ k\mathrm{N}, \tag{9}$$

where C_R is coefficient of residual resistance, found from series diagram for large C_b ships. Shape correction coefficients were not used as only approximate resistance was needed for the large number of ships.

4. RESULTS

4.1 RELATIVE LENGTH

Relative length l of a ship is defined as:

$$l = \frac{L_{pp}}{\sqrt[3]{D / \rho}},\ \mathrm{m} \tag{10}$$

It is a useful characteristic used at the early stage of ship design to determine future ship's length based on previous designs. It shows how elongated the ship is.

It is usually determined with formulas based on statistical data as a function of the ship's desired speed v.

The formula proposed by (Kokhanovskiy & Larkin, 1979) for container and general cargo ships:

$$l_{koh} = 3.45 + 0.144\mathrm{v} \tag{11}$$

The formula proposed by (Nogid, 1964) for all cargo ships:

$$l_{nog} = \left(2.13 \div 2.3\right) + \sqrt[3]{\mathrm{v}} \tag{12}$$

The formulas are somewhat dated, but still applicable for small and medium-sized container and general cargo ships, as their hull contours have not changed much, and the ships investigated in the study are not newbuilds. Therefore, there were no studies updating them.

For the fuel ships in this paper, both factual and recommended values fall between 4 and 5 m, the average factual value being 5.03 m. However, it is shown in Table. 2, that the actual value l_e of this parameter varies between 5 and 7 m for the given ships, with an average value of 5.76, which is much higher than the recommended values.

This discerption is caused by the philosophy of all-electric ship design. While fuel-powered container ships have higher speeds around 12 kn, even when "slow steaming" (Gurning, et al., 2017), for all-electric ships such speed is an unaffordable luxury. In order to keep the required power low and thus necessary battery

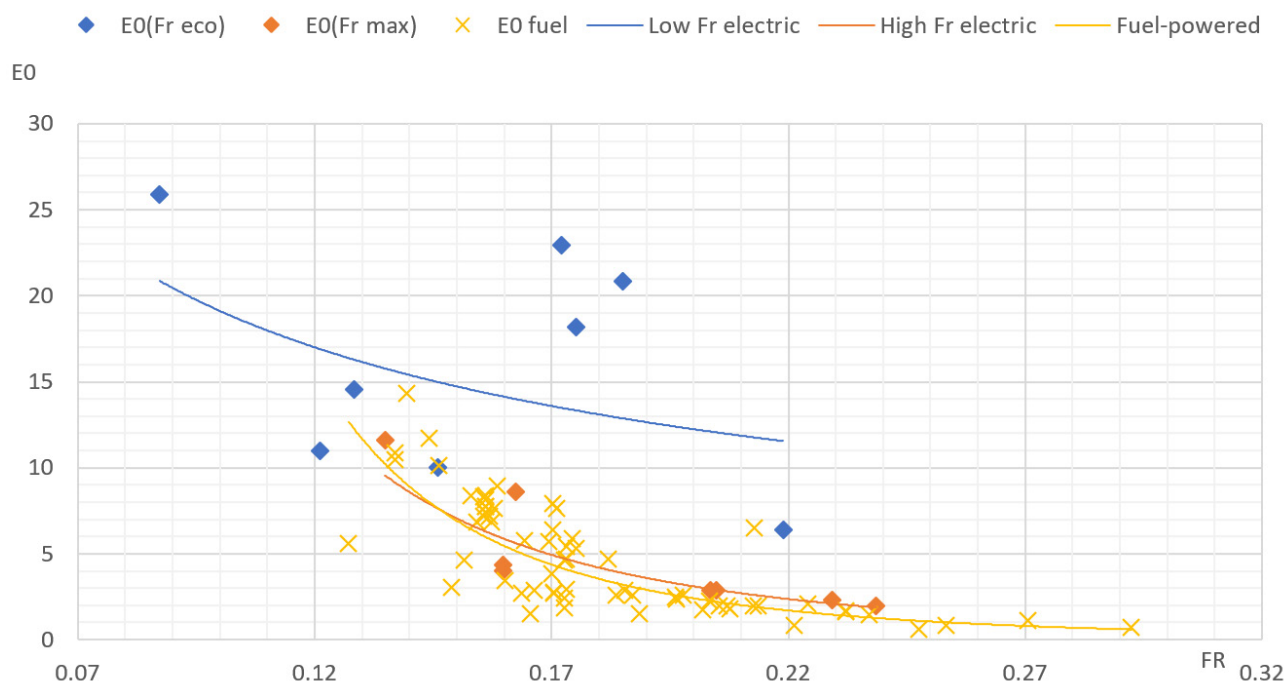

Figure 2. Graph of efficiency vs Fr number for all-electric and fuel powered vessels with approximating curves.

capacity and weight low, water resistance has to be minimized. Water resistance consists of friction and residual resistance. the latter being by large, a function of Froude Number (Fr):

$$Fr = \frac{\mathrm{v}}{\sqrt{gL}}, \tag{13}$$

where v is ship speed in m/s.

As the Froude number slowly increases, the resistance increases exponentially. So, with a given length, the lower the ship speed the lower the resistance. The speed can be reduced up to a certain limit when the delivery time becomes too long or a water current is faster than the ship or the manoeuvrability is limited; therefore, the length being the only free variable has to increase to further decrease the resistance. That is the apparent reason for the high relative length of all-electric ships.

4.2 MEASURING EFFICIENCY

4.2 (a) Efficiency calculation method

To quantify and compare transport vehicles' efficiency weight-to-power ratio (WPR) is often used, the larger it is, the more efficient the vehicle. Usually, full vehicle weight or engine weight is considered, but for our purposes, deadweight Dw will be used in their place, as we only care about the cargo mass transported by the ship, and not the displacement. It is not to be confused with "weight to power" ratio for propulsion plants.

$$E_0 = \mathrm{WPR} = \frac{Dw}{P_i}, \frac{t}{kW} \tag{14}$$

However, in Fig. 2, it can be seen that WPR remains relatively the same for electric and fuel vessels. And electric vessels' WPR at max speed is less than WPR at the economic speed, but it gives no consideration to shipping time.

What it shows is that measuring a ship's efficiency based on WPR is not a good solution. The difference in the efficiency of different vessels of the same cargo type lies mostly not in ship structure but in fuel type. Therefore, another method should be applied.

The other method is a comparison of the ship's net weekly revenue per displacement tonne (parameter E). A weekly basis was chosen because it's normal for a ship to operate a week without stopping for repair or other issues. In future research, yearly revenue should be considered, factoring in the repair and standby time. All figures are in US dollars.

$$E = \frac{Nr_w}{\mathrm{D}} \tag{15}$$

Weekly net revenue:

$$Nr_w = I_w - C_w \tag{16}$$

Weekly income:

$$I_w = \mathrm{n{*}Tc{*}}r_T, \tag{17}$$

where n – number of trips per week;

Tc – "*normal*" TEU capacity of a ship;

r_T – freight rate per TEU.

Weekly costs:

$$C_w = n*C_e*C_c, \quad (18)$$

where C_e – cost of energy, electricity or fuel spent during one trip;
C_c – crew cost.

Table 3: Data on shipping routes

№	Route	Distance R, miles	Rate r_c, USD/ TEU
1	Guangzhou-Hong Kong	83	55
2	Shanghai - Seoul	502	160
3	Shanghai - Tokyo	1048	185
4	Shanghai - Singapore	2237	233

All-electric ships from the data are assumed to have a crew of 3, because they are not big and easy to handle. It is common practice for river ships of such size to have 3-5 crew members, with electric propulsion, there is no need for a specialized engineer as it is very stable and easy to handle so 4 crew members with a daily cost of 250$ per person is chosen. Their cost is assumed 1000 $/day based on salaries and food cost. For the larger, fuel-powered ships (L = 200-300m), a crew of at least 10 is required, including the engineering department, which costs 2500 $/day.

For electric ships, C_e is calculated based on the average price of electricity in China, which is r_e =0.11 $/kWh and is found as:

$$C_e = t_s*P*r_e \quad (19)$$

When the consumption of energy during a long trip exceeds the installed (specified in the data set), it is assumed that additional E-Powerboxes are installed on the ship, and their amount is deducted from T amount used in the income calculation.

For fuel-powered ships:

$$C_e = t_s*P*f*r_f, \quad (20)$$

where f = 0.0002 T/kWh – specific fuel consumption (link);
r_f = 540 – MGO fuel price $/T. MGO is chosen because at least for short-distance trips, the areas have emissions restriction policies.

Number of trips per week is calculated as:

$$n = \frac{168}{t_s + t_p}, \quad (21)$$

where t_s is sailing time;

t_p – port time.

Sailing time:

$$t_s = R / v, \quad (22)$$

where R is sailing distance, v is ship speed.

Port time:

$$t_p = 2*Tc*a, \quad (23)$$

where a = 50 – container processing speed containers per hour

4.2 (b) Efficiency calculation result

The calculations were performed for the following routes shown in table X. It is important to note, that profitability of a trip is determined heavily by distance and freight rate. While it is true, that distance impacts freight rates positively because of fuel costs, the shipping market has always been volatile and the freight rates are not so much determined by distance but by economic and political factors (Gouvernal & Slack, 2012). However, the freight rates count not simply be set equal for all the distances, because the distance is a factor in freight rates, so they were taken from (UNCTAD, 2017). Only the stable prices were chosen, thus not counting a significant drop in one of the years. Also, 55 $ was taken as the minimal price for the shortest route as no data is available for very short routes. Albeit these prices are not exact, there are not exact prices on the market, and they only serve the purpose to illustrate freight rate growth with distance, to account for energy (fuel) costs in this paper.

Two interesting observations can be made while looking at the graphs in figures 3-6. The graphs show the E vs L relationship for every route. The relative position of the graphs and the absolutes values of E are of importance.

Following notation is used to name graphs:
Ef-P1-P2-P3 (A)
Ef – efficiency;
P1 – ship type: E – electric, F – fuel;
P2 – speed: M – max speed, S – slow speed;
P3 – route number from Table 3.
(A) – A stands for approximated
e.g. **Ef-E-S-1** stands for **E**fficiency of **E**lectric ships at **S**low speed on route **1**.

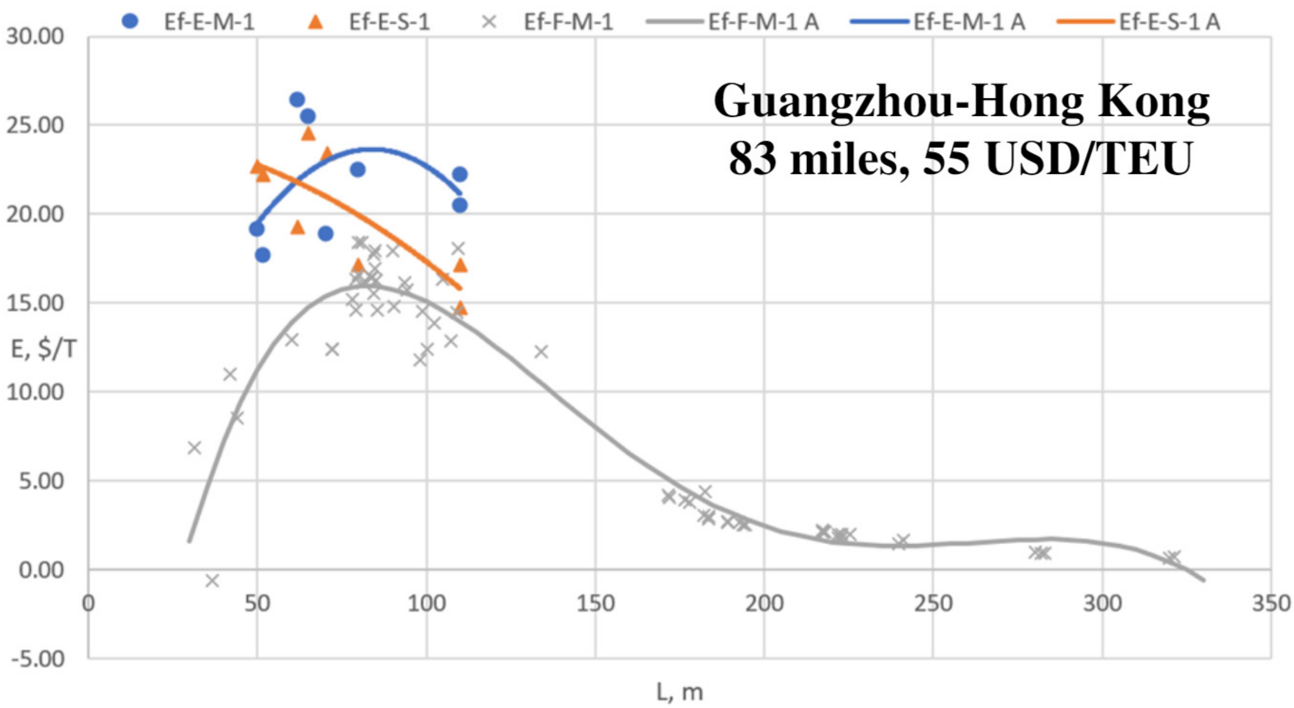

Figure 3. Route 1. Graph of E vs L for all-electric (at max and eco speeds) and fuel-powered vessels

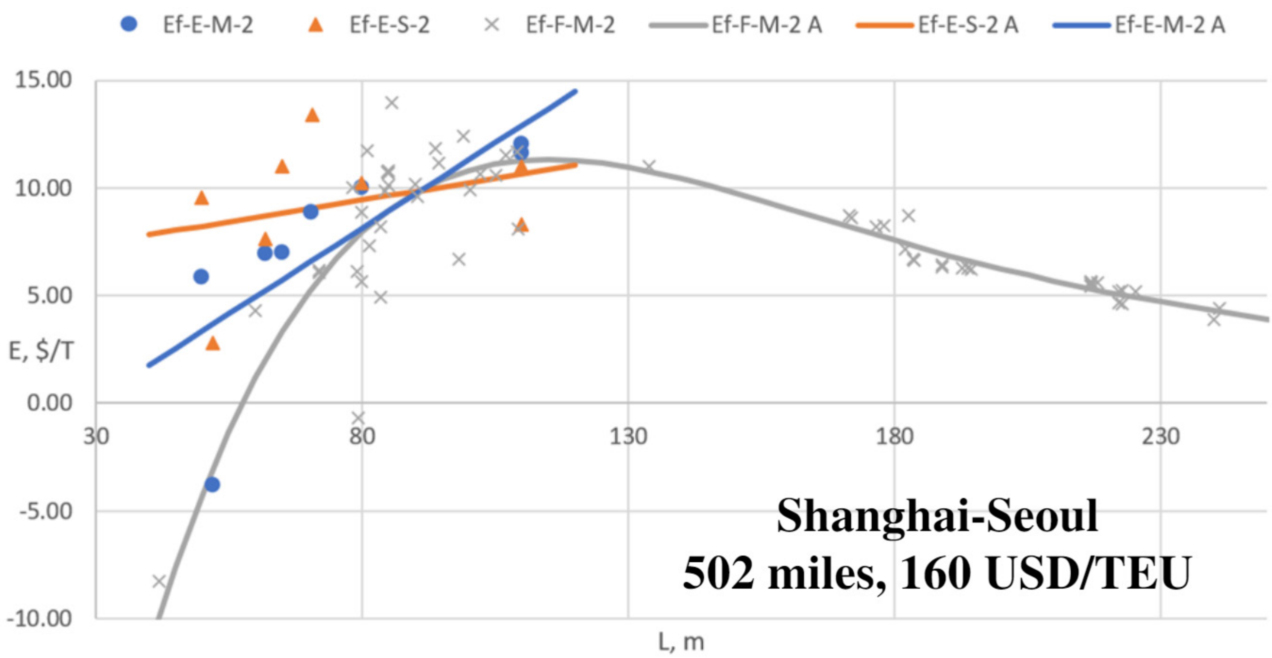

Figure 4. Route 2. Graph of E vs L for all-electric (at max and eco speeds) and fuel-powered vessels

The most important observation is the relationship between the efficiency and distance of the two energy types.

- It can be seen, that at a short distance of under 100 miles (Fig. 3.), all-electric vessels going at full speed are the most efficient (in terms of parameter E), the slow-steaming electric ships fall a little behind and finally, the fuel ships are the least effective (more than 3 times less effective). Short ships are more effective than long.

As the distance of the trip goes up, all-electric vehicles hold less of an advantage over fuel ships.

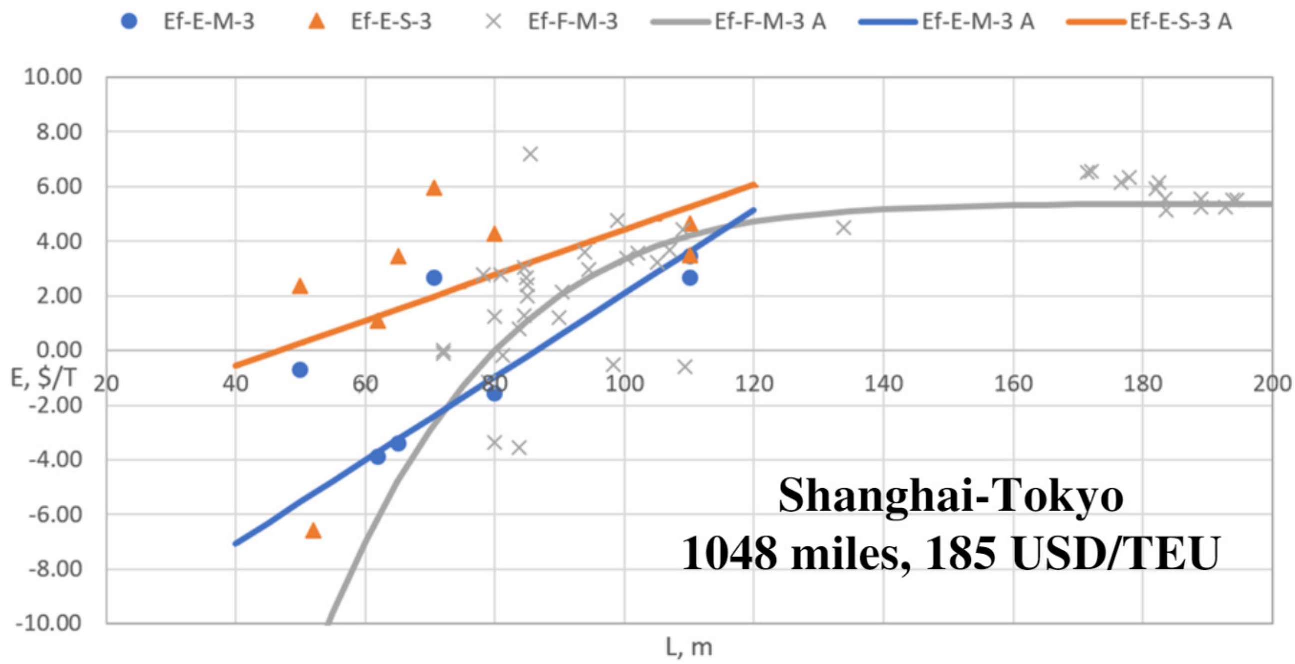

Figure 5. Route 3. Graph of E vs L for all-electric (at max and eco speeds) and fuel-powered vessels

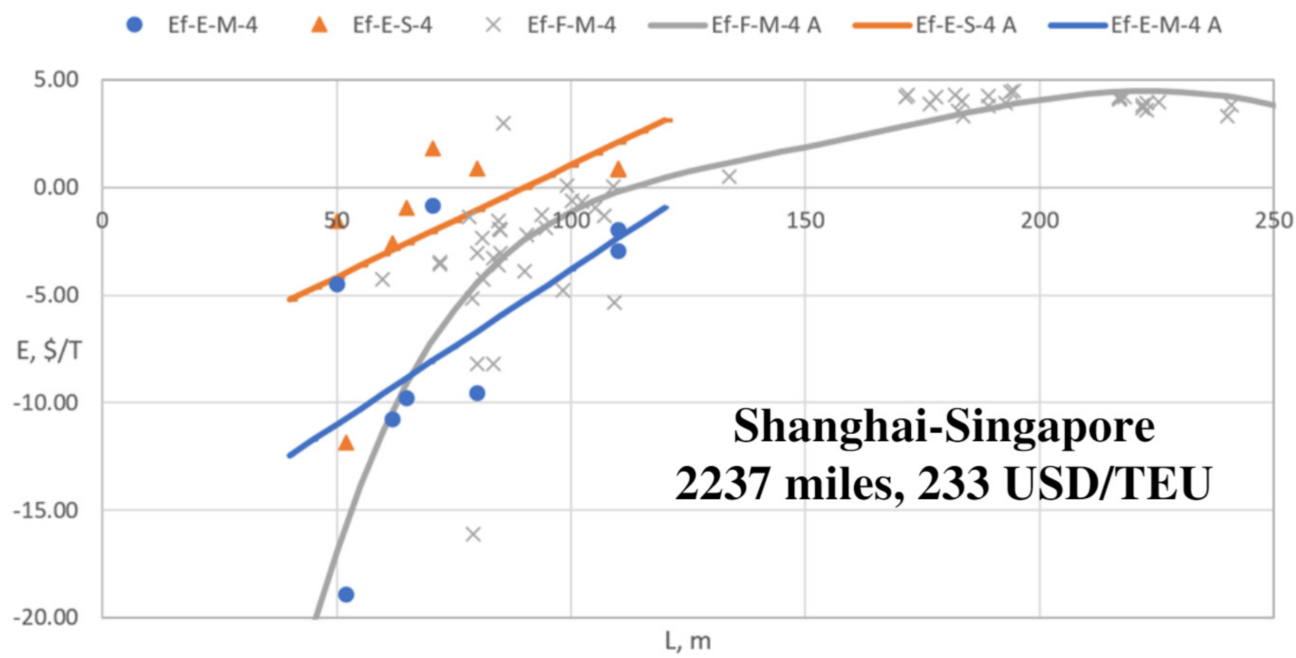

Figure 6. Route 4. Graph of E vs L for all-electric (at max and eco speeds) and fuel-powered vessels

- At a range of 500 miles (Fig. 4) they are overall as efficient as fuel ships. Also, at this range, running electric ships at the max speed no longer gives an efficiency advantage over slow steaming.

At a length of 90 m, there is a notable point where the three graphs intersect – at this ship length efficiency is equal for all fuel types. If the length is under 90 m, electric ships tend to be more efficient, if over 90 m – fuel ships take over the lead.

- At a range of 1000 miles (Fig. 5), most electric ships are less efficient than fuel ships, some being as efficient, and many even bringing negative revenue.
  It is very interesting, that the slow-steaming electric ships are still as efficient as fuel ships in this range, even while a notable portion of their TEU capacity is used for additional energy storage! Slow steaming was not calculated for fuel ships, but it was proven they are more effective. (Gurning, et al., 2017)

- At a range of over 2000 miles (Fig.6) electric vessels operate with negative revenue regardless of their speed –at this distance, their batteries take up almost all of the cargo space. Fuel ships under 110 m are not profitable, while longer fuel ships are.

The second, minor observation, is that at a very short distance, shorter electric ships are more efficient. At medium and long distances, longer electric ships have relatively higher efficiency.

On short trips, longer fuel ships are also less efficient; as the distance increases, efficiency grows with length. This re-affirms the observations made in section 4.1.

Conventional ship design practices can't be blindly applied to electric vessels. Analysis of existing specimens and their effectiveness shows, that for an electric ship to excel at its main role of transporting cargo, its principal particulars and characteristics have to differ from those of standard for fuel ships. These characteristics most notably include relative length, deadweight utilization coefficient and Froude number. The compartments have to also be arranged differently.

As electric ships only have a small machine compartment for pumps, space and displacement that would have been used for the main engine can be utilized for stowing cargo.

Lastly, electric ships use electrical energy directly almost without losses, while even the best diesel generators have an efficiency of no more than 50%.

5. CONCLUSIONS

All-electric ships are about 50% more efficient at short-distance trips than fuel ships. This is explained by the following factors:

Electric energy is cheaper than fuel, even when not considering emissions. If emissions are to be paid for, electricity becomes even more attractive.

The battery capacity-mandated low speed of electric vessels leads to lower resistance and thus lower power requirements.

Electric ships require two to three times less crew because of their reliability compared to fuel ships. It results in significantly lower operational costs. Also, the engine compartment volume can be used for cargo in certain cases.

Moreover, improved reliability also means less time spent repairing and more cargo runs can be made during a ship's lifetime. If revenue was calculated on a yearly basis and not weekly, it could be expected that this factor will contribute greatly in favour of electric vessels.

However, to analyse ship repair time, one has to look at the ship's life cycle or at least at a time of 10 years. The specimen ships were only built in a recent couple of years, some are still in the final phases of construction and testing, therefore it is too early to reliably consider their repair time.

It would be interesting to perform the same analysis including reliability and repair time statistics that would have been gathered during this decade.

All-electric container ships, unlike popular belief, can be as or more efficient as fuel ships for medium-distance cargo trips. Additional modular batteries (in form of containers) can be installed in place of cargo containers. The exact distance at which they are still efficient is determined by freight rate, which is subject to volatile changes and depends on many variables, so the viability of running an electric ship on a medium or long-distance trip is to be calculated case-by-case basis.

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